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ABORDAGEM DE PROCESSOS PARA A MEDIÇÃO E CONTROLE DO DESEMPENHO ENERGÉTICO EM MANUFATURA

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À minha esposa Sirlei por estar sempre ao meu lado, mesmo nas horas difíceis.

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Thomas Edison

Se quiser ter uma boa idéia, tenha uma porção de idéias.

Thomas Edison

Se, a princípio, a ideia não é absurda, então não há esperança para ela.

Albert Einstein

RESUMO

Até o final do século XX o tema energia não era compreendido como estratégico pela maioria das manufaturas. A literatura em eficiência energética industrial indica que essa constatação deva mudar, influenciada tanto pelo uso crescente de energia, quanto pelos problemas ambientais derivados desse consumo, associado à elevada dependência dos combustíveis fósseis. A eficiência energética pode ser um pilar importante, no que se refere à contribuição para o uso racional de energia. Neste estudo, ela é posicionada dentro do programa de pesquisa da sustentabilidade. O presente trabalho teve por objetivo, com base nas contribuições da revisão sistemática de literatura, no campo da eficiência energética industrial, desenvolver uma abordagem de processos para a medição e controle do desempenho energético. A manufatura é considerada como uma fronteira intermediária, na qual o desempenho energético pode ser estudado. Uma vez que se encontra no centro da cadeia de suprimentos, podem ser integrados a ela tanto processos anteriores, quanto posteriores. A melhoria do desempenho energético ocorre de forma contínua, dependendo de fatores contingenciais internos ou externos à organização. No caso desta tese, a organização tem o escopo de uma Empresa Estendida. O problema do desempenho energético é representado por três construções indutivas: (i) *framework* de processos para a medição do desempenho energético integrado; (ii) mapa de indicadores da eficiência energética de processos; (iii) modelo insumo-produto de processos longitudinal para a medição contínua do desempenho energético. A abordagem do problema do desempenho energético desenvolveu-se por meio de três construções dedutivas: (i) proposição de indicadores com base na eficiência empresarial; (ii) desenvolvimento de uma abordagem de simulação para alimentar o modelo na sua forma longitudinal; (iii) construção de uma abordagem para visualização multidimensional dos indicadores. Dentre as principais contribuições desta tese destacam-se: (a) organização da literatura em eficiência energética industrial, de modo que foi possível identificar os principais grupos e temas de pesquisa da área; (b) integração do *framework* que descreve a dinâmica e a estrutura do desempenho energético, do mapa que suporta o entendimento da criação de indicadores de desempenho energético em um modelo insumo-produto longitudinal; (c) entendimento e desenvolvimento de indicadores individuais e integrados nos processos para acompanhar a medição contínua do desempenho energético; (d) implementação da abordagem proposta em uma estrutura representando os processos reais de uma Empresa Estendida para manufaturar telhas, com dados simulados, utilizando a ferramenta R; (e) desenvolvimento de um sistema de gráficos em painéis para visualização multidimensional dos indicadores.

Palavras-chave: Eficiência Energética Industrial. Desempenho Energético. Indicadores de Eficiência Energética. Rede de Processos.

ABSTRACT

Until the end of the 20th century the theme of energy was not understood as strategic by most manufactures. The literature on industrial energy efficiency indicates that this finding should change, influenced both by the increasing use of energy, and by the environmental problems derived from this consumption, associated to the high dependence of fossil fuels. Energy efficiency can be an important pillar in contributing to the rational use of energy. In this study, the energy efficiency is positioned within the sustainability research program. This paper aims to develop a process approach for the measurement and control of energy performance based on the contributions of the systematic literature review in the field of industrial energy efficiency. Manufacturing is considered as an intermediate boundary, in which energy performance can be studied. Since it is at the center of the supply chain, both earlier and later processes can be integrated into it. The improvement of energy performance occurs continuously, depending on contingent factors internal or external to the organization. In the case of this thesis, the organization has the scope of an Extended Enterprise. The problem of energy performance is represented by three inductive constructions: (i) framework of process for the measurement of the integrated energy performance; (ii) map of energy efficiency indicators of processes; (iii) longitudinal input-output process model for the continuous measurement of energy performance. The approach to the energy performance problem developed through three deductive constructs: (i) proposition of indicators based on enterprize efficiency; (ii) developing a simulation approach to feed the model in its longitudinal form; (iii) construction of an approach for multidimensional visualization of indicators. Among the main contributions of this thesis are: (a) organization of the literature on industrial energy efficiency, so that it was possible to identify the main research groups and themes of the area; (b) integration of the framework that describes the dynamics and structure of the energy performance, of the map that supports the understanding of the creation of energy performance indicators in a longitudinal input-output process model; (c) understanding and developing individual and integrated indicators in the processes to accompany the continuous measurement of energy performance; (d) implementation of the proposed approach in a structure representing the real processes of an Extended Enterprise to manufacture tiles with simulated data using the tool R; (e) development of a system of graphics panel for multidimensional visualization of the indicators.

Keywords: Industrial Energy Efficiency. Energy Performance. Energy Efficiency Indicators. Network of Processes.

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ANN	*Artificial Neural Network* (Redes Neurais Artificiais)
BP-SRWE	*British Petroleum - Statistical Review of World Energy* (Revisão Estatística da Energia Mundial)
BTU	*British Thermal Unit* (Unidade Térmica Britânica)
CED	*Cumulative Energy Demand* (Demanda Cumulativa de Energia)
CHP	*Combined Heat and Power* (Calor e Energia Combinados)
COLS	*Corrected Ordinary Least Squares* (Mínimos Quadrados Corrigidos)
COP	*Conference of Parties* (Conferência das Partes)
CRS	*Constant Returns to Scale* (Retornos Constantes de Escala)
CH_4	Metano
CO_2	Dióxido de Carbono
CSC	*Conservation Supply Curves* (Curva de Conservação do Abastecimento)
DEA	*Data Envelopment Analysis* (Análise Envoltória de Dados)
DM	*Data Mining* (Mineração de Dados)
DOE-IEA	*Department of Energy-Energy Information Administration* (Departamento de Energia - Administração de Informação de Energia)
DSR	*Direct Secondary Reuse* (Reuso Secundário Direto)
EBM	*Environmentally Benign Manufacturing* (Manufatura Ambientalmente Amigável)
EC	*European Commission* (Comissão Europeia)
EE	Empresa Estendida
EED	Eficiência Energética Direta
EEI	Eficiência Energética Indireta
EER	Eficiência Energética Relativa
EI	*Energy Intensity* (Intensidade Energética)
EIO	*Economics Input Output* (Economia do Insumo-Produto)
EEMs	*Energy Efficiency Measures* (Medidas de Eficiência Energética)
EEP	*Embodied Energy of Products* (Energia Incorporada de Produtos)
EETs	*Energy Efficient Technologies* (Tecnologias Eficientes em Energia)
EIO-LCA	*Economic Input-Output Life Cycle Assessment* (Economia do Insumo-Produto Análise do Ciclo de Vida)
EIP	*Eco-Industrial Parks* (Parques Eco-Industriais)
EJ	*Exajoule* (10^{18} joules)

EPA	*Environmental Protection Agency* (Agência de Proteção Ambiental)
EPE	*Energy Product Embodied* (Energia Incorporada no Produto)
ESCOs	*Energy Service Companies* (Empresas de Serviços Energéticos)
GWh	*Giga-Watt-hora* (10^9 Wh)
IAC	*Industrial Assessment Center* (Centro de Avaliação Industrial)
IAC-ISA	*Industrial Assessment Centers-industrial Saving Assessment* (Centro de Avaliação Industrial- Avaliação de Economia Industrial)
IDA	*Index Decomposition Analysis* (Análise de Decomposição de Índices)
IEA	*International Energy Agency* (Agência Internacional de Energia)
IOA	*Input-Output Analysis* (Análise Insumo-Produto)
IPCC	*Intergovernmental Panel on Climate Change* (Painel Intergovernamental de Mudanças Climáticas)
IS	*Industrial Symbiosis* (Simbiose industrial)
Kcal	Quilocaloria
KPI	*Key Performance Indicator* (Indicador de Desempenho Chave)
KPMG	*Klynveld, Peat, Marwick, Goerdeler*
LCA	*Life Cycle Analysis* (Análise do Ciclo de Vida)
LCI	*Life Cycle Inventory* (Inventário do Ciclo de Vida)
LMDI	*Logarithmic Mean Divisia Index* (Índice de Divisão Média Logarítmica)
LPG	*Liquefied Petroleum Gas* (Gás Liquefeito de Petróleo)
MEE	Mudança na Eficiência Energética
MWh	*Mega-Watt-hora*
MTCE	*Mega Tonnes of Coal Equivalent* (Mega Toneladas de Carvão Equivalente)
N_2O	Óxido Nitroso
NT	*Numerical Taxonomy* (Taxonomia Numérica)
ONGs	Organizações não Governamentais
QEP	Questões *ex post*
OECD	*Organisation for Economic Co-operation and Development* (Organização para Cooperação e Desenvolvimento Econômico)
OPEC	*Organization of the Petroleum Exporting Countries* (Organização dos Países Exportadores de Petróleo)
OPEP	Organização dos Países Exportadores de Petróleo
PCA	*Principal Component Analysis* (Análise de Componentes Principais)

PIBIC	Programa Institucional de Bolsas de Iniciação Científica
PDCA	*Plan-Do-Chek-Act*
PDSA	*Plan-Do-Study-Act*
PJ	Petajoule (10^{15} joules)
PROCEL	Programa Nacional de Conservação de Energia Elétrica
REM	*Resource Efficiency Manufacturing* (Manufatura Eficiente em Energia)
RSL	Revisão Sistemática de Literatura
SDA	*Structural Decomposition Analysis* (Análise de Decomposição Estrutural)
SEA	*Swedish Energy Agency* (Agência Sueca de Energia)
SEC	*Specific Energy Consumption* (Consumo Específico de Energia)
SIC	*Standard Industrial Classification* (Classificação Industrial Padrão)
SFA	*Stochastic Frontier Analysis* (Análise de Fronteira Estocástica)
SMEs	*Small and Medium-sized Enterprises* (Empresas Pequenas e Médias)
SNA	*Social Network Analysis* (Análise de Redes Sociais)
TWh	Tera Watt Hora (10^{12} Wh)
UNDP	*United Nations Development Programme* (Programa de Desenvolvimento das Nações Unidas)
WCED	*World Commission on Environment and Development* (Comissão Mundial sobre Meio Ambiente e Desenvolvimento)

SUMÁRIO

1 INTRODUÇÃO

O tema energia ganhou destaque desde a crise do petróleo da década de 70. Os países voltaram a atenção para esse recurso em particular, uma vez que um planejamento energético inadequado é capaz de desestabilizar um sistema econômico inteiro, gerando gargalos. Com a criação da Agência Internacional de Energia em 1974, tornou-se perceptível que o problema não é individual de determinado país, mas do sistema como um todo. Na atualidade, a agência conta com a associação de aproximadamente 30 países, divulgando inúmeras publicações sobre política energética. Nesses relatórios destacam-se vários motivos que tornam o tema energia relevante como: segurança energética, impacto econômico e social do preço da energia, preocupação com as mudanças climáticas, competitividade das empresas, entre outros (International Energy Agency - IEA, 2014a). Segundo a Agência Internacional de Energia, suas recomendações podem provocar uma redução de 32% na emissão de CO2 na indústria, 29% em transportes, 25% em prédios, 10% em dispositivos diversos e 5% em iluminação (IEA, 2011). Apesar das medidas de política energética, Nobuo Tanaka, ex-diretor executivo da Agência Internacional de Energia, considerando uma série de indicadores, conclui que "*Como consequência, estamos caminhando para um futuro energético insustentável*" (*Worldwide Trends in Energy Use and Efficiency*, IEA, 2008, p. 2).

O problema é que a dependência de combustíveis fósseis é elevada, chegando a 80% da matriz energética mundial. Esse fato é agravado devido ao crescimento populacional, pois em 15 anos 2016-2030 o mundo terá, aproximadamente, 1 bilhão de pessoas a mais, segundo o relatório do Programa das Nações Unidas para o Desenvolvimento (UNDP, 2015). O consumo de energia está diretamente relacionado com a riqueza. Baseado em Perroni *et al.* (2016a), o consumo energético *per capita*, medido em toneladas de petróleo, nos países da Organização para a Cooperação e Desenvolvimento Econômico (OECD), foi três vezes maior (4,19/1,42) do que no Brasil. Juntamente com outros 54 países, o Brasil é classificado como país de elevado desenvolvimento humano. Dentro dessa disposição, 49 países são classificados com desenvolvimento humano muito elevado, 37 possuem desenvolvimento médio e 43 países apresentam baixo desenvolvimento humano. No Brasil o índice foi de 0,755, variando de 0,348 na República do Níger a 0,944 na Noruega. A equalização desejada, em relação ao desenvolvimento mundial, provocaria um aumento no consumo de energia maior que todos os outros fatores em conjunto, necessitando de uma solução alternativa em relação as que estão sendo apresentadas (UNDP, 2015).

Conforme reconhecido por Tanaka (IEA, 2008), o cenário desejado envolve ações múltiplas, tanto do lado da demanda quando do lado da oferta de energia. Do lado da oferta, esforços têm sido feitos para viabilizar fontes renováveis de energia como biomassa, ondas do mar, geotérmica, eólica e solar (WEE *et al.*, 2012). Conforme relatório da Agência Internacional de Energia (*Tracking Clean Energy Progress* - IEA, 2014b), tendo por base o ano de 2011, a participação de energias renováveis no processo de geração de energia foi de 20%, mas esse cenário está mudando, pois em relação ao mesmo ano, o crescimento de energias renováveis foi de 2,7% nos países que não fazem parte da OECD e 6,7% nos países da OECD. O investimento necessário em busca da transição para a energia limpa foi estimado em 1% do produto global (0,8 Trilhões US$ para um PIB mundial de 83 Trilhões US$) (IEA, 2014b).

Considerando o lado da demanda, reconhece-se que a eficiência energética pode ser um pilar importante de forma a contribuir para o uso mais racional e sustentável da energia. Segundo a IEA, a contribuição da eficiência energética para redução do CO2 pode chegar a 44% (IEA, 2014b). Com base em seu banco de informações, a agência afirma que se não fossem as ações para a melhoria da eficiência energética, o consumo de energia em 2005 teria sido 58% maior (IEA, 2008).

O problema energético é multidimensional e envolve todas as instituições organizadas. Muitas medidas destacadas pelos relatórios da Agência Internacional de Energia são medidas agregadas, ou gerais de políticas para o estímulo do uso racional de energia. A literatura acadêmica recente tem postulado que a função de se preocupar com a eficiência e gestão da energia não é somente dos órgãos governamentais e não governamentais, ou mesmo de empresas e indústrias consideradas intensivas em energia (GORDIC *et al.*, 2010; BUNSE *et al.*, 2011; NEGAI *et al.*, 2013; SHULZE *et al.*, 2016). A preocupação retratada nesta tese é com os aspectos da incorporação da gestão de energia nos sistemas produtivos, sendo que um desses aspectos refere-se ao acompanhamento do desempenho energético. O problema é que, conforme reconhecido por Bunse *et al.* (2011), no âmbito da gestão do desempenho energético, falta a construção de *frameworks*, bem como o desenvolvimento e a interpretação de indicadores para a medição do desempenho energético, e há uma escassez de modelos na qual a lógica da eficiência energética pode ser operacionalizada.

Com base na literatura consultada em Gestão e Operações (PINHEIRO DE LIMA *et al.*, 2009), a medição do desempenho é fundamental tanto para acompanhar a formulação da estratégia como para desenvolver planos de ações que têm o objetivo de melhorar o resultado. Assim, a temática deve ser discutida com mais interesse devido ao fato de que na área de energia existem muitas discrepâncias a respeito de como o desempenho energético de sistemas produtivos pode ser projetado e operacionalizado tanto no nível de processos, quanto de cadeias de produção.

Com embasamento nas contribuições de uma revisão sistemática da literatura, no campo da eficiência energética industrial, o objetivo desta tese foi desenvolver uma abordagem de processos para medição e controle do desempenho energético integrado. A terminologia - integrado - refere-se ao nível de agregação do desempenho por meio de processos. A principal pergunta de pesquisa para esta tese é: como desenvolver uma abordagem de processos para a medição contínua do desempenho energético, que tenha flexibilidade na composição de processos e possibilidade de escolha de indicadores que sejam relevantes ao contexto da análise?

No contexto desta tese, a palavra processo refere-se a processos de produção, sendo este o mecanismo responsável pela transformação dos insumos [*input*] em produtos/serviços [output] (ALBINO *et al*., 2003; SLACK *et al*., 2007; KUHTZ *et al*., 2010). Um processo pode ser definido como "*uma abordagem para atingir os objetivos gerenciais por meio da transformação de insumos em produtos*" (SHEHABUDDEN, *et al*., 1999, p. 14). A definição nesse formato torna mais fácil a hierarquização do sistema produtivo, afinal uma máquina que transforma matéria prima (insumo) em algum tipo de produto (recurso intermediário) está dentro do escopo da definição. Considerando uma empresa ou uma cadeia, como um conjunto de processos responsáveis pela transformação de insumos em produtos/serviços, o processo de produção pode ser composto em diferentes níveis de agregação. O conjunto de processos pode formar uma rede, com produtos intermediários e produtos finais (SLACK *et al*., 2007; KUHTZ *et al*., 2010).

Os processos são considerados como a base na qual o desempenho energético se concretiza, sendo possível a criação de indicadores para os processos e a integração desses indicadores em uma rede de processos ou Empresa Estendida (EE). O conceito EE foi apresentado primeiramente por O'Neill e Sackett (1994), com a possibilidade de criar uma estrutura de governança complementar. A Enterprise Estendida é uma organização baseada no conhecimento que utiliza as forças intelectuais distribuídas de seus membros, explorando a sinergia necessária para satisfazer a diversidade exigida pelos clientes e inovar, não apenas no produto, mas também nas práticas de gestão (O'NEILL; SACKETT, 1994).

O desempenho energético, por sua vez, está relacionado com a eficiência energética ou ao menor uso de energia para determinado fim (PATTERSON, 1996). Três hipóteses *ad hoc* são fundamentais para esta tese: (i) o problema da eficiência energética faz parte da heurística positiva do cinturão protetor do programa de pesquisa da sustentabilidade; (ii) é possível identificar tanto medidas, quanto tecnologias, e com sua implementação elas possam melhorar o desempenho energético dos processos; (iii) é possível dividir uma entidade organizacional (Empresa, Cadeia, Empresa Estendida) em um número finito de processos principais. Essas hipóteses podem ser interpretadas como pressupostos criados com o objetivo de sustentar o desenvolvimento desta tese.

1.1 PROBLEMA DE PESQUISA

Independentemente de ser ou não intensiva em energia (THOLLANDER; OTTOSSON, 2010), baseado na gestão de operações sustentáveis (MACHADO, 2015) qualquer organização que utilize energia nos seus processos deveria se preocupar com a gestão de energia (BUNSE *et al*., 2011). Esta tese baseia-se em pesquisas sobre o uso de energia, pelo ramo de manufatura, mas como ele se comporta como um fluxo, as aplicações (medidas, modelos, indicadores, entre outros) podem envolver os processos anteriores ou posteriores à manufatura. O problema muitas vezes é desconhecido devido ao fato de a atenção estar voltada apenas para à energia direta gasta nos processos em questão, como: eletricidade, diesel, gás natural, térmica, entre outras. Quando é adotada a perspectiva de uma cadeia ou rede de produção, o cenário fica mais completo. Produtos que aparentemente seriam de baixa intensidade energética, em um primeiro momento, podem ser altamente intensivos em energia, porque utilizam produtos e serviços altamente intensivos em energia. Um exemplo clássico no Brasil é o setor de transportes, responsável por quase 30% do consumo de energia do país (PERRONI *et al*., 2016a). Uma empresa não intensiva pertencente à manufatura de bebidas, por exemplo, que utiliza intensivamente o transporte, não tem informações sobre o impacto que os seus produtos causam, porque não conhecem o desempenho em termos da energia incorporada em seus produtos ou cadeia de processos.

Como a energia se comporta como um fluxo nas operações de produção é importante conhecer tanto o desempenho direto quanto o desempenho acumulado. O problema é que, conforme reconhecido por Bunse *et al*. (2011) e evidenciado em Schulze *et al*.,(2016), faltam *frameworks* em que essa sistemática pode ser pensada, bem como o desenvolvimento e a interpretação de indicadores, e há uma escassez de modelos em que a lógica da eficiência energética possa ser operacionalizada.

O problema do desempenho energético é complexo porque envolve uma grande multidisciplinaridade. A atração de várias áreas pelo tema desempenho/eficiência energética pode ser explicada, de uma forma geral, pela busca da produção e consumo sustentável de bens e serviços (MACHADO, 2015).

Com base na literatura (PAKARINEN *et al*., 2010; BUNSE *et al*., 2011; KHANNA *et al*., 2014), o problema do desempenho energético está relacionado ao paradigma emergente da sustentabilidade. O interesse dos pesquisadores pelo tema vem de uma preocupação real com a sobrevivência ou (auto sobrevivência), tendo como objetivo a proliferação da espécie. No contexto desta tese, a sustentabilidade é compreendida como um programa de pesquisa de Lakatos (1978).

Na estrutura das revoluções científicas de Kuhn (1962), a ciência é paradigmática, cujo progresso ocorre em três fases: (i) pré-ciência, (ii) ciência normal e (iii) crise/revolução. Na pré-ciência as ideias ou teorias não estão organizadas de uma forma que explique completamente o fenômeno, uma vez que não existe a hegemonia de uma explicação específica. O estágio da ciência normal é aquele em que o paradigma é estabelecido, sendo desenvolvidas construções mais elaboradas (métodos, técnicas, entre outros) de forma a explicar de maneira adequada os problemas. Na ciência normal, os cientistas se debruçam para resolver "quebra-cabeças", que estão ligados ao campo científico. Com a apresentação de novos problemas, impossíveis de serem resolvidos pelas construções do paradigma vigente, ocorre a crise e revolução, e não havendo diferentes versões teóricas para explicar o problema, surge um novo paradigma.

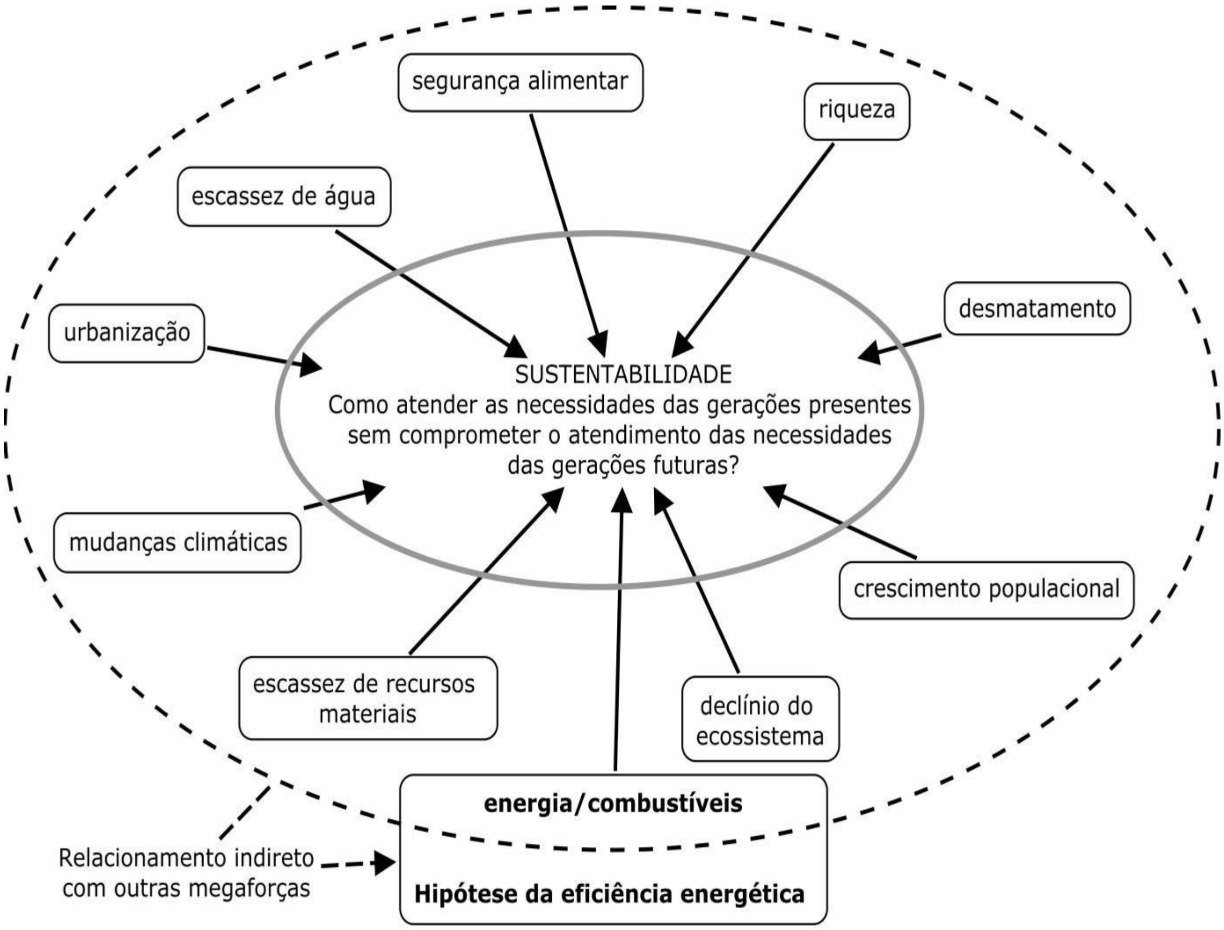
Na busca da junção da ciência progressiva de Karl Popper e dos paradigmas de Thomas Kuhn, o trabalho de Imre Lakatos (LAKATOS, 1978) "A metodologia dos programas de pesquisa científica" [*The methodology of scientific research Programmes*] propõe que a ciência se desenvolve por meio de programas de pesquisa. Este, por sua vez, tem um núcleo rígido que é protegido da falsificação por um cinturão de hipóteses auxiliares. Os cientistas se debruçam a resolver determinados problemas dentro do cinturão protetor, identificando os que serão resolvidos (heurística positiva) e os que serão deixados de lado (heurística negativa).

Seja denominado como paradigma de Kuhn (1969) ou núcleo rígido de Lakatos (1978), o arcabouço, para a presente tese, está associado à questão da sustentabilidade. A principal hipótese do núcleo da sustentabilidade está relacionada à pergunta: como atender às necessidades das gerações presentes sem comprometer o atendimento das necessidades das gerações futuras? Essa pergunta apareceu no relatório Brundtland de 1987 (WCED, 1987). A complexidade do programa de pesquisa da sustentabilidade é grande, uma vez que, conforme relatório da KPMG (2012), a sustentabilidade global envolve o estudo de dez forças:

mudanças climáticas, escassez de recursos materiais, declínio do ecossistema, segurança alimentar, energia/combustíveis, crescimento populacional, urbanização, escassez de água e desmatamento (MACHADO, 2015). Pode-se argumentar que as forças globais levantadas pelo KPMG (2012) formam a heurística positiva do programa de pesquisa de Lakatos (1978) para a sustentabilidade.

De acordo com essas proposições, a hipótese da eficiência energética faz parte do cinturão protetor do núcleo/paradigma da sustentabilidade. Para ser sustentável é pré-requisito ser energeticamente eficiente. Dessa forma, existe maior dificuldades no falseamento da hipótese ou pressuposto (LAKATOS, 1978). A Figura 1 situa a eficiência energética no programa de pesquisa da sustentabilidade.

Figura 1 - Posicionamento da eficiência energética no programa de pesquisa da sustentabilidade



Fonte: Adaptado de Lakatos 1978; WCED, 1987; KPMG, 2012; Machado, 2015

O que torna o tema energia/eficiência energética complexo, dentro do programa de pesquisa, é o relacionamento que a energia tem com todos os outros nove temas relevantes, sendo algumas relações mais evidentes, enquanto, outras menos aparentes, como o relacionamento da energia com as mudanças climáticas, utilização de materiais, urbanização, riqueza entre outras. A revisão sistemática da literatura, conduzida por esta tese, confirma o relacionamento descrito acima (PERRONI *et al*., 2016b).

Quando o problema do desempenho energético é estudado em nível empresarial, notam-se "escalas práticas diferentes". Autores como Bunse *et al*. (2011) e Schulze *et al*. (2016) reconhecem a necessidade do *benchmarking* da eficiência energética. A questão é como fazer o *benchmarking* se as empresas não fazem o controle do seu próprio desempenho? É reconhecido amplamente na literatura (CHRISTOFERSEN *et al*., 2006; THOLLANDER; OTTOSSON 2010; ATES; DURKBASA, 2012; RUDBERG *et al*., 2013; SCHULZE *et al*., 2016) que a gestão de energia não tem prioridade elevada. Isso implica que as empresas não gastarão os seus recursos para medir algo que não lhes interessa. A relação causa e efeito pode ser:

a) As empresas começam a se interessar por gestão de energia;
b) As empresas querem controlar o seu desempenho energético em termos de melhoria;
c) Existirá a percepção que o problema da energia não é um problema isolado de uma empresa em específico;
d) Existirá, posteriormente, a necessidade de fazer *benchmarking* entre empresas e cadeias.

O problema de pesquisa descrito na tese está relacionado ao efeito do interesse pela gestão de energia, no qual a maioria dos artigos da revisão da literatura reitera que irá se intensificar (SCHULZE *et al*., 2016). De acordo com a presente tese, o efeito de querer "monitorar o desempenho" dependerá da evolução do chamado "programa de pesquisa da sustentabilidade" da Figura 1. Ou seja, quanto mais as hipóteses que reforçam o programa de pesquisa se tornem latentes, como aumento do custo da energia, problemas ambientais e escassez de recursos energéticos mais as empresas aderirão à gestão de energia e naturalmente, vão querer monitorar o seu desempenho. Colocado dessa forma, o gradiente do problema do desempenho energético é condicional, ou seja, dependendo principalmente de fatores contingenciais. Esse posicionamento de evolução está de acordo tanto com as pesquisas da área de medição do desempenho (BITITCI *et al*., 2012), quanto com as pesquisas da área de energia (NEGAI *et al*., 2013).

Segundo estudo acerca dos desafios futuros da área de medição de desempenho, conduzido por uma equipe multidisciplinar, especializada nesta mesma área, incluindo: gestão de operações, gestão de manufatura, gestão de serviços, gestão estratégica, engenharia industrial, gestão de instalações, gestão do setor público, psicologia, gestão de recursos humanos e gestão da mudança a evolução da literatura, em medição de desempenho, depende do contexto emergente. Esse mesmo estudo chega à conclusão que os principais desafios futuros para medição do desempenho são entender a medição do desempenho como: (i) um sistema social; (ii) um sistema que aprende; (iii) uma rede auto poética (BITITCI *et al*., 2012).

O desenvolvimento do presente trabalho faz-se necessário porque as instituições sociais (empresas, governos, ONGs) têm apenas controle parcial sobre os fatores de contingência (escassez de recursos energéticos, problemas ambientais, crescimento populacional, entre outras), pelo menos em um horizonte de médio prazo. O cenário descrito dessa forma fará uma pressão contingencial cada vez mais forte no sistema energético, que está relacionado à dez (10) forças da sustentabilidade (Figura 1), exigindo em médio e longo prazo controle do desempenho, com o objetivo de reduzir ou otimizar o uso de energia. Como a energia está relacionada aos fatores contingenciais: mudanças climáticas, urbanização, escassez de água, produção de alimentos, crescimento da riqueza, desmatamento, crescimento populacional, ecossistema e materialização/desmaterialização; no futuro (longo prazo) um novo sistema que interliga essas questões será necessário, complementando o atual sistema financeiro contábil das empresas e governos. Esse sistema deverá ser menos volátil e mais realista, porque trabalharia com a evolução da produtividade/inovação real das empresas ou cadeias, evitando as atuais especulações financeiras dos mercados.

1.2 OBJETIVOS DA PESQUISA

O desempenho energético é um assunto complexo porque é multidimensional, ou seja, pode englobar muitas variáveis e, dificilmente, o estudo acerca desse tema poderia ser abordado sem o desenvolvimento de construções múltiplas, pois ele possui objetivos múltiplos.

O Quadro 1 desdobra o principal objetivo da tese em oito objetivos específicos. Os objetivos foram extraídos de oito artigos que fazem parte do projeto de pesquisa da tese. Este, por sua vez, será apresentado na próxima seção.

Os objetivos desta tese não estão linearmente relacionados com os objetivos dos artigos, embora as extrações feitas para a construção deste trabalho estão contidas nos artigos.

Quadro 1- Objetivos da tese

Objetivo Geral		**Desenvolver uma abordagem de processos para a medição e controle do desempenho energético integrado**
Objetivos Específicos	**I.**	Destacar a importância do aspecto macro energético para a eficiência energética
	II.	Identificar as principais contribuições teóricas e práticas para a medição do desempenho energético no campo eficiência energética industrial aplicando uma revisão sistemática de literatura
	III.	Propor um *framework* de processos para a medição do desempenho energético integrado
	IV.	Construir um mapa de indicadores da eficiência energética de processos
	V.	Propor um modelo insumo-produto de processos longitudinal para a medição contínua do desempenho energético
	VI.	Desenvolver indicadores para a medição do desempenho energético baseado na abordagem de processos proposta
	VII.	Desenvolver uma abordagem de simulação para o modelo insumo-produto de processos longitudinal.
	VIII.	Construir uma abordagem para visualização multidimensional dos indicadores

Fonte: o autor, 2017.

1.3 PROJETO DE PESQUISA

Conforme destacado anteriormente, o objetivo desta tese é apresentar uma abordagem de processos para a medição e controle do desempenho energético integrado. Esta seção apresenta os artigos da pesquisa, a abordagem metodológica e o mapa da tese. Este mapa exibe o relacionamento de construção entre os objetivos da tese, a metodologia e as informações extraídas dos artigos e de outras fontes que fizeram parte do projeto de pesquisa.

Além dos artigos que estão integralmente nos Apêndices F ao M, duas outras fontes de informação fazem parte do projeto de pesquisa: 6 projetos de iniciação científica, conforme Apêndice E, e um Estudo Independente, que é um estudo dirigido ao tema da tese. O relacionamento insumo-produto foi o Estudo Independente escolhido, de acordo com o Apêndice D.

a) Artigos do projeto de pesquisa

A construção da presente tese deu-se a partir da elaboração de sete (7) artigos propostos para estudar o desempenho energético, mais um (1) artigo de síntese que agrega o desenvolvimento dos sete artigos anteriores, elaborados ao longo de 4 anos (2013-2016), publicados em congressos e revistas, os quais podem ser vistos na Tabela 1 e de forma integral nos apêndices F ao M.

Tabela 1- Relação de artigos do projeto de pesquisa

Artigos	**Objetivo**	**Metodologia**	**Submissão Revista**	**Congresso**	**Status Revista**
1	Estimar e analisar a elasticidade renda da matriz energética brasileira	Cointegração, ANCOVA	IJEEP - International Journal of Energy Economics and Policy	-	Publicado
2	Avaliar o impacto da poupança de energia do programa de eficiência energética sobre o risco das empresas de energia	EQMA, EWMA, Regressão em Painel, Regressão Polinomial	IJEEP - International Journal of Energy Economics and Policy	-	Publicado
3	Propor um modelo de processo para a revisão sistemática da literatura aplicado no campo eficiência energética industrial	Modelo, Análise de Redes Sociais, Análise de Conteúdo, Matemática e Mineração de Texto	SORMS - Surveys in Operations Research and Management Science	POMS-2015	Primeira Revisão
4	Apresentar o resultado de uma revisão sistemática da literatura no campo da eficiência energética industrial com a perspectiva da gestão de energia	Análise de Redes Sociais, Análise de Conteúdo, Mineração de Texto e *Framework*	RSER - Renewable & Sustainable Energy Reviews	POMS-2016	Submetido
5	Proposta de um modelo para avaliar o desempenho energético industrial	Revisão de Literatura, *Framework*	-	ICPR-2014	-
6	Investigar o relacionamento entre eficiência empresarial e a adoção de práticas em eficiência energética	DEA, SFA, COLS, Regressão Quantílica	IJPE - International Journal of Production Economics - 2016	ICPR-2015	Aceito Online
7	Propor um processo dinâmico visual baseado no modelo insumo-produto empresarial	*Framework*, Mapa, Modelo, Simulação	-	P&OM-2016	-
8	Abordagem de processos para a medição contínua do desempenho energético	*Framework*, Mapa, Modelo, Simulação	Revista a ser definida	EPPGEP-2017	-

Fonte: O autor, 2016.
Nota: Artigo-Apêndice: 1-F; 2-G; 3-H; 4-I; 5-J; 6-K; 7-L; 8-M.

Os artigos apresentados não configuram a tese propriamente dita, mas as construções destes balizam a evolução do projeto de pesquisa.

Os artigos 1 e 2 apresentados nos Apêndices F e G (PERRONI *et al.*, 2015a; PERRONI *et al.*, 2016a) foram propostos antes da revisão da literatura, com o objetivo de entender de forma quantitativa (utilizando-se de métodos quantitativos) a demanda de energia entre setores, planejamento energético, bem como o funcionamento da política energética.

Dois projetos de iniciação científica (PIBIC, 2013-2014) contribuíram para o estudo dos fatores tecnológicos, políticos, econômicos e ambientais que influenciaram o uso de energia (Apêndice E). O Estudo Independente que investigou o relacionamento insumo-produto contribuiu para o entendimento dos modelos insumo-produto (Apêndice D).

Os artigos 3 e 4, exibidos nos Apêndices H e I (PERRONI *et al.*, 2015b; PERRONI *et al.*, 2016b), apresentam a revisão sistemática da literatura. A revisão sistemática foi processada no campo Eficiência Energética Industrial. Ela possui a função de mapear as principais contribuições no campo da eficiência energética industrial.

Os artigos 5,6 e 7, Apêndices J, K e L (PERRONI *et al.*, 2014; PERRONI *et al.*, 2016c; PERRONI *et al.*, 2016d) fazem parte do núcleo da tese. No artigo 5 (PERRONI *et al.*, 2014) é proposto um modelo para avaliar o desempenho energético. No artigo 6 (PERRONI *et al.*, 2016c) é discutido o relacionamento entre desempenho e eficiência energética. O artigo 7 (PERRONI *et al.*, 2016d) propõe um processo dinâmico visual, baseado no modelo insumo-produto de processo para o monitoramento e controle das ações de gestão de energia da Empresa Estendida (EE).

O artigo 8 (PERRONI *et al.*, 2017) faz uma síntese integrando elementos dos artigos anteriores, principalmente os 5,6 e 7. O objetivo do artigo 8 é o mesmo da tese, o desenvolvimento de uma abordagem de processos para a medição e controle do desempenho energético.

b) Abordagem metodológica

Como pode ser observado na Tabela 1, cada um dos oito artigos apresentou uma discussão metodológica pertinente ao objetivo proposto. A grande questão a ser respondida é: qual a abordagem metodológica para a tese?

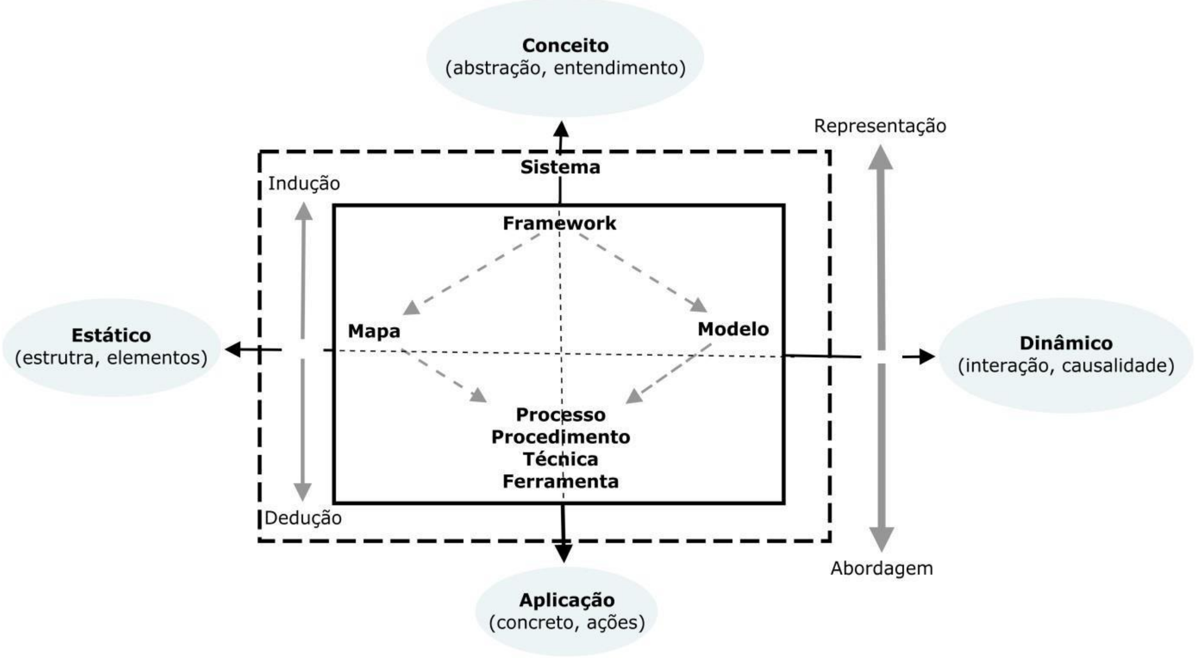
Devido à complexidade gerada pelo problema da eficiência energética, a metodologia para “desenvolver uma abordagem de processos para a medição e controle do desempenho energético integrado”, deve ser robusta o suficiente para incorporar os relacionamentos sistêmicos.

As questões complexas, com as quais os pesquisadores de gestão se defrontam, podem ser descritas de muitas maneiras, levando à confusão de terminologias. Tomando como base a perspectiva da gestão da manufatura, o Instituto de Manufatura da Universidade de Cambridge [*Institute for Manufacturing, University of C*ambridge] apresenta definições em termos de como os problemas poderiam ser representados e abordados do ponto de vista da engenharia (SHEHABUDDEN, *et al*., 1999). A Figura 2 mostra como a representação e a abordagem de problemas pode ser idealizada.

Assim como em Kuhn (1962), o ponto de partida é o posicionamento do problema dentro do paradigma, o qual, como foi discutido na seção anterior, o problema do desempenho energético foi posicionado dentro do paradigma emergente da sustentabilidade. Na definição de Shehabudden, *et al*. (1999, p. 7) "*um paradigma descreve suposições e convenções estabelecidas que sustenta uma perspectiva particular em uma questão de gestão*". Paradigma definido dessa forma se assemelha mais ao programa de pesquisa de Lakatos (1978).

Na Figura 2, as representações e abordagens são posicionadas em quatro dimensões: conceitual, aplicada, estática e dinâmica. As representações (*framework*, mapa, modelo) são maneiras de relatar os problemas mais conceituais. As abordagens (processo, procedimento, técnica e ferramentas), de cunho mais prático, são maneiras de implementar os conceitos contidos nas representações. Outra dimensão relevante é a interação dos elementos da composição do problema, pois sendo estática se parece mais com um mapa, e sendo dinâmica assemelha-se mais com um modelo. As abordagens e representações funcionam dentro de um sistema, sendo este "*um conjunto de elementos inter-relacionados delimitados com propriedades emergentes sendo representado dentro do contexto do paradigma*" (SHEHABUDDEN, *et al*., 1999).

Figura 2- Metodologia da representação e abordagem da pesquisa



Fonte: Adaptado de Shehabudden, *et al*. (1999)

Para propor uma abordagem de processos para a medição e controle do desempenho energético integrado é necessário ter uma delimitação ou foco. Durante a construção dos trabalhos, que deram origem ao primeiro objetivo específico, pesquisaram-se fatores históricos relacionados à energia e a eficiência energética, bem como o relacionamento entre as matrizes de energia nacional e o modelo insumo-produto. Contudo, concluiu-se que o setor industrial é relevante para o foco da pesquisa, tanto pelo uso considerável de energia, quanto pelo impacto que causa em relação aos demais setores. A atividade econômica é dividida entre agricultura, indústria e serviços, conforme sistema de classificação internacional padrão [*International Standard Industrial Classification* (SIC)]. O setor industrial é composto pelas subdivisões: Indústria Extrativista (divisão 10-14), Manufatura (divisão 15-37), Oferta de Eletricidade, Gás e Água (divisão 40-41) e Construção (divisão 45) (NAPP, *et al*., 2014). Os processos industriais consomem aproximadamente um terço da energia global (NAPP et al., 2014), mas essa taxa varia entre os países, chegando a 70% na China (SHI et al., 2010; SHEN et al., 2012). Segundo uma classificação mais ampla, feita pela agência de informações do departamento de energia dos Estados Unidos DOE-EIA (2010), incluindo a manufatura, a agricultura, a mineração e a construção o consumo do setor industrial chega a aproximadamente 50% da energia mundial entregue. Quando acrescentados os problemas ambientais, derivados do uso de combustíveis fósseis, como mais um agravante, torna-se indispensável à incorporação da gestão de energia na gestão da produção industrial

O foco principal desta tese está na atuação da manufatura, enquanto usuária de diversas fontes de energia. Baseado em Napp *et al*. (2014), diversos trabalhos acadêmicos referem-se ao setor industrial, quando na verdade estão trabalhando com a manufatura. O setor de manufatura é considerado por esta tese como uma fronteira intermediária, na qual o desempenho energético pode ser estudado. Uma vez que a manufatura está próxima do centro da cadeia de suprimentos, podem ser integrados tanto processos anteriores quanto posteriores.

O segundo objetivo específico está relacionado ao foco da pesquisa, em que foi realizada uma revisão sistemática da literatura no campo de eficiência energética industrial. Ela contribuiu com a identificação do quadro teórico e prático da pesquisa, dando suporte às discussões, ao desenvolvimento das representações e abordagens realizadas por esta tese.

O terceiro objetivo específico é propor um *framework* estrutural do desempenho energético integrado. Conforme Figura 2, um *framework* tem um nível conceitual mais elevado sendo que "*suporta o entendimento, comunicação da estrutura e o relacionamento dentro do sistema para um propósito definido*" (SHEHABUDDEN, *et al*., 1999, p. 9). O *framework* estrutural do desempenho energético integrado apresenta duas questões fundamentais: (i) o desempenho energético pode ser melhorado continuamente; (ii) o desempenho energético pode ser integrado em um fluxo ou rede.

O quarto objetivo específico é a proposta de um mapa dos indicadores de eficiência energética de processos. Um mapa "*suporta o entendimento do relacionamento estático entre os elementos do sistema*" (SHEHABUDDEN, *et al*., 1999, p. 11). Os elementos do sistema para esse objetivo são a gama de indicadores que podem ser criados para representar o desempenho energético.

Ainda na parte da representação, na Figura 2, o quinto objetivo específico é a proposta de um modelo insumo-produto de processo longitudinal. Um modelo "*suporta o entendimento da interação dinâmica dos elementos do sistema*" (SHEHABUDDEN, *et al*., 1999, p. 13). Segundo Ragsdale (2008), existem vários tipos de modelos: mental, visual, físico e matemático. Dentre estes últimos encontram-se os prescritivos, os preditivos e os descritivos (RAGSDALE, 2008). O modelo proposto se assemelha ao matemático descritivo. A função do modelo é descrever como o sistema irá operar se houver uma mudança em determinadas variáveis, em outras palavras, capturar o relacionamento de causa e efeito (SHEHABUDDEN, *et al*., 1999).

Os três últimos objetivos específicos (construção de indicadores, abordagem de simulação e visualização) estão relacionados ao fato de como abordar de maneira operacional o problema do desempenho energético, identificando procedimentos e técnicas que podem ser aplicadas como: procedimentos para construir as tabelas insumo-produto, técnicas de cálculos matriciais, técnicas de construção de indicadores de eficiência, entre outros.

A abordagem do problema do desempenho energético pode ser construída e implementada utilizando-se de processos, procedimentos, técnicas e ferramentas como destacadas na Figura 2. O processo pode ser definido como "*uma abordagem para atingir os objetivos gerenciais por meio da transformação de insumos em produtos*" (SHEHABUDDEN, *et al*., 1999, p. 14). Para esta tese, os processos são unidades fundamentais para calcular e integrar o desempenho energético, medindo o desempenho de forma contínua. Para atingir esse objetivo foi utilizado o modelo insumo-produto de processos (LIN; POLENSKE, 1998; POLENSKE; MCMICHAEL, 2002), adaptado para funcionar de forma longitudinal. Um procedimento "*é uma série de passos para operacionalizar um processo*", enquanto uma técnica *"é uma maneira estruturada para completar parte de um procedimento*", por sua vez a ferramenta *"facilita a aplicação prática da técnica*" (SHEHABUDDEN, *et al*., 1999, p. 15). Os procedimentos e técnicas para operacionalizar o modelo insumo-produto de processos são dados por Lin e Polenske (1998), derivado dos trabalhos de Wassily Leontief (1966). A ideia central do modelo insumo-produto é que existe vínculo fundamental entre o volume de produção em cada processo e o vulto de insumos que ele absorve. A relação descrita acima é linear entre a quantidade de insumos energéticos e a quantidade a ser produzida de produtos e serviços. O modelo insumo-produto de processos tem procedimentos e técnicas específicas como a elaboração das tabelas insumo-produto e o cálculo dos coeficientes direto-indiretos (LIN; POLENSKE, 1998).

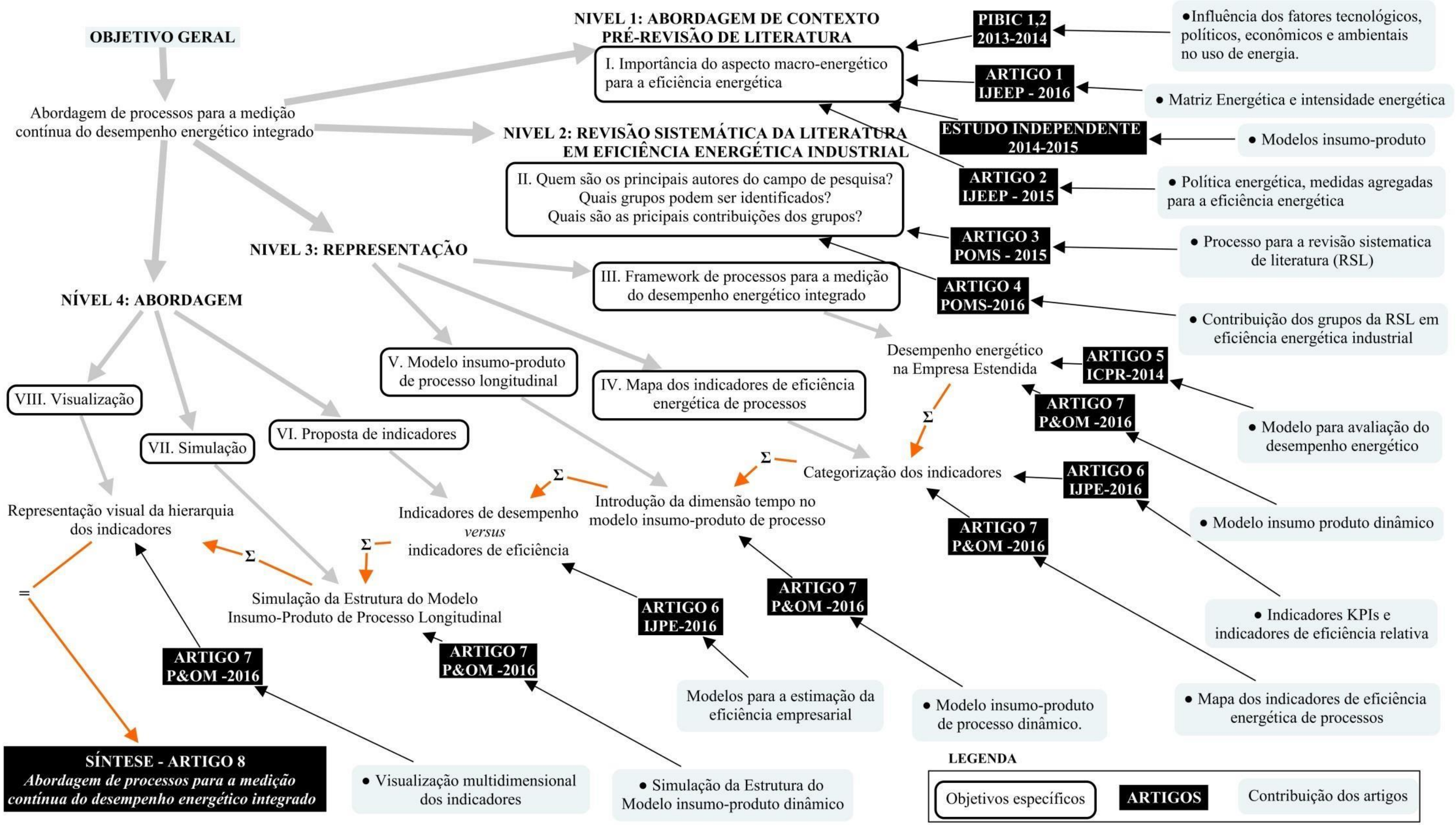
c) Mapa da tese

A Figura 3 faz a integração dos objetivos da pesquisa com a abordagem metodológica em um mapa conceitual, sendo estabelecidas quatro divisões: (i) objetivo geral, (ii) objetivos específicos, (iii) artigos e (iv) contribuições dos artigos. É importante salientar que os objetivos dos artigos não estão linearmente relacionados aos da tese, ou seja, a construção desta é uma composição da contribuição dos artigos. O Quadro 1 e a Tabela 1 apresentaram os objetivos da tese e dos artigos, respectivamente.

A apresentação dos capítulos desta tese está organizada conforme os quatro níveis estabelecidos no mapa da Figura 3. O nível 1 é apresentado no capítulo 2. A construção deste capítulo origina-se de uma abordagem de contexto anterior à revisão de literatura, em que o tema energia ou eficiência energética é tratado de forma agregado. O embasamento para a construção desse capítulo surge a partir de: (i) dois projetos de iniciação científica (PIBIC, 2013-2014 – Apêndice E), (ii) artigos 1 e 2 (PERRONI *et al.*, 2015a; PERRONI *et al.*, 2016a – Apêndices F e G), (iii) e um Estudo Independente (Apêndice D). No segundo capítulo destacam-se elementos do aspecto macro energético para a eficiência energética, bem como os fatores tecnológicos, políticos, econômicos e ambientais que influenciaram o uso de energia ao longo do tempo. A matriz de energia, intensidade energética setorial, fluxo de energia com o modelo insumo-produto e política energética também são discutidos.

No nível 2 decorre a revisão sistemática da literatura em eficiência energética industrial, apresentada no capítulo 3. Este capítulo exibe o modelo de processo para a revisão sistemática da literatura, bem como a sua aplicação no campo da eficiência energética industrial descrita no artigo 3 (PERRONI *et al.*, 2015b – Apêndice H). Ele também expõe uma discussão dos grupos e temas de pesquisa da literatura que foi trabalhado no artigo 4 (PERRONI *et al.*, 2016b – Apêndice I).

Figura 3 - Mapa conceitual do projeto de pesquisa



Fonte: o autor, 2016.

Nota: Por uma questão de espaço os objetivos específicos não estão escritos conforme o Quadro 1.

No nível 3 ocorre a modelagem do problema do desempenho energético. E no nível 4 se dá a lógica da aplicação da abordagem de processos (PERRONI *et al*., 2014; PERRONI *et al*., 2016c; PERRONI *et al*., 2016d – Apêndices J, K e L).

O nível 3 é apresentado no capítulo 4 e foram desenvolvidas três formas para representar o problema, conforme os objetivos específicos do Quadro 1: (iii) *framework* de processos para a medição do desempenho energético integrado; (iv) mapa dos indicadores de eficiência energética de processos; (v) modelo insumo-produto de processos longitudinal para a medição contínua do desempenho energético (PERRONI *et al*., 2017 – Apêndice M).

O nível 4 está descrito no capítulo 5 que integra algumas técnicas como a construção de indicadores, cálculos matriciais e simulação atendendo aos objetivos específicos: (vi) baseado na eficiência empresarial, propor indicadores para acompanhar continuamente o desempenho energético; (vii) a partir de uma estrutura real de processos, desenvolver uma abordagem de simulação para alimentar o modelo; (viii) construir uma abordagem para visualização multidimensional dos indicadores (PERRONI *et al*., 2017 – Apêndice M).

No capítulo 6 é apresentada a conclusão em relação aos objetivos, contribuição, limitações e sugestões para trabalhos futuro.

2 IMPORTÂNCIA DO ASPECTO MACRO ENERGÉTICO PARA A EFICIÊNCIA ENERGÉTICA

Com base nas pesquisas de Tanaka (2011), o uso de energia é influenciado por vários fatores: tecnológicos, processos, produtos, fonte de energia, preço da energia, política, economia, situação do negócio, prioridade gerencial e paradigma de tomada de decisão. Alguns desses fatores como a prioridade gerencial e a escolha dos processos estão sob o poder de decisão de uma unidade de negócio ou empresa, enquanto outros, como o preço da energia e a política dependem dos fatores em conjunto formando o sistema macro energético. Conforme mapa da tese da Figura 3, o objetivo desse capítulo foi analisar a importância do aspecto macro energético para a eficiência energética. Esse capítulo tem origem em dois artigos exibidos nos Apêndices F e G (PERRONI *et al*., 2015b; PERRONI *et al*., 2016b), em dois projetos de iniciação científica (PIBIC, 2013-2014) do Apêndice E, e no Estudo Independente apresentado no Apêndice D, pertencentes ao projeto de pesquisa.

A seção 2.1 apresenta a evolução histórica dos paradigmas em energia, procurando analisar os fatores históricos que levaram a eficiência energética a se tornar tão relevante. A seção 2.2 descreve a matriz de energia nacional, intensidade energética setorial, bem como uma técnica de planejamento energético que é o modelo insumo-produto e o fluxo de energia relacionado. A seção 2.3 descreve o escopo das políticas de eficiência energética no setor industrial. A seção 2.4 faz uma breve discussão de alguns aspectos macro energéticos relevantes para à eficiência energética.

2.1 EVOLUÇÃO HISTÓRICA DOS PARADIGMAS EM ENERGIA – FATORES TECNOLÓGICOS, POLÍTICOS, ECONÔMICOS E AMBIENTAIS QUE INFLUENCIARAM O USO DE ENERGIA

O objetivo desta seção é apresentar os principais fatores históricos que levaram a eficiência energética a se tornar relevante como tema de estudo e a técnica de paradigmas e trajetórias tecnológicas será utilizada (NELSON; WINTER 1977; DOSI, 1982). Entende-se paradigma tecnológico como sendo "*um modelo ou padrão de solução de problemas tecnológicos selecionados, baseado em princípios selecionados derivados das ciências naturais e em tecnologias selecionadas*" (DOSI, 1982, p.52). Para dar suporte ao paradigma, Dosi (1982) utiliza o conceito de trajetória tecnológica como um "*padrão normal de atividades de solução de problemas*".

Os paradigmas e trajetórias tecnológicas foram pesquisados por Freeman e Soete (1998). Estes autores desenvolveram extensa pesquisa para estudar tanto a evolução das constelações das inovações em produtos e processos, quanto tentativas para explicar como muitas dessas inovações partiram de dentro das empresas. Nessas pesquisas os paradigmas e trajetórias tecnológicas em energia têm um papel central. O Gráfico 1 apresenta um resumo esquemático usando o formato linha do tempo, relacionando os paradigmas em energia aos fatores tecnológicos, políticos, econômicos e ambientais. Como informação adicional, no Gráfico 1, é apresentado o preço do barril do petróleo entre 1861-2015 e o uso primário mundial de energia no período 1965-2015 (BP-SRWE[1], 2016).

O descobrimento da energia elétrica foi um subproduto de um paradigma maior, que é o da eletricidade no qual fazem parte invenções como: pilha, telégrafo, usina elétrica, transmissão de sinais de rádio, lâmpada, transistores, chip, semicondutores entre outros (FREEMAN; SOTE, 1998; REVCIEN, 2012).

Conforme Freeman e Soete (2008) e RevCien (2012), a descoberta da energia elétrica ocorreu por volta de 1890, com base nas pesquisas de Tomas Edson e Nicola Tesla, sendo que as principais inovações foram a lâmpada, a usina elétrica e a corrente trifásica. Para transformar as invenções em inovações, houve a necessidade de mobilizar um montante grande de capital fixo, dado a demanda em energia elétrica principalmente nos produtos de aço para a maquinaria e construção civil. As empresas que entraram nesse ramo como a General Eletric (fundada em 1892) e a Westinghouse (fundada em 1886) tornaram-se grandes monopolistas.

Segundo Freeman e Soete (2008) e Benito (2013), o petróleo surgiu como fonte de energia por volta de 1860. Dez anos mais tarde, Rockefeller descobriu que podia dominar o mercado introduzindo a inovação da integração vertical, controlando desde a extração até a distribuição. A Standard Oil (fundada em 1870) tornou-se uma grande empresa monopolista, mas foi dividida em várias companhias pela lei Sherman Antitruste[2]., transformando-se em um grande oligopólio. O petróleo se tornou cada vez mais importante para a sociedade industrializada do século XX devido à necessidade para o transporte, nos motores de combustão interna, locomotivas a diesel, óleo combustível, petroquímica, construção civil, entre outros.

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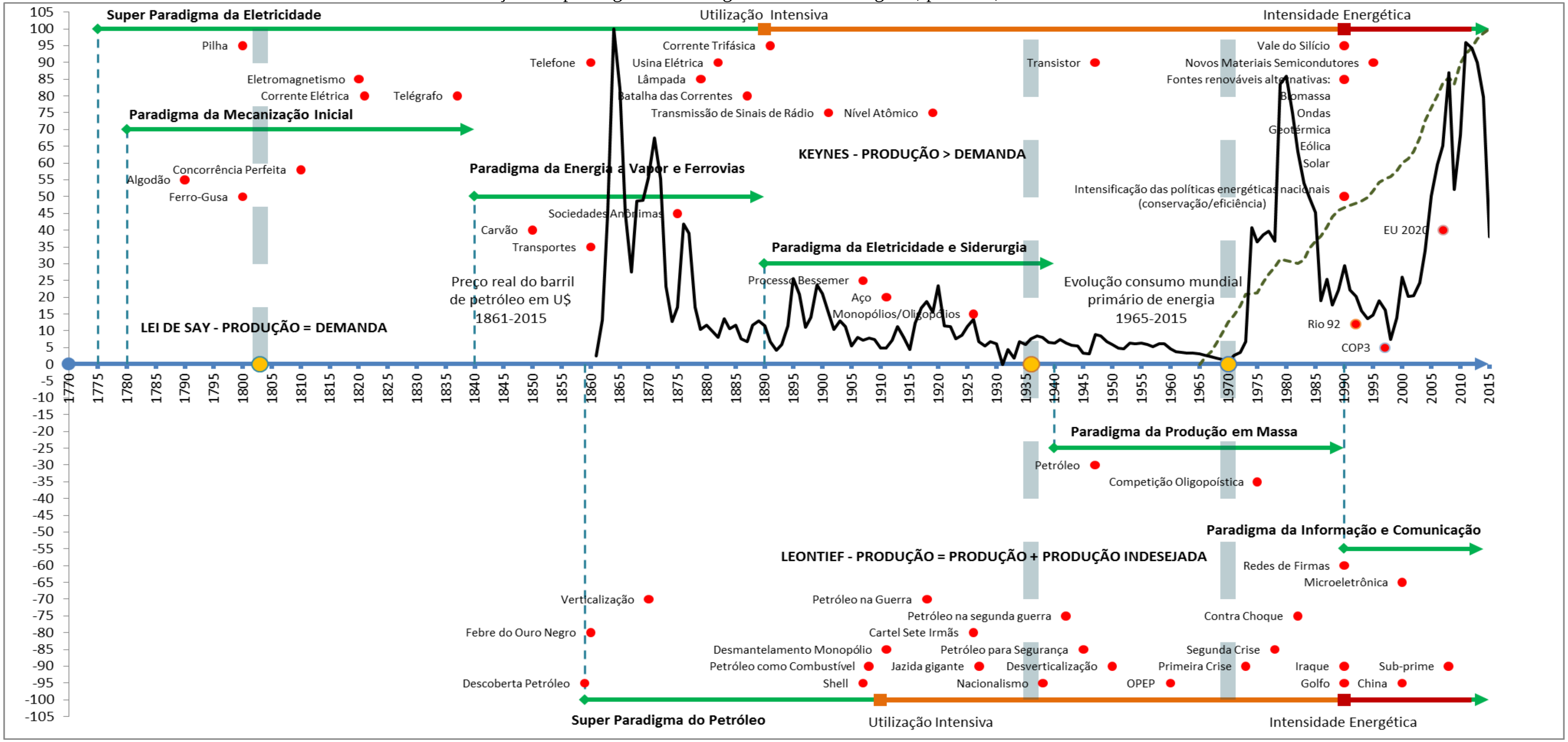
[1] British Petroleum - Statistical Review of World Energy (BP-SRWE) - bp.com/en/global /corporate/energy-economics/statistical-review-of-world-energy.html. Acessado em 26/07/16.

[2] A lei Sherman de 1890 (Sherman Act, em inglês) foi um ato de regulação que visava garantir a concorrência entre as empresas nos Estados Unidos (pt.wikipedia.org/wiki/Lei_Sherman_Antitruste, acessado em 28/07/16).

Gráfico 1 - Evolução dos paradigmas em energia: fatores tecnológicos, políticos, econômicos e ambientais.



Fonte: Elaborado pelo autor a partir das informações em: (Freeman; Soete, 2008; Benito, 2013; Tanaka, 2011; REVCIEN, 2012; Wee *et al*., 2012; PIBIC-2014/2015, BP-SRWE, 2016).

Nota: (a) A escala vertical age apenas como separadora das informações; (b) A escala horizontal são os anos; (c) Os pontos amarelos com linhas tracejadas refere-se a mudança de pensamento da equalização entre demanda e a produção agregada; (d) As curvas representam o preço do barril do petróleo entre 1861-2015 e o uso primário mundial de energia no período 1965-2015 Os dados do preço real do barril do petróleo e do consumo primário mundial de energia foram padronizados assumindo o intervalo 0-100; (e) O preço do petróleo é uma *proxy* do preço da energia (Perroni *et al*., 2016a).

Conforme Pinto Jr. *et al*. (2007), a economia industrial do século XX foi impulsionada em grande parte devido a essa fonte barata de energia, pelo menos até a década de 70 (preço do barril de petróleo na década de 70 no Gráfico 1).

As principais crises da década de 70 ocorreram, principalmente, devido à distribuição desigual do petróleo na crosta terrestre, ou seja, os países do cartel da OPEP[3] detinham o monopólio desse recurso. Após quase um século de preços baixos, conforme pode ser observado no Gráfico 1, o preço real do petróleo teve aumento exponencial nesse decênio, provocando uma corrida tanto por fontes alternativas de energia, dentre elas: biomassa, ondas do mar, geotérmica, eólica e solar (WEE *et al*., 2012), quanto pela criação dos programas de conservação e eficiência energéticas nacionais (TANAKA, 2011). As medidas de conservação, associadas aos fatores econômicos e políticos dos países da OPEP, fizeram o preço do petróleo recuar nas décadas de 80 e 90, mas no Gráfico 1 observa-se que a utilização primária de energia foi sempre crescente entre 1965 e 2015, fazendo uma pressão constante no uso de todas as fontes de energia. Outra adversidade que emerge, discutida, singularmente, desde o começo dos anos 90 (Rio-92, COP3-1997)[4], refere-se aos problemas ambientais relacionados ao consumo de energia derivada dos combustíveis fósseis principalmente a emissão de CO2.

2.2 MATRIZ DE ENERGIA, INTENSIDADE ENERGÉTICA SETORIAL E FLUXO DE ENERGIA

Esta seção preocupa-se, principalmente, com o uso de energia no nível setorial do ponto de vista do consumo de energia, bem como o planejamento em nível agregado. Com relação a isso, dois pontos podem ser destacados: a mudança na matriz de energia e a distribuição do consumo de energia nos setores. Devido aos fatores tecnológicos, políticos, econômicos e ambientais levantados no Gráfico 1 dos paradigmas da energia, a matriz de energia que um país tem à sua disposição pode sofrer mudanças ao longo do tempo. O Gráfico 2 apresenta a participação das fontes energéticas na matriz energética mundial, comparando

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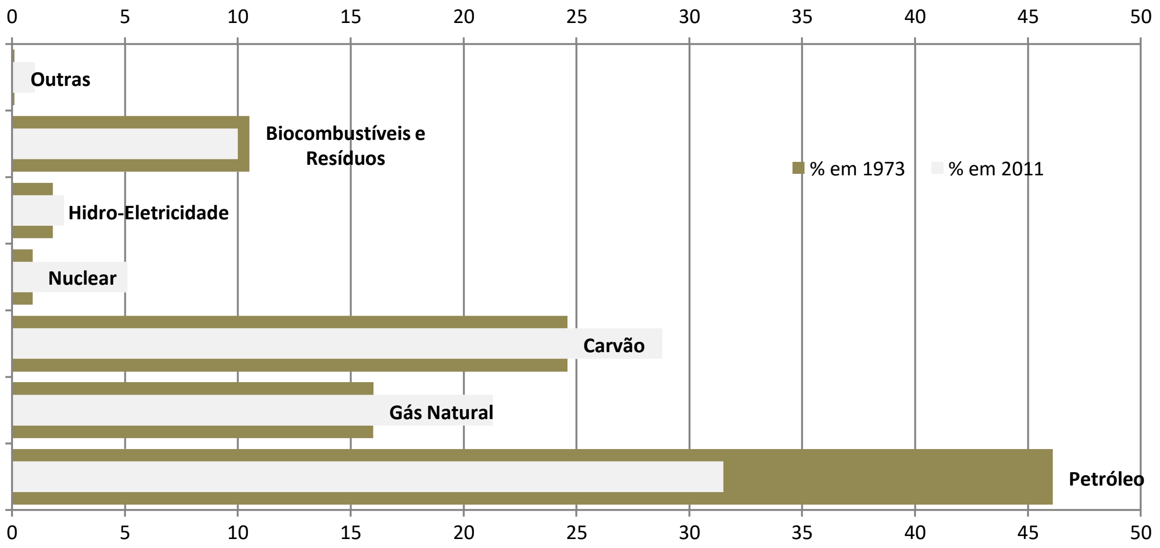
[3] OPEP - Organização dos Países Exportadores de Petróleo. OPEC - Organization of the Petroleum Exporting Countries. Países membros (Iran, Iraque, Kuwait, Arábia Saudita, Venezuela, Qatar, Indonésia, Líbia, Emirados Árabes, Algeria, Nigéria, Equador, Gabão e Angola) (opec.org/, acessado 28/07/16)

[4] Rio-92(aconteceu no Rio de Janeiro em Junho de 1992, onde participaram 179 países, resultando em um documento chamado Agenda 21, que aborda o desenvolvimento sustentável, mudanças climáticas e a biodiversidade (mma.gov.br/responsabilidade-socioambiental/agenda-21/agenda-21-global); COP3 (aconteceu em Dezembro de 1997 em Kyoto no Japão, onde foi assinado por muitos países o Protocolo de Kyoto (unfccc.int/cop3/). Sites acessados em 28/07/16.

os anos de 1973 e 2011 e o Gráfico 3 possui as mesmas informações para o mesmo período no Brasil.

Com base nos dois gráficos apresentados, observa-se que a mudança na matriz de energia reflete os fatores (tecnológicos, políticos, econômicos e ambientais) destacados no capítulo anterior. Em nível mundial (Gráfico 2) é visível a queda na participação do petróleo, e no caso do Brasil (Gráfico 3) uma substituição da lenha pelo petróleo, além do aumento de energia renovável.

Gráfico 2 - Mudança da matriz energética mundial



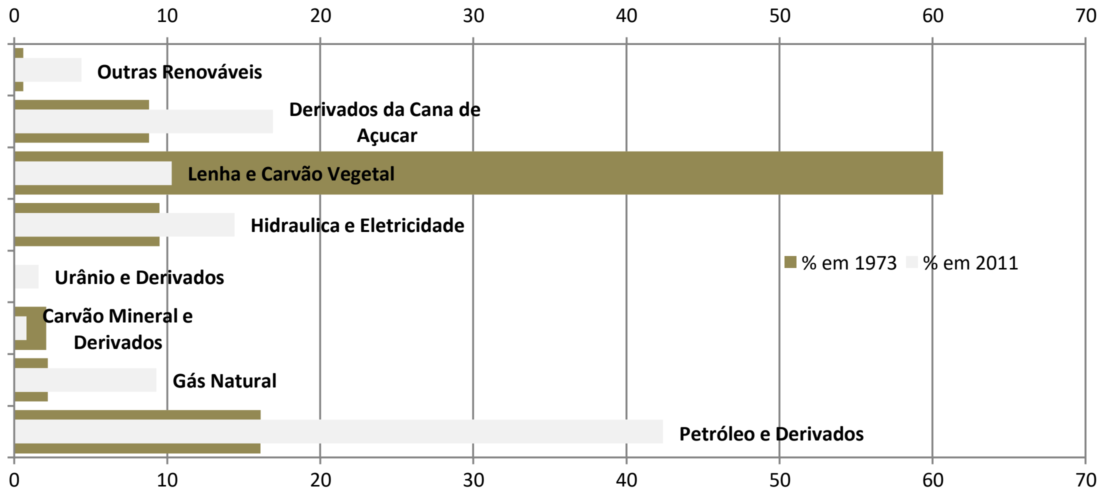
Fonte: Perroni *et al*. (2016a) – Apêndice F.

A diminuição do consumo de petróleo na matriz energética mundial foi compensada pelo aumento de combustível fóssil (gás natural e carvão) e energia nuclear. O problema é que a queima do carvão é altamente poluidora. A energia nuclear, além de gerar resíduos, provou ser instável e, como exemplo, pode-se citar o acidente de Fukushima em 2011 no Japão. Em relação ao gás natural, embora seja menos poluente, é um recurso não renovável.

Conforme Gráfico 3, embora o Brasil possua vantagem relativa em sua matriz energética por ter aumentado a participação de recursos renováveis como, por exemplo, a cana e a hidroeletricidade, a diminuição do uso da lenha, como fonte energética, foi compensada, em parte, pelo aumento do consumo do petróleo.

O segundo ponto diz respeito ao consumo desigual de energia pelos setores. O Gráfico 4 apresenta a participação do consumo de energia pelos setores industriais e não industriais, bem como as elasticidades do consumo de energia.

Gráfico 3 - Mudança da matriz energética brasileira



Fonte: Perroni *et al*. (2016a) – Apêndice F.

Nota-se no Gráfico 4 que o setor de transporte (rodoviário) é um *outlier* para o Brasil. As elasticidades apresentadas (lado direto do Gráfico 4) podem ser interpretadas como indicadores de intensidade energética ou conteúdo energético percentual agregado por setor. A interpretação poderá ser feita da seguinte forma: o aumento de 1% na renda gera o aumento de 1,47% no consumo de energia para o setor de papel e celulose. As barras da direita do Gráfico 4 medem a intensidade energética de cada setor. Como esperado, os setores de ferro ligas, não ferrosos (alumínio), ferro gusa e aço são os mais intensivos no uso de energia (PERRONI *et al*., 2016a).

As transações do consumo de energia entre setores podem ser representadas pelo modelo insumo-produto [*input-output*] desenvolvido por Leontief[5] (LEONTIEF, 1936, LEONTIEF 1966; MILLER; BLAIR, 2009). O modelo insumo-produto identifica e quantifica as interdependências de produção entre as várias partes do sistema econômico (setores do sistema produtivo, como os do Gráfico 4). É identificada a interdependência de cada setor em relação a todos os outros.

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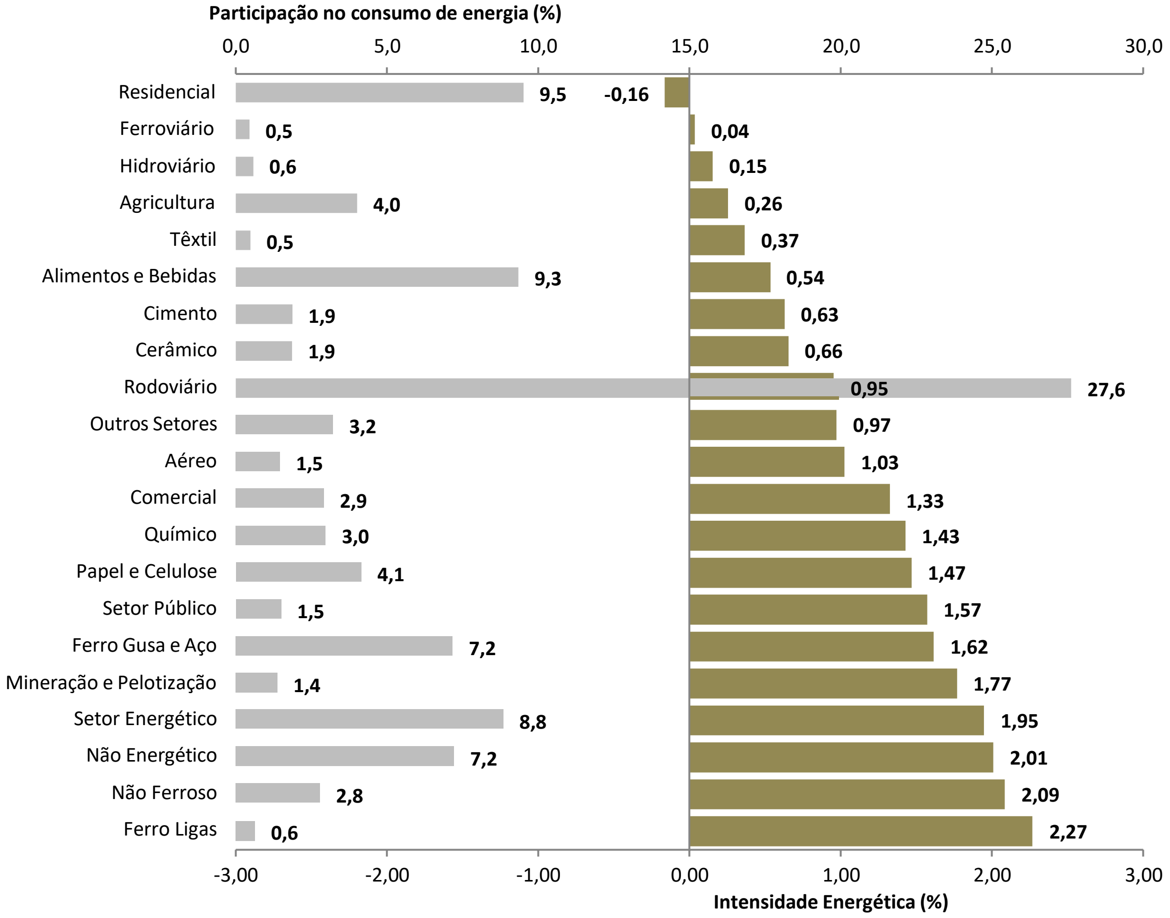
[5] "Economista russo, radicado nos Estados Unidos desde 1931, Wassily Leontief é considerado o 'Apóstolo do Planejamento Econômico' pela criação da técnica do insumo-produto na análise dos grandes agregados econômicos. Inspirando-se no sistema abstrato de equações do equilíbrio geral de Walras, deu-lhe um conteúdo empírico, por meio de dados sobre os diferentes setores que se inter-relacionam no processo econômico. Ao mesmo tempo, ***usando análise matemática e computação***, Leontief estabeleceu, a maneira de Quesnay, um 'quadro econômico' dos Estados Unidos, onde a economia é escrita em termos de circulação, isto é, como um ***sistema integrado de fluxo e transferências de insumos e produtos*** de um setor para outro da produção industrial. Desse forma, cada setor absorve insumos de outros setores, além de produzir bens e serviços que são posteriormente utilizados por outros setores para serem processados ou para um consumo final. ***Esse método pode ser tanto aplicado aos modelos macroeconômicos de planejamento e desenvolvimento econômico nacionais, como aos modelos microeconômicos de análise de empresas individuais*** ou nos programas de desenvolvimento urbano" Leontief (1966) apresentação Langoni (1986): A Economia do Insumo-produto.

Gráfico 4 - Intensidade energética setorial e participação no consumo de energia pelos setores



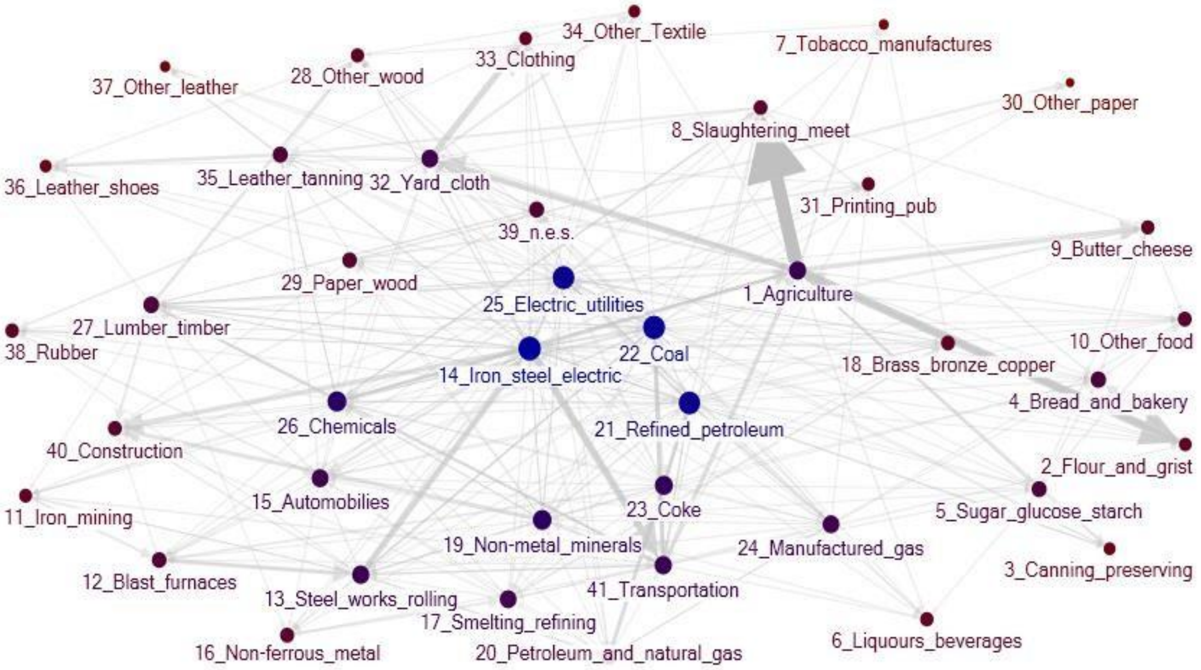
Fonte: Adaptado de Perroni *et al*. (2016a) – Apêndice F.

O modelo pode ser utilizado como ferramenta de planejamento energético, uma vez que indica e quantifica a interdependência de energia entre os setores. Referente ao modelo de Leontief (1936), a pergunta clássica que se faz, por exemplo, é: qual a quantidade de energia necessária para aumentar a produção de um determinado setor (aço) em 10%? A resposta apresentada pelo modelo construído por Wassily Leontief (1936, 1976) possui duplo sentido: o primeiro, de que será consumida mais energia na produção do aço adicional (energia direta). O segundo será preciso mais energia para todos os insumos do aço (energia indireta), por exemplo, mais energia para a produção do pneu do caminhão que transportou o ferro, ou mais energia para a produção da máquina do processo de fabricação do pneu. Assim, o objetivo central do modelo insumo-produto de Leontief (1936, 1970), quando se analisa a matriz de energia, é quantificar o conteúdo energético total (energia direta mais energia indireta na produção de um produto), possibilitando um melhor planejamento energético agregado.

A matriz insumo-produto de Leontief (1936) pode ser visualizada por meio de uma rede social. A Rede 1 mostra a interdependência setorial dos EUA em 1919 com os dados do artigo seminal (LEONTIF, 1936).

Constata-se que, na Rede 1, o setor de energia representado por carvão, petróleo e máquinas elétricas (*proxy* do uso de eletricidade) está na posição central da rede, indicando maior conexão com todos os outros setores. Com base nessa rede, a primeira aproximação com uma abordagem de processos pode ser feita, de modo que cada setor dessa rede é uma composição limitada de muitos processos, sendo possível interpretá-la como rede de processos agregados. Dentro da rede de processos agregados existe um fluxo de energia direto e outro fluxo indireto. O fluxo de energia direto sai dos processos (setores) ofertantes de energia para os processos consumidores (todos os outros setores), enquanto o fluxo de energia indireto ocorre com base na comercialização dos produtos/serviços em que a energia está incorporada.

Rede 1 - Interdependência setorial da matriz insumo-produto

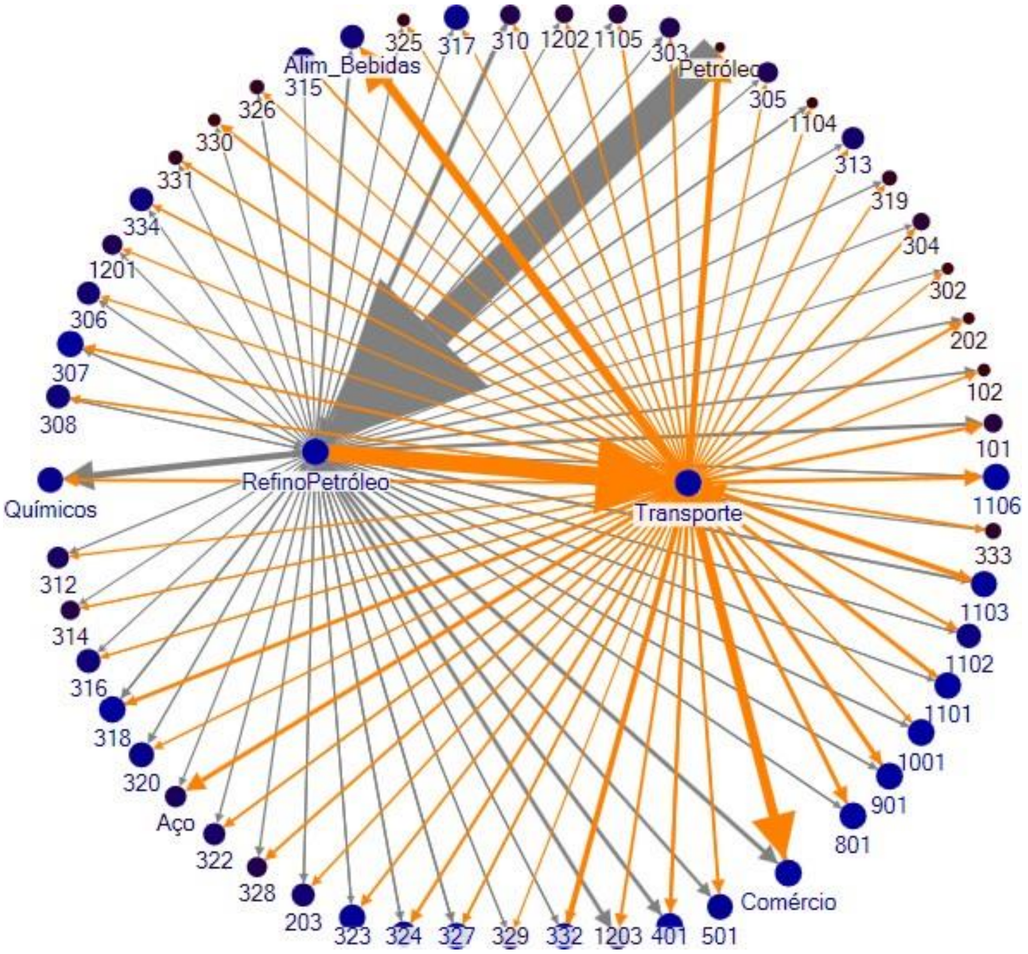


Fonte: – Elaborado pelo autor a partir do Apêndice D.
Nota: (a) Elaborado a partir dos dados do artigo "*Quantitative input and output relations in the economic system of the United States*" (Leontief, 1936). (b) A cor e o tamanho dos vértices são proporcionais à centralidade auto vetorial e a espessura das arestas são proporcionais aos pesos da matriz (Hansen, *et al*., 2011; Prell, 2012). (c) O algoritmo de distribuição utilizado foi o *Harel-Koren Fast Multiscale* (Hansen, *et al*., 2011).

A Rede 2 mostra os relacionamentos da matriz insumo-produto brasileira dos produtos de refino do petróleo e os transportes, referente ao ano de 2005. Quando apenas os relacionamentos do setor de energia são visualizados, o fluxo de energia direta torna-se aparente. Essa rede revela que o setor de refino do petróleo está relacionado a todos os outros setores, além de ficar mais clara a ideia de fluxo de energia, que o modelo de Leontief (1936) conduz. O petróleo é extraído, posteriormente, refinado e distribuído aos demais setores. Observa-se na Rede 2 que o setor de transporte recebe a maior parte do petróleo no Brasil. Esse fato se torna mais evidente ao analisar o Gráfico 4, em que o transporte rodoviário tem um consumo bem maior de energia, principalmente, óleo diesel (PERRONI *et al*., 2016a).

As técnicas matriciais, desenvolvidas por Leontief (1966), possibilitam o cálculo dos coeficientes diretos e indiretos. Os coeficientes, gerados a partir desse modelo, podem ser interpretados como indicadores de intensidade energética, em outras palavras, a energia por unidade monetária. Exemplos de cálculos e equações do modelo podem ser vistos no Apêndice D.

Rede 2 - Fluxo de energia da matriz insumo-produto para o Brasil



Fonte: – Elaborado pelo autor a partir do Apêndice D.
Nota: (a) Elaborado a partir da matriz insumo-produto do Brasil para o ano de 2005, disponível em ibge. gov.br/home/estatistica/economia/matrizinsumo_produto (Oferta e demanda da produção, Tabela 3) (b) Composição dos produtos em refino de petróleo (gás liquefeito de petróleo, gasolina automotiva, gasoálcool, óleo combustível, óleo diesel, outros produtos do refino de petróleo e coque). (c) A cor e o tamanho dos vértices são proporcionais à centralidade auto vetorial e a espessura das arestas são proporcionais aos pesos da matriz (o peso da matriz são as quantidades de recursos transacionados do setor A para o setor B, e vice-versa). O algoritmo de distribuição utilizado foi o Círculo (Hansen, *et al*., 2011; Prell, 2012).

Na Rede 2, apenas os setores de energia (Petróleo) e Transporte foram representados. Para facilitar a interpretação, ela pode ser feita da seguinte forma: a energia é comprada pelo setor de Refino de Petróleo e distribuída para todos os outros setores, bem como para o de Transporte. A questão fundamental dessa rede é que o setor de Transporte não vende energia, mas sim serviços de transporte. Cada um dos setores recebe a energia direta do setor de Refino de Petróleo mais a energia indireta incorporada no serviço de transporte.

Quando todos os setores são apresentados, o relacionamento torna-se extremamente complexo, exigindo análises insumo-produto como as realizadas pelas técnicas desenvolvidas por Leontief (1966). Além do fluxo de energia, utilizando o modelo insumo-produto, é possível estudar o fluxo do que Leontief (1966) denominou de produção indesejada, ou seja, qualquer tipo de resíduo ou poluição.

2.3 POLÍTICA ENERGÉTICA E MEDIDAS AGREGADAS PARA A EFICIÊNCIA ENERGÉTICA

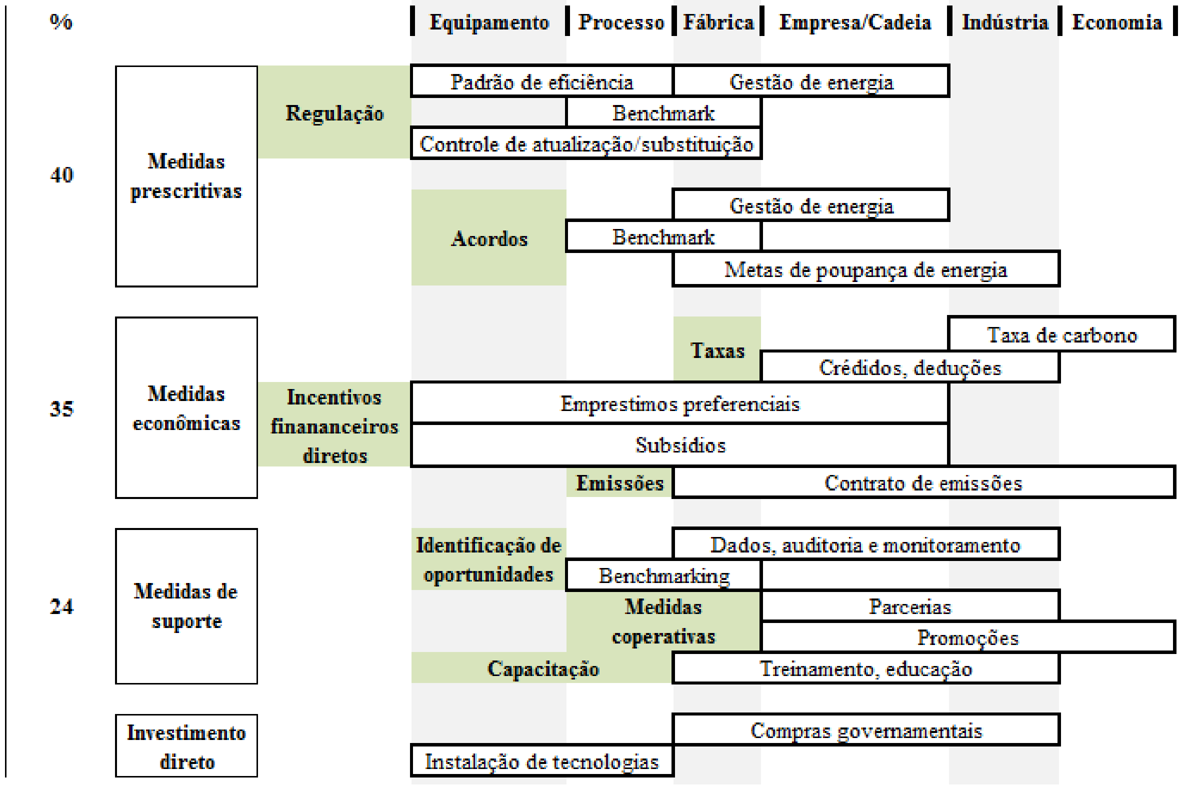
As seções anteriores demonstraram que o setor de energia é central para o sistema produtivo, fazendo com que os governos voltem sua atenção para o gerenciamento das matrizes de energia de seus países. Um dos primeiros exemplos de intervenção no sistema energético foi o desmantelamento do monopólio da Standard Oil, pela lei Sherman, ocorrido por volta de 1910, conforme Gráfico 1. Desde essa época os governos operam como reguladores do sistema energético, intensificando suas ações na década de 70. A partir desse decênio, a maioria dos países intensificou as ações da política energética, com o objetivo de garantir a estabilidade do sistema. Ocorre que nas últimas décadas, a política energética não está preocupada apenas com o planejamento energético no sentido de equalizar a demanda e a oferta de energia, mas também com a redução do consumo de energia por unidade de produção, em outras palavras, eficiência energética.

Os problemas ambientais se intensificaram na década de 90. Assim sendo, tornou-se necessária a cooperação de muitos países e a presença dos mesmos em eventos que foram promovidos, tais como: Rio-92 e COP3. A centralidade do setor de energia ocorre por dois fatores principais: econômico e ambiental. Econômico porque a falta de energia poderia levar o sistema econômico/produtivo a entrar em colapso, com efeitos sentido nas crises do petróleo da década de 70, e ambiental porque a queima de combustíveis fósseis provoca danos ao meio ambiente. Conforme Gráfico 3, aproximadamente ,80% da energia consumida no mundo vêm de combustíveis fósseis (PERRONI *et al*., 2015a; PERRONI *et al*., 2016a).

A Figura 4 apresenta a política de eficiência energética industrial classificada em três grupos: prescritiva, econômica e de suporte (TANAKA, 2011). Vale ressaltar que as medidas podem ser aplicadas em toda a estrutura organizacional da indústria envolvendo equipamentos, processos, empresa, cadeia e economia como um todo. O trabalho de Tanaka (2011) pesquisou 304 ações políticas, encontrando 570 medidas nos países da Agência Internacional de Energia (IEA) incluindo Brasil, Índia, México, Rússia e África do Sul, nas quais 40% das políticas eram de suporte, 35% econômicas e 24% prescritivas.

O trabalho de Perroni *et al*. (2015a) identificou 41 mudanças na legislação de ações de política energética entre 1985 e 2008 para o Brasil. Tomando como base o ano de 2012, os projetos economizaram 9.097 Giga-Watt-hora (GWh), devido à implementação das medidas de eficiência energética. Esse número corresponde a 2,03% do consumo total de energia elétrica no país (PERRONI *et al*., 2015a).

Figura 4 – Medidas políticas para a eficiência energética industrial



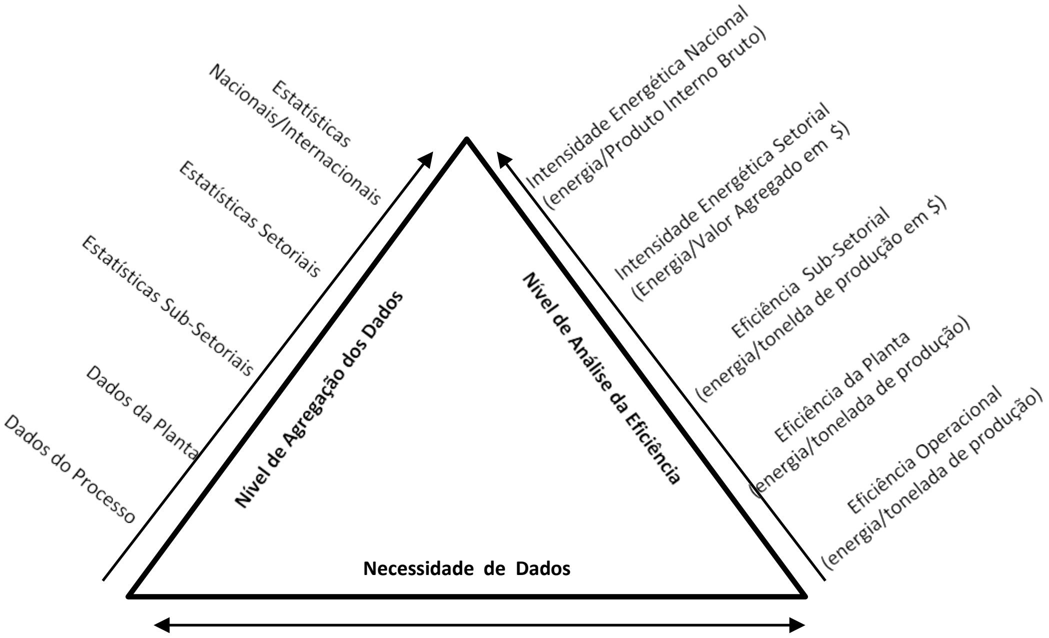
Fonte: Adaptado de Tanaka , 2011.

Com base nas informações da Agência Internacional de Energia, se não fossem as ações para a melhoria da eficiência energética, o consumo de energia no ano de 2005 seria 58% maior (IEA, 2008).

As medidas da Figura 4 estão de acordo com a chamada pirâmide da eficiência energética, apresentada na Figura 5. Essa pirâmide descreve uma hierarquia de indicadores que vão desde os equipamentos até a economia como um todo.

O desenvolvimento da pirâmide da eficiência energética demonstra uma preocupação da medição do desempenho energético (eficiência energética) em todos os níveis hierárquicos do sistema produtivo, sendo que do lado direito da pirâmide estão os indicadores, representados como uma razão energia *versus* produção, tanto em valores monetários como físicos (toneladas), e do lado esquerdo a agregação dos dados necessários para a construção desses indicadores (PERRONI *et al.*, 2015a).

Figura 5 - Pirâmide de indicadores da eficiência energética



Fonte: IEA 2014a; Perroni *et al.*, 2015a – Apêndices G e J.

O trabalho de Bunse *et al.* (2011) identifica que os dados estão disponíveis no nível setorial ou de países, havendo escassez de dados nos níveis das plantas, processos e equipamentos.

2.4 DISCUSSÃO DO ASPECTO MACRO ENERGÉTICO DA EFICIÊNCIA ENERGÉTICA

De acordo com o mapa da tese na Figura 3, apresentado no primeiro capítulo, as informações para a construção deste capítulo vieram de quatro estudos (Estudo Independente, PIBIC 2013-2014, Artigo 1 e Artigo 2), em que informações adicionais podem ser obtidas nos

Apêndices D ao G. A justificativa para um estudo macro energético é que, conforme percebido por Tanaka (2011), quando se trata de energia existem fatores que estão na alçada de decisão de uma empresa ou grupo de empresas; mas existem fatores que não, por exemplo: o planejamento da matriz energética e as políticas energéticas. Neste capítulo, dá-se destaque aos muitos fatores que influenciaram o uso de energia ao longo do tempo, entre eles: o desenvolvimento de novos produtos que utilizam algum tipo de energia para funcionar ou até mesmo os processos de produção que são intensivos em energia. A história demonstra que acompanhando toda evolução do uso de energia desde, principalmente, a descoberta do petróleo por volta de 1860, a política sempre teve uma influência na governança dos assuntos de energia. A política citada acima se refere à participação do governo nas decisões referentes à energia. O papel dessa organização ficou evidente durante as crises do petróleo da década de 70. Após esse decênio, os governos desempenharam um papel mais intervencionista na governança do sistema energético, incentivando o uso racional de energia por todos os agentes. O trabalho de Tanaka (2011), sintetizado na Figura 4, é um dos mais completos ao destacar a gama de ações em que os governos podem atuar para conscientizar ou obrigar os agentes a fazer uso da energia de forma eficiente. O modelo desenvolvido por Leontief (1936, 1966) é uma referência que facilita o planejamento energético, pois demonstra o relacionamento e a dependência de energia entre todos os setores da economia (BLAIR; MILLER, 2009).

A indústria, principalmente, a manufatura, revelou-se importante devido ao uso de energia em relação aos outros setores. Os processos industriais consomem aproximadamente um terço da energia global (NAPP *et al.*, 2014), mas essa taxa varia entre os países, chegando a 70% na China (SHI *et al.*, 2010; SHEN *et al.*, 2012). Segundo uma classificação mais ampla, feita pela agência de informações do departamento de energia dos Estados Unidos DOE-EIA (2010), incluindo a manufatura, a agricultura, a mineração e a construção o consumo do setor industrial chega a aproximadamente 50% da energia mundial entregue. Quando acrescentados os problemas ambientais, derivados do uso de combustíveis fósseis, como mais um agravante, torna-se indispensável à incorporação da gestão de energia na gestão da produção industrial. O desempenho energético pode ser utilizado como um fator de competitividade (BUNSE *et al.*, 2011). O principal objetivo do próximo capítulo é apresentar a revisão sistemática da literatura no campo da eficiência energética industrial, que irá contribuir com a identificação do quadro teórico e prático da pesquisa, oferecendo suporte as discussões, e o desenvolvimento da representação e da abordagem proposta por esta tese.

3 REVISÃO SISTEMÁTICA DA LITERATURA EM EFICIÊNCIA ENERGÉTICA INDUSTRIAL

O segundo capítulo demonstrou que o setor de energia sempre foi vital ou central para o sistema produtivo, de modo que os desequilíbrios no setor de energia se refletem em todos os outros setores. Conforme o Gráfico 1, os eventos ocorridos principalmente desde a crise do petróleo forçaram os governos a tomarem medidas, tanto do lado da oferta quanto da demanda de energia. As medidas de políticas para a eficiência energética industrial, da Figura 4, podem ser interpretadas como ações agregadas para influenciar, de maneira direta ou indireta, no comportamento dos agentes quanto ao consumo responsável de energia. A questão que emerge é: como assegurar se dado agente pratica o consumo responsável de energia? A forma de responder a essa pergunta seria dizendo quando esse agente é eficiente. Então, torna-se relevante dizer que, como a eficiência em termos do uso de energia pode ser medida para cada agente, é possível atestar se ele pratica ou não o consumo responsável.

É importante salientar que a energia é um insumo diferente dos demais porque forma uma rede completa (com mais ligações), ou pelo menos mais completa que a grande maioria das outras relações insumo-produto, como determinados tipos de materiais (aço, cimento, algodão, entre outros) (LEONTIEF, 1936, LEONTIEF, 1966; MILLER; BLAIR, 2009).

As pesquisas realizadas no segundo capítulo identificaram que o setor industrial, principalmente, o manufatureiro, é importante no contexto mundial porque utiliza, em média, um terço da energia primária produzida e também devido ao impacto indireto gerado nos demais setores. A eficiência energética na indústria não é mais vista apenas como uma preocupação macroscópica no nível das políticas governamentais. A literatura recente aponta que a principal responsabilidade das empresas está na implementação da gestão de energia em seus processos (BUNSE *et al*., 2011; SHULZE, *et al*., 2016).

Conforme descrito no mapa da tese na Figura 3, o setor industrial foi o escolhido para realização de uma revisão sistemática da literatura em eficiência energética, tendo como objetivo identificar as principais contribuições teóricas e práticas para a medição do desempenho energético no campo da eficiência energética industrial. Embora a palavra industrial seja utilizada, o foco ou núcleo da pesquisa está no ramo manufatureiro da indústria. A apresentação deste capítulo tem origem em dois artigos do projeto de pesquisa exibidos nos Apêndices H e I (PERRONI *et al*., 2015b; PERRONI *et al*., 2016b).

A seção 3.1 apresenta um modelo de processo para a revisão sistemática da literatura e a seção 3.2 aplica o modelo na área de eficiência energética industrial, para descobrir quem são os principais autores, bem como os grupos formados por esses autores. A seção 3.3 descreve as contribuições dos grupos encontrados na revisão sistemática da literatura em eficiência energética industrial. A seção 3.4 faz a discussão da revisão.

3.1 MODELO DE PROCESSO PARA A REVISÃO SISTEMÁTICA DA LITERATURA

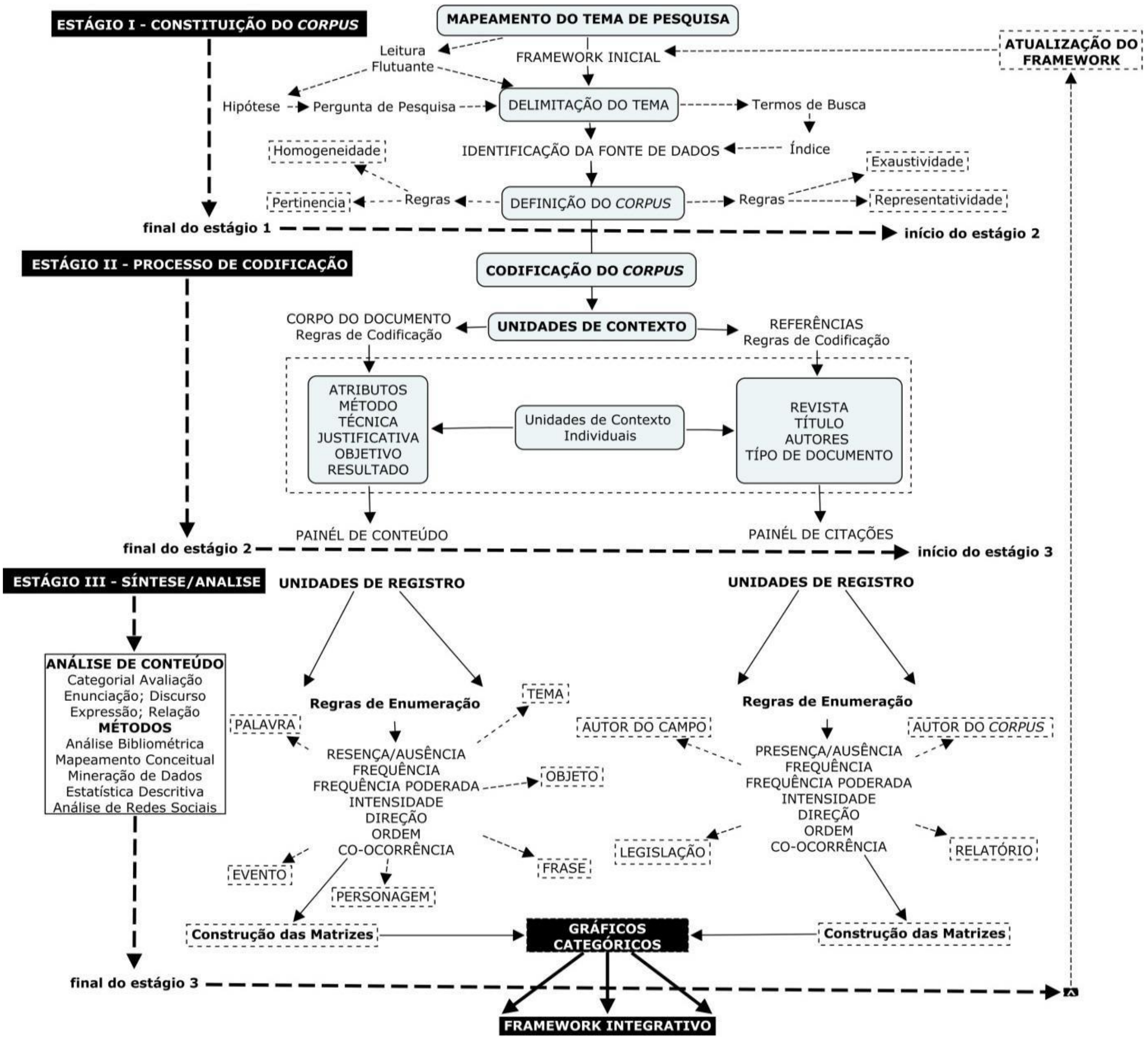
A revisão sistemática da literatura (RSL) é interpretada como uma abordagem para organizar e desenvolver um processo de revisão de literatura. O desenvolvimento do processo da RSL possibilita a identificação, mapeamento e análise das pesquisas relevantes de um problema ou tópico de pesquisa específico. A revisão sistemática pode ser apontada como uma solução na busca da eliminação dos vieses, possibilitando um processo mais seguro, controlável, confiável e replicável do que os métodos não sistemáticos (COOK *et al*., 1997; TRANFIELD *et al*., 2003; KITCHENHAM, 2004; BIOLCHINI *et al*., 2007).

O protocolo do processo da RSL é geralmente dividido em três estágios: planejamento da revisão [*input*], execução/condução da revisão (processamento) e análise/*report* da revisão [*output*] (TRANFIELD *et al*., 2003). O processo de revisão sistemática é iterativo, sendo que o estágio do planejamento envolve fases como a delimitação do escopo dos estudos, baseados na pergunta de pesquisa e a construção do protocolo de pesquisa. A condução da pesquisa é o estágio de identificação dos estudos e envolve uma série de fases, entre elas: avaliação da qualidade dos estudos, extração dos dados e síntese. No estágio de análise, o objetivo é identificar as principais categorias e temas como: quem são os autores? Qual o país de origem da pesquisa? Quais os principais artigos? Quais os principais temas? Como estes temas estão interconectados?

O modelo de processo para essa revisão pode ser visualizado na Figura 6, fazendo a junção dos estágios do processo de revisão sistemática (KITCHENHAM, 2004; BIOLCHINI *et al*., 2007) no modelo de análise de conteúdo de Bardin (1977). Para operacionalizar a análise no nível dos procedimentos alguns métodos podem ser integrados como: análise de redes sociais, mapas conceituais, mineração de texto e análise bibliométrica. O modelo é proposto em três estágios (constituição do *corpus*, processo de codificação, síntese/análise) (PERRONI *et al*., 2015b).

O primeiro estágio ocorre com a constituição do *corpus*, que segundo Bardin (1977), é o conjunto dos documentos selecionados para serem submetidos aos procedimentos analíticos. A constituição do *corpus* implica escolhas, aplicação de regras e seleção. Inicialmente o tema é estudado utilizando-se de um processo de leitura flutuante, com o objetivo de estabelecer a pergunta de pesquisa e possíveis hipóteses iniciais, possibilitando assim a construção de um *framework* inicial e a delimitação do tema de pesquisa. A leitura é chamada flutuante porque os objetivos e regras ainda não foram definidos. O passo de delimitação cristaliza-se com a aplicação dos termos de busca nas bases de dados escolhidas. Estes termos são uma lista dos principais termos que representam a pergunta de pesquisa, sendo um índice ou indicador de presença, uma vez que é a menção explícita de um termo em uma parte específica da mensagem (resumo, título, corpo do texto, entre outros) (BIOLCHINI *et al*., 2007; BARDIN, 1977). Algumas regras comuns podem ser aplicadas no processo de seleção do *corpus*:

Figura 6 - Modelo de processo para a revisão sistemática da literatura



Fonte: Perroni *et al*., 2015b; Perroni *et al*., 2016b – Apêndices H e I.

- Exaustividade: não podem ser deixados de fora elementos que possam ser importantes.

- Representatividade: a seleção do *corpus* deve representar o universo.
- Homogeneidade: os elementos do *corpus* devem ser homogêneos, obedecendo a critérios precisos de escolhas.
- Pertinência: o *corpus* deve ser adequado aos objetivos da pesquisa.

As quatro regras contribuem com o processo de seleção levantado por Tranfield *et al*. (2003) e Biolchini *et al*. (2007) na fase de planejamento da revisão sistemática.

Baseado em Bardin (1977), a codificação corresponde a uma transformação dos dados brutos do texto, permitindo uma representação do conteúdo ou da sua expressão, suscetível de esclarecimento por parte do analista. Segundo Saldanã (2013, p. 3), "*Um código em uma pesquisa qualitativa é na maioria das vezes uma palavra ou frase curta que atribui simbolicamente um atributo sumativo, saliente, de captura de essência e/ou evocativo para uma porção de dados visuais ou linguísticos*". A codificação não é uma ciência precisa, sendo uma ação interpretativa, de modo que os dados são condensados e não, simplesmente, reduzidos. Codificar é uma forma de arrumar as coisas em ordem sistemática de forma que possibilite a categorização.

Duas unidades úteis para a organização do processo de codificação são: o estabelecimento das unidades de contexto e das unidades de registro. As unidades de contexto podem ser entendidas como partes do texto nas quais se encontram as unidades de registro (palavras, temas, objetos, entre outras). Baseado em Bardin (1977), e especificado no modelo de processo da Figura 6, o recorte para a codificação pode ser feito utilizando a unidade de contexto e a de registro em um processo de análise textual. Neste processo de análise textual a unidade de contexto serve de unidade de compreensão para codificar a unidade de registro subsequente, correspondendo ao segmento da mensagem, em que as dimensões são superiores às unidades de registro.

Nesse estágio os documentos (*corpus*) são divididos em duas unidades de contexto gerais: o corpo do documento e as referências. O processo de codificação gera as unidades de contexto individuais. A codificação primária representa, para o corpo do documento, extrair os objetivos, a justificativa, o método, as técnicas e os resultados, além de alguns atributos como departamento, instituição, revista, cidade e país no caso de artigo científico. A codificação significa, para as referências do documento, a extração dos autores, o título, a revista e o tipo de documento. As unidades de contexto serão posteriormente analisadas pela seleção das unidades de registro. A organização das referências do documento ocorre de maneira que possa ser aplicada à análise bibliométrica (TSAY, 2008; PLYTIUK *et al*., 2014).

À medida que as extrações são realizadas, é construído um painel de conteúdo para o corpo do documento e um de citações para as referências dos documentos.

O terceiro estágio é a continuação do processo de codificação em que são estabelecidas as unidades de registro. O esclarecimento de três elementos é fundamental no estágio da análise: unidade de registro, regras de enumeração e métodos/técnicas de análise que podem ser utilizadas. Segundo Bardin (1977), a unidade de registro geralmente é menor que a de contexto, sendo a unidade de significação codificada, visando à categorização por meio da aplicação das regras de enumeração (maiores esclarecimentos estão no Apêndice H). As unidades de registro mais utilizadas são: palavra, tema, objeto, personagem e evento não se restringindo somente a essas, uma vez que podem ser selecionadas outras de acordo com o campo e objetivos da pesquisa. As regras de enumeração mais comuns são: presença/ausência (pode ser um indicador ou representar um sentido), frequência (a importância de uma unidade de registro aumenta com a frequência de aparição), frequência ponderada (podem ter unidades de registro que possam ter mais importância do que outras para o contexto), intensidade (geralmente utilizando-se de atributos qualitativos como o tempo do verbo, advérbios e adjetivos), direção (pode ser positiva, negativa ou neutra), ordem (a ordem de aparição das unidades de registro pode ser pertinente), coocorrência (presença simultânea de duas ou mais unidades de registro em uma unidade de contexto).

O uso das regras de enumeração está relacionado com o método de análise empregado, sendo possível encadear mais de uma regra de enumeração como o uso de um conjunto de métodos. Resumidamente, a unidade de registro informa o que se conta e, por sua vez, a regra de enumeração informa como contar, estando atrelada a um método de análise específico.

Existem métodos que podem ser utilizados a partir de uma mesma base, ou seja, de matrizes de incidência (termo/documento) e adjacência (coocorrência) semelhantes, e entre esses métodos podem ser destacados: Análise de Redes Sociais, Mapas Conceituais, Mineração de Texto e Análise Bibliométrica (PERRONI *et al.*, 2015b).

3.2 APLICAÇÃO DO MODELO DE PROCESSO NA ÁREA DE EFICIÊNCIA ENERGÉTICA INDUSTRIAL

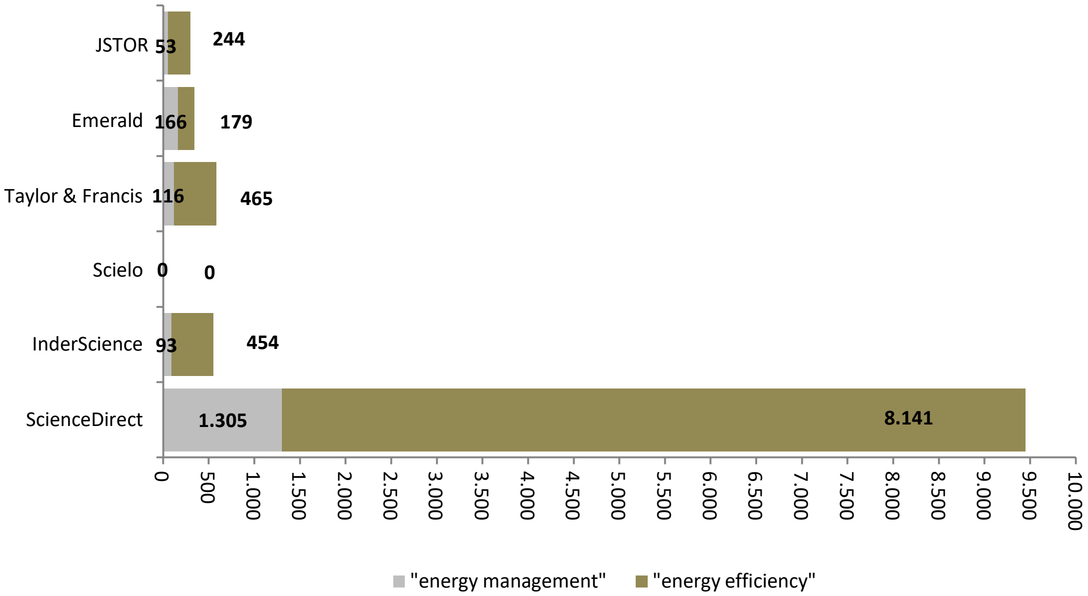
O campo eficiência energética industrial é uma subárea da eficiência energética. Este termo remete ao estudo das preocupações e ações desenvolvidas pelas indústrias com relação à eficiência energética dos seus processos produtivos. O intuito da aplicação do modelo de revisão sistemática é mapear e analisar as pesquisas em que a eficiência energética faz parte do contexto de gestão nas indústrias, principalmente as manufatureiras, sendo possível descobrir quem são os principais autores, bem como os grupos formados por esses autores e suas contribuições.

Conforme modelo de processo da Figura 6, a finalidade do primeiro estágio é a constituição do conjunto de documentos para compor o referencial teórico (*corpus*). Considerando os estudos exploratórios realizados, inicialmente em livros, relatórios de agências governamentais, Agência Internacional de Energia e artigos científicos, parte deles são destacados na importância do aspecto macro energéticos para a eficiência energética, apresentado no capítulo 2 (PERRONI *et al*., 2015a PERRONI *et al*., 2016a PIBIC 2013-2014).

Dentre os estudos exploratórios, destacam-se: (PHILIPSEN *et al*., 1997; BEAMON, 1998; LIN; POLENSKE, 1998; BITITCI *et al*., 2000; POLENSKE; MCMICHAEL, 2002; FOLAN; BROWN, 2005; PINTO JR, *et al*., 2007; IEA, 2008; BUNSE *et al*., 2011; TANAKA, 2011; NEGAI *et al*., 2012; SMITH; BALL, 2012; BEN, 2012; BITITCI *et al*., 2012; JAIN *et al*., 2013; MONN *et al*., 2013; NEGAI *et al*., 2013; VIKHOREV *et al*., 2013), utilizados para delimitar o tema e a pergunta de pesquisa. A pergunta inicial de pesquisa levantada foi: "*Como o desempenho energético pode ser medido, levando em conta tanto a eficiência como a efetividade na gestão da manufatura?*" (PERRONI *et al*., 2014). Após levantamento e análise entre as principais bases científicas, tais como: ScienceDirect, InderScience, SciELO, Taylor & Francis, Emerald e JSTOR, constatou-se a existência de um conjunto de trabalhos significativos na área da eficiência energética industrial, com um viés de gestão na qual a Science Direct é a base científica que reúne periódicos de relevância na área, com a apresentação de um número superior a 100 revistas associadas à área de energia, estando muitas delas entre as primeiras no ranking SJR da área de energia da Scimago.

As palavras-chave de controle "*energy management*" e "*energy efficiency*" foram utilizadas para testar a escolha das bases científicas. O Gráfico 5 mostra o número de trabalhos que contém as palavras-chave de teste no título, resumo e palavras-chave dos documentos. Nesse gráfico é possível identificar com facilidade que a Science Direct reúne trabalhos com maior interesse relativo em comparação com outras bases de dados acerca do mesmo tema.

Gráfico 5 - Palavras-chave de controle



Fonte: O autor (2014)
Nota: Consulta realizada em 25/03/2014

A Science Direct foi escolhida, buscando-se por artigos científicos, uma vez que esses são capazes de revelar a fronteira do conhecimento. Após sucessivas tentativas de combinação de palavras no buscador da base de dados, os termos selecionados foram:

> [“industrial energy efficiency” OR “industrial energy management” OR “energy efficiency manufacturing” OR (“energy efficiency” AND “manufacturing”) OR (“energy management” AND “industry”) OR (“industrial symbiosis” AND “energy”) OR (“energy management” AND “manufacturing”)].

Como escopo do indicador de presença, para os termos de busca, foram selecionados, o título, o resumo e as palavras-chave dos artigos. A busca foi efetuada durante o mês de maio/2014, retornando 574 artigos, dos quais, 178 foram pesquisados e selecionados com base na análise do resumo. Dos 178 artigos, 104 foram selecionados para a constituição do *corpus*, observando os quatro critérios mencionados no modelo da Figura 6: exaustividade, homogeneidade, representatividade e pertinência, em acordo com a pergunta de pesquisa a ser respondida. A execução do primeiro estágio se deu no período de abril/2013 a maio/2014.

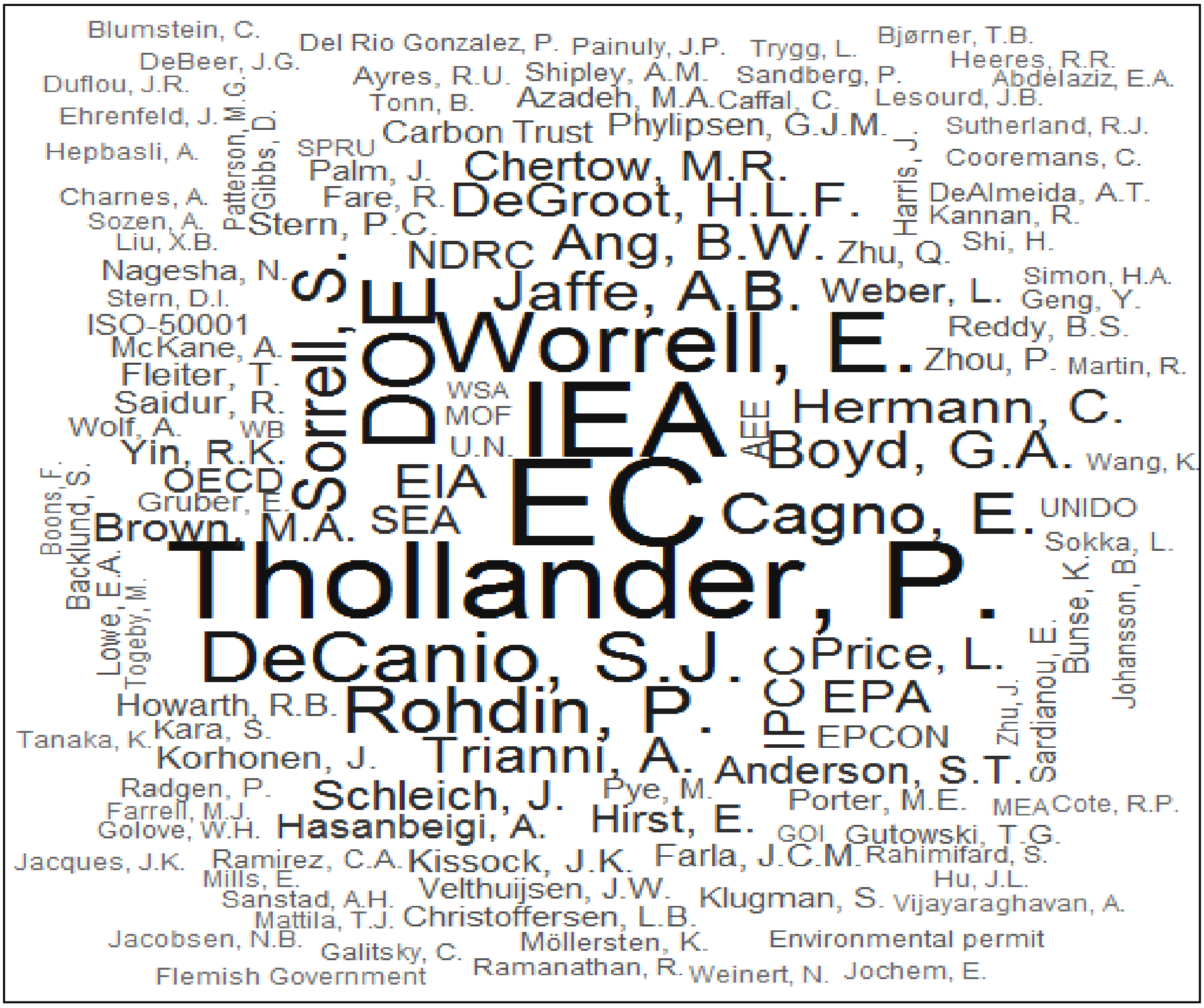
Conforme modelo de processo da Figura 6, o objetivo do segundo estágio é a codificação do *corpus*. O processo de codificação se dá com a construção de duas bases: painel de conteúdo e de citações. Realizou-se a leitura integral dos 104 artigos, sendo feitas extrações para uma planilha do Excel®. Tanto no painel de conteúdo quanto no de citações foram registradas as unidades de contexto (extração de partes específicas da mensagem)

(BARDIN, 1977), conforme regras de codificação do modelo na Figura 6. A composição do painel de conteúdo se deu com a extração de 61.202 palavras, tendo em média 588 por artigo, com mínimo de 288 e máximo de 985 palavras. O painel de citações foi construído a partir da seleção do primeiro autor de cada referência e totalizou 4.466 citações das quais 1.255 são publicações em revista.

3.2.1 Citações, palavras-chave, metodologias e atributos da literatura

Os 104 artigos do *corpus* apresentam 4.466 citações, dessas, 2.411 não se repetem, incluindo: artigos de revista, artigos de congresso, relatórios de agências governamentais, trabalhos acadêmicos, entre outros. A Figura 7 apresenta as 130 maiores citações da literatura em eficiência energética industrial.

Figura 7 – As 130 maiores citações da literatura em eficiência energética industrial



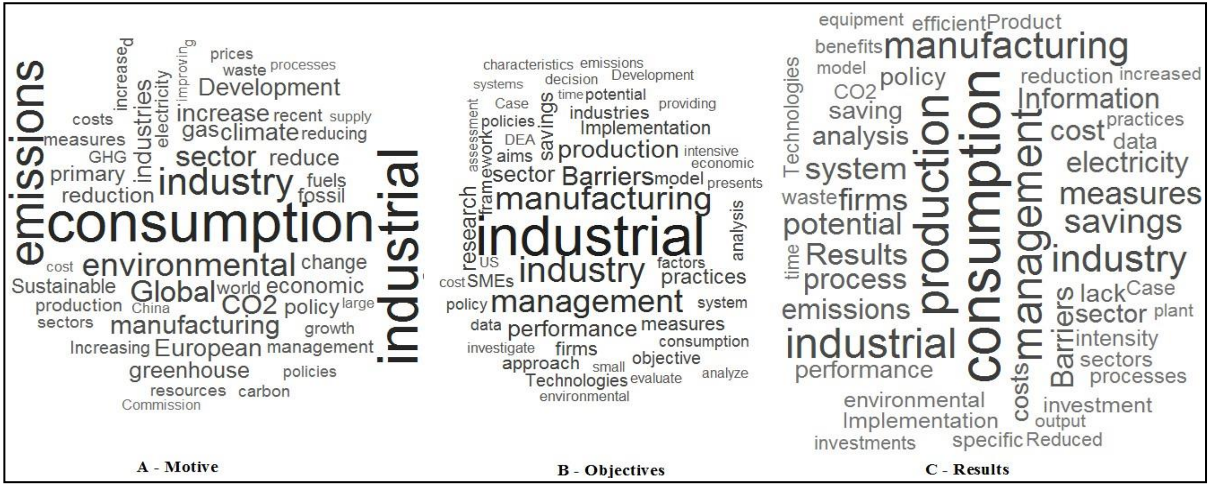
Fonte: Perroni *et al.*, 2015b; Perroni *et al.*, 2016b – Apêndices H e I.

As citações mais frequentes são[6]: [(EC, 76); (Thollander, P., 66); (IEA[7], 65); (Worrell, E., 49); (DOE, 48); (DeCanio, S.J., 41); (Rohdin, P., 37); (Sorrell, S., 33); (Cagno, E., 31); (Jaffe, A.B., 28); (Boyd, G.A., 26); (Ang, B.W., 25); (Trianni, A., 24); (Hermann, C., 23); (DeGroot, H.L.F., 23); (EIA, 23); (IPCC, 22); (EPA, 22); (Price, L., 20); (Schleich, J., 19); (Chertow, M.R., 19); (Brown, M.A., 17); (SEA, 16)].

Dentre os documentos mais citados constam: os relatórios da Comissão Europeia (EC), Agência Internacional de Energia (IEA), Departamento de Energia Americano (DOE), Agência de Informações em Energia dos EUA (EIA), Painel Intergovernamental de Mudanças Climáticas (IPCC), Agência de Proteção Ambiental Americana (EPA), Agência de Energia da Suécia (SEA), entre outras.

A Figura 8 expõe as 50 palavras que aparecem com mais frequência na justificativa [*motive*], objetivo [*objective*] e resultado [*results*] dos 104 artigos. As palavras *energy* e *efficiency* foram excluídas por serem *outliers*. Nota-se que as palavras utilizadas para a constituição da justificativa dos artigos têm um apelo ambiental maior.

Figura 8 – As 50 palavras mais frequentes da justificativa, objetivo e resultado extraídos do painel de conteúdo



Fonte: Perroni *et al*. 2016b – Apêndices H e I.

Devido a falta de espaço para a visualização a Rede 3 foi construída com palavras-chave que apareceram pelo menos duas vezes nos 104 artigos. Esses artigos utilizaram 286

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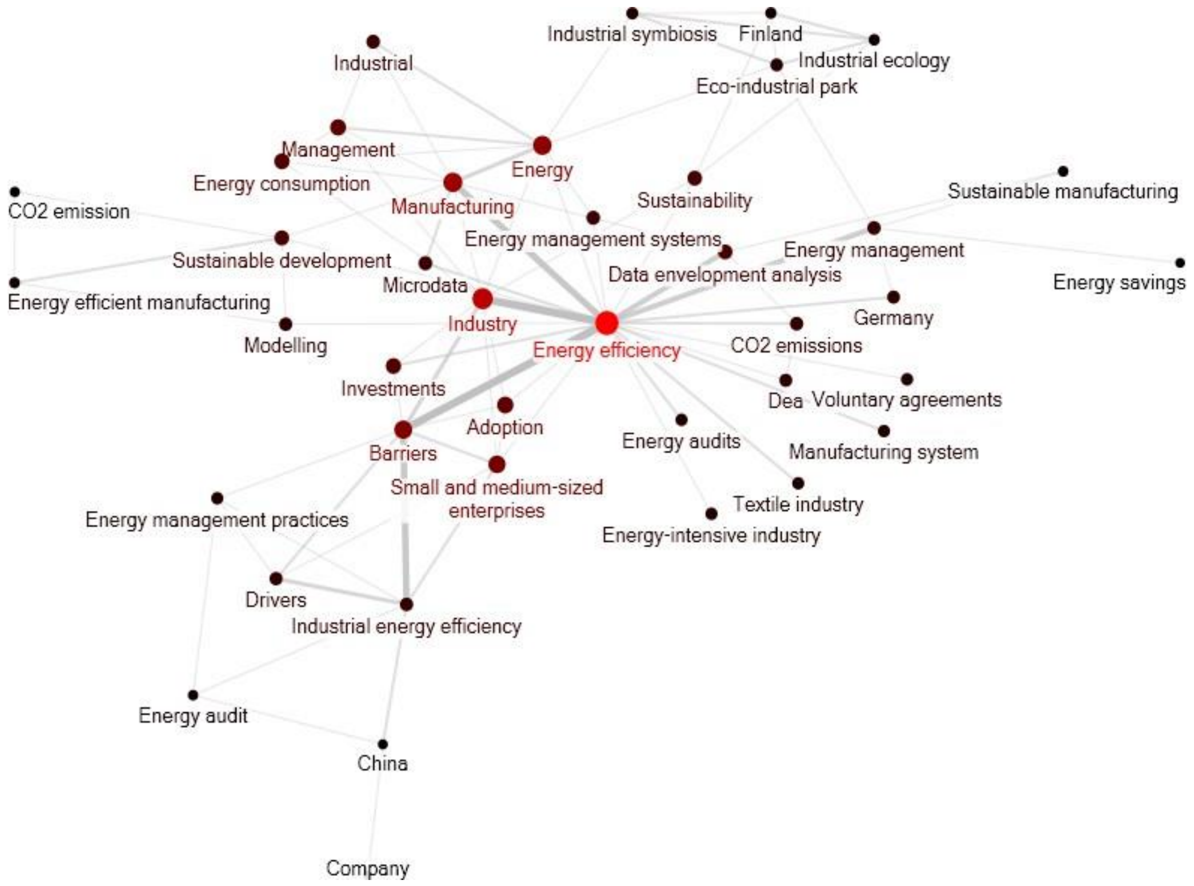
[6] Citação e quantidade de citações, considerando o primeiro autor.

[7] Entre os títlos dos relatórios mais citados da Agência Internacional de Energia, destacam-se: *“Key world energy statistics”; “World Energy Outlook”; “Assessing Measures of Energy Efficiency Performance and Their Application in Industry”; “25 energy efficiency policy recommendations”; “Tracking industrial energy efficiency and CO2 emissions”; “Worldwide trends in energy use and efficiency – key insights from IEA Indicator Analysis”; “Voluntary actions for energy related CO2 abatement”; “Indicators of energy use and Efficiency”; “Implementing Energy Efficiency Policies”*

palavras-chave, das quais 40 foram mencionadas mais de uma vez, além de estarem representadas na mesma rede. Como esperado, o termo eficiência energética é central, e devido à espessura das arestas, destaca-se a ligação mais forte com os termos: *Barriers*, *Industry*, *Manufacturing*, *Data Envelopment Analysis e Energy Management.*

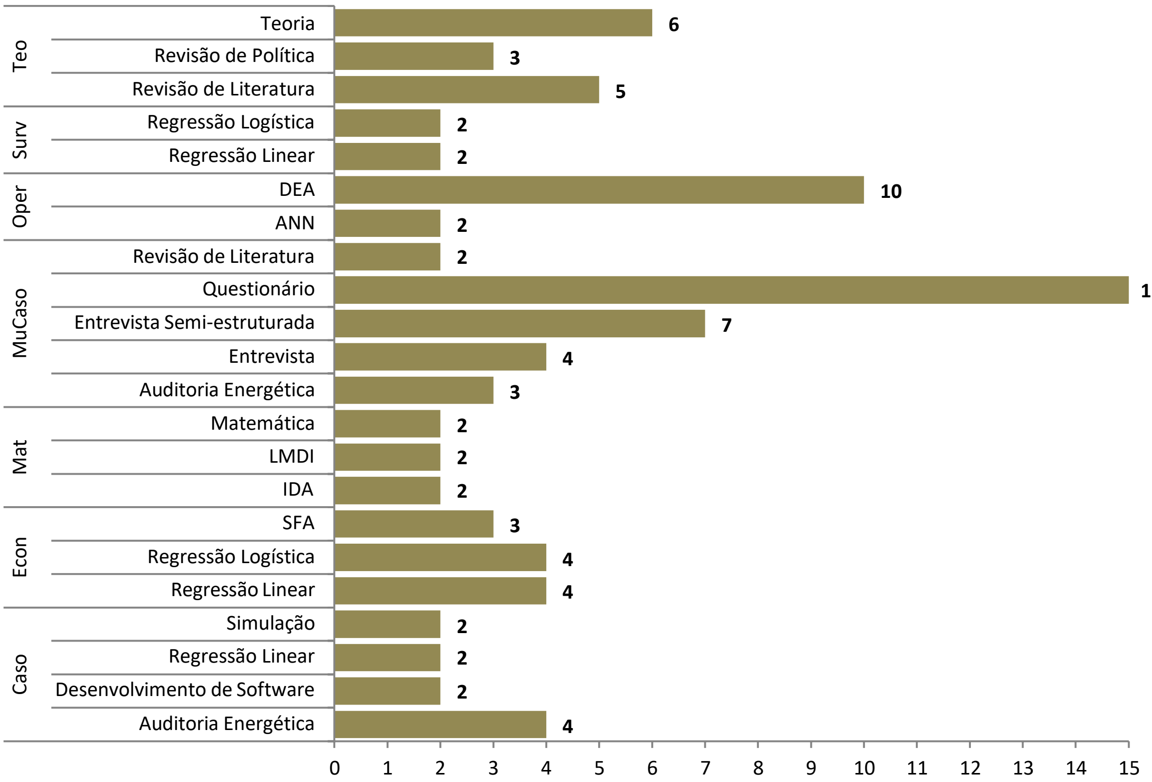
Rede 3 - Relacionamento entre as palavras-chave mais frequentes



Fonte: Perroni *et al.*, 2015b; Perroni *et al.*, 2016b – Apêndices H e I.

O Gráfico 6 apresenta a utilização das técnicas/métodos pelas abordagens de pesquisa. Apenas as técnicas utilizadas mais de uma vez, considerando os 104 artigos, foram apresentadas. As técnicas mais utilizadas são: a análise envoltória (DEA) e o questionário. Conforme esperado, as abordagens qualitativas como (estudo de caso/múltiplo) estão relacionadas às técnicas de questionários e entrevistas, enquanto as abordagens de pesquisa como (*Operations Analytics*, Econometria e *Survey*) geralmente utilizam com maior frequência as técnicas de análise envoltória de dados e regressão logística.

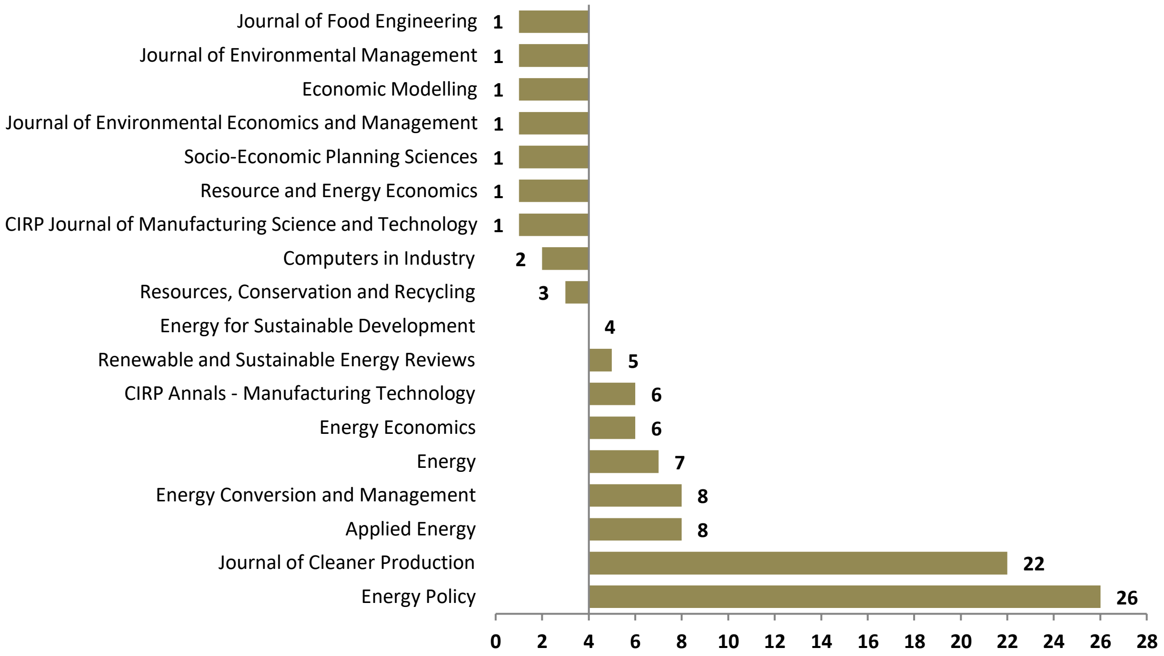
Gráfico 6 - Abordagens de pesquisa *versus* métodos/técnicas utilizadas



Fonte: Perroni *et al*. 2015b – Apêndices H e I.
Nota: Teo – Teoria; Surv – Survey; MuCaso – Estudo de caso múltiplo; Caso – Estudo de caso simples; Econ – Estudo Econométrico; Oper- Estudo baseado em Operations Analytics; Mat – Matemática.

O Gráfico 7 denota a quantidade de artigos nas dezoito revistas da composição do conjunto de documentos (*corpus*).

Gráfico 7 - Quantidade de artigos por revistas científicas

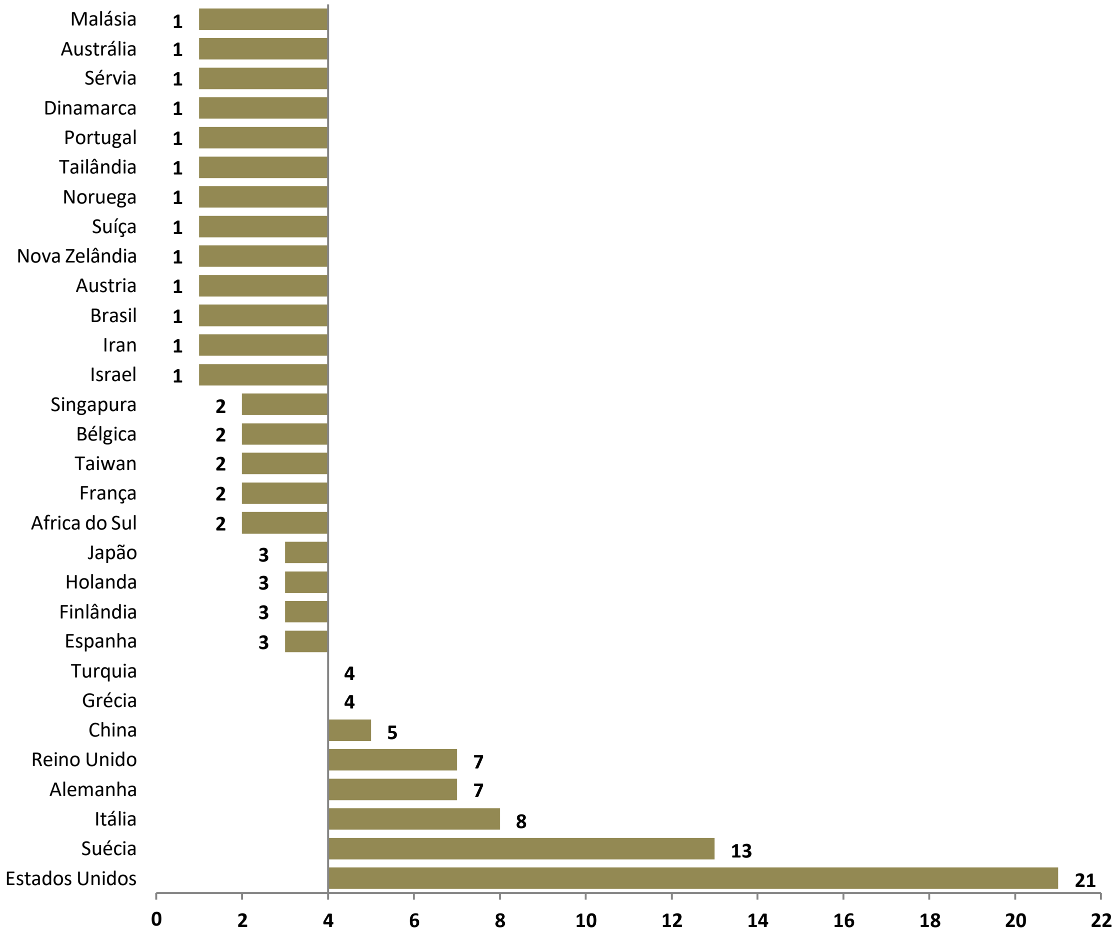


Fonte: Perroni *et al*. 2015b - Apêndices H e I.

Com base no Gráfico 7, oito revistas tiveram cinco ou mais artigos pertencentes ao *corpus* e duas revistas se destacam como sendo as principais da área de eficiência energética industrial: a *Energy Policy* e a *Journal of Cleaner Production*. As oito revistas estão entre as 50 com melhor ranking SJR do Scimago, considerando um total de 753 periódicos cadastrados na área de energia.

O Gráfico 8 apresenta a quantidade de artigos por país de origem do primeiro autor dos artigos. Vale ressaltar que se trata de um tema discutido internacionalmente por muitos países, embora apenas seis países tenham cinco ou mais artigos. Em números, isso representa (58/104), aproximadamente, 60% do total.

Gráfico 8 - Quantidade de artigos por país do primeiro autor



Fonte: Perroni *et al*. 2015b - Apêndices H e I.

Com base em Perroni *et al*. (2015b), e nos Apêndices H e I, outros atributos do conjunto de documentos destacam-se. As instituições mais centrais pertencem aos Estados Unidos da América, com liderança da Agência de Proteção Ambiental Americana (US-EPA). Esse fato indica que, interiormente, existe nos Estados Unidos uma rede de cooperação maior trabalhando acerca desse tema. As maiores ligações (cooperações) estão entre Itália/Holanda (*Politecnico di Milano/Copernicus Institute of Sustainable Development*); Itália/Suécia (*Politecnico di Milano/Linköping University*) e Alemanha/Austrália (*Technische Universität Braunschweig/University of New South Wales*).

Pode ser destacado, mesmo que de forma intuitiva a abrangência do tema de estudo pelo número de instituições e departamentos da composição do *corpus*. Os 104 artigos tiveram a contribuição de 107 instituições de 30 países diferentes. Foram identificados 83 departamentos e, dentre eles, novos departamentos foram criados, como: Sustentabilidade, Engenharia Ecológica, Mudanças Climáticas, Recursos Ambientais, Recursos Energéticos, entre outros com o objetivo de estudar o tema. As maiores centralidades envolvem as áreas de Engenharia, Gestão e Sustentabilidade. A Engenharia Mecânica e a Gestão exercem maior intermediação da informação por terem a estatística de grau mais elevada [*degree centrality*]. As ligações mais frequentes ocorrem entre: Engenharia, Gestão, Economia e Engenharia Industrial (PERRONI *et al*., 2016b).

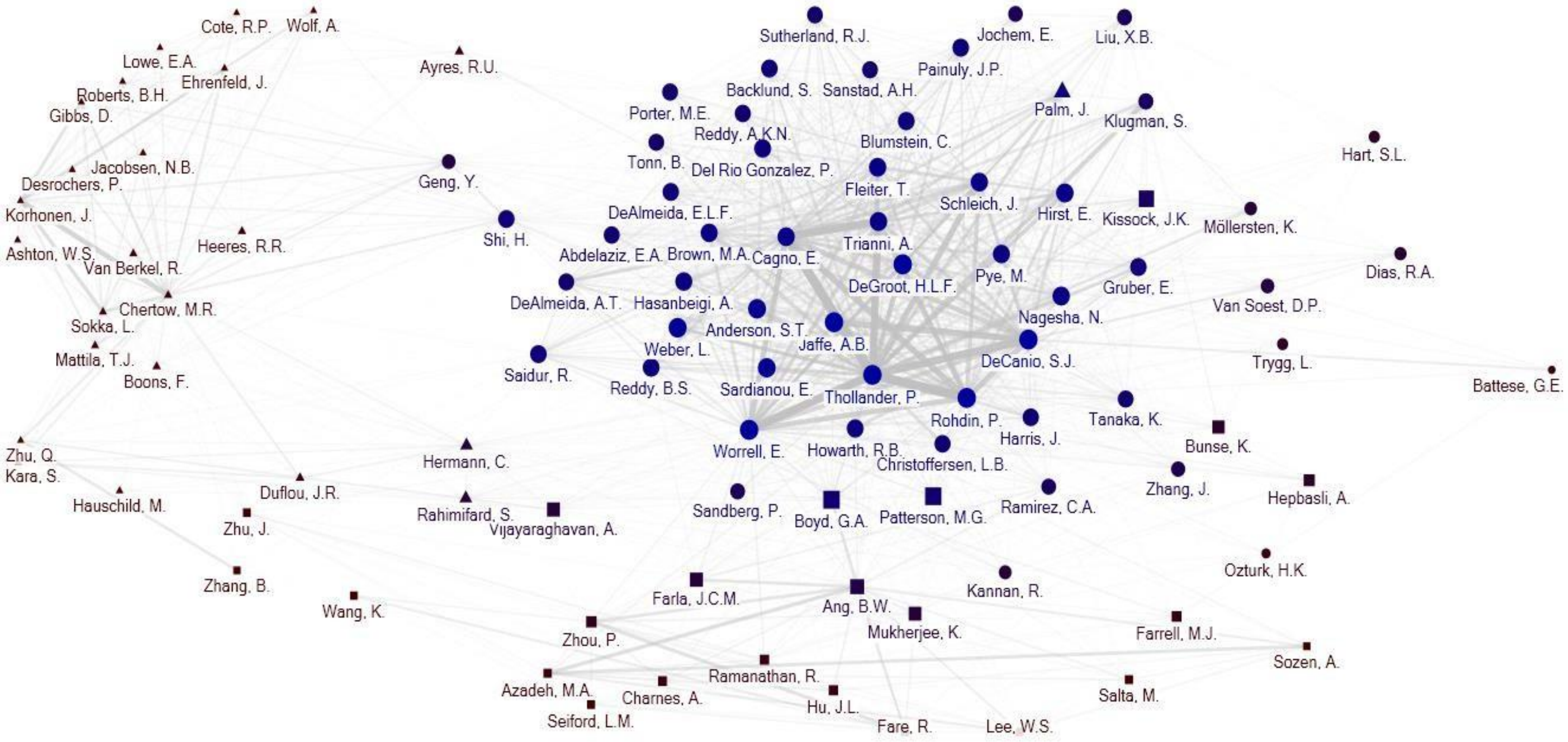
3.2.2 Identificação dos grupos de autores e temas na área de eficiência energética industrial

A aplicação do modelo de processo da Figura 6 possibilitou a identificação das principais vertentes teóricas, bem como as categorias e temas que os pesquisadores do conjunto de documentos (*corpus*) trabalham, apontando uma atualização do *framework* existente além de destacar as tendências para pesquisas futuras (PERRONI *et al*., 2015b).

A Rede 4 apresenta o relacionamento (coocorrência) dos 100 autores mais citados, considerando os 1.255 pertencentes às publicações em revistas científicas nos 104 artigos. Com base na distribuição que o algoritmo *Harel-Koren Fast-Multiscale* executou (HANSE, *et al*., 2011), e nos temas de interesse dos trabalhos, a rede foi classificada em três grupos categóricos, conforme sua forma geométrica: Esfera - Gestão/Eficiência Energética; Quadrado – Desempenho Quantitativo; Triângulo - Sustentabilidade Envolvendo Rede de Firmas [*Sustainable Inter-Firm Relations*].

A Rede 5 mostra o relacionamento dos temas em que os 104 artigos trabalharam. Foram selecionados entre dois e cinco temas por artigo. Na rede de temas também foi possível identificar os três grupos em que a literatura trabalha (PERRONI *et al*., 2015b).

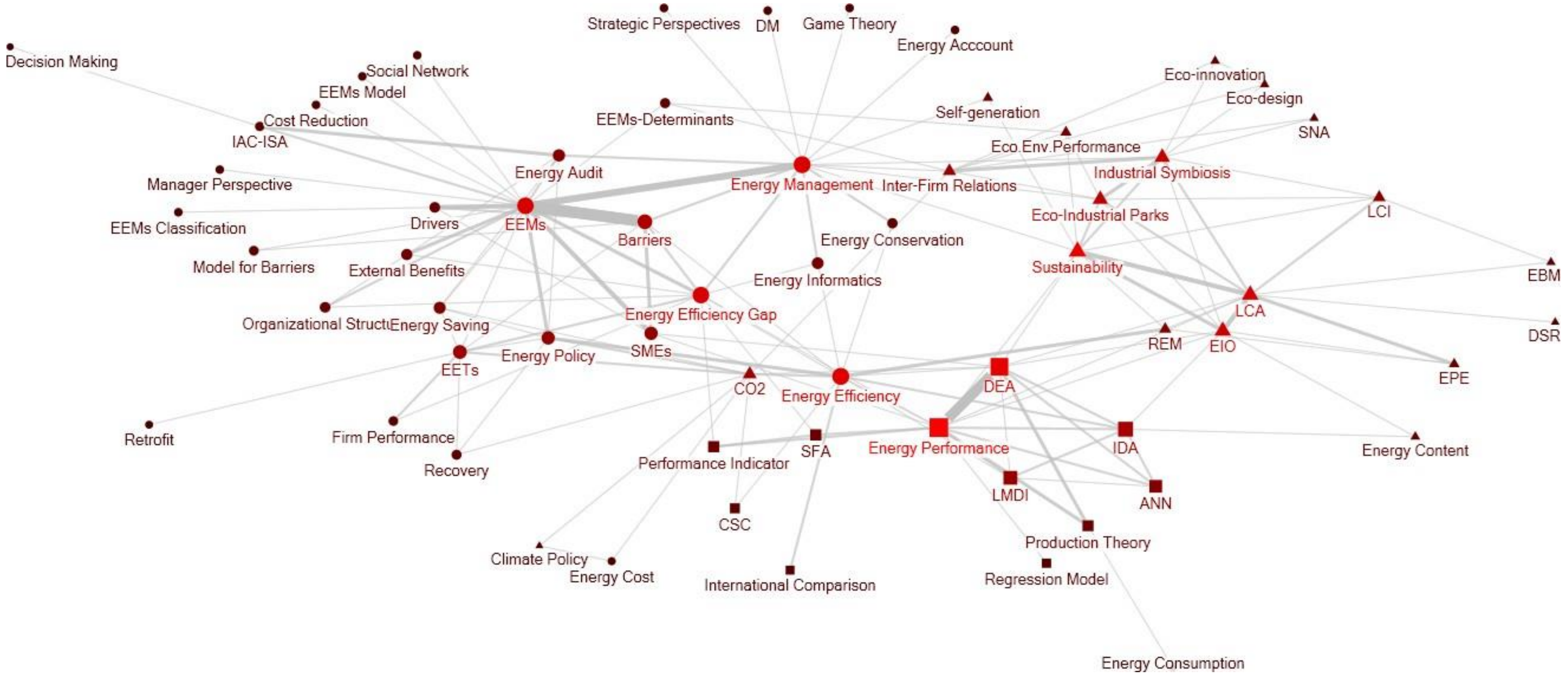
Rede 4 - Rede dos 100 autores mais citados pela literatura



Fonte: Perroni *et al*. 2015b - Apêndices H e I.

Nota: (a) Grupos categóricos - Esfera: Gestão/Eficiência Energética; Quadrado: Desempenho Quantitativo; Triângulo: Sustentabilidade Envolvendo Rede de Firmas. (b) Cor e tamanho dos vértices são proporcionais a centralidade auto vetorial [*eigenvector centrality*]; (c) Espessura e opacidade das arestas são proporcionais ao peso da aresta. (d) Algoritmo utilizado para a distribuição: Harel-Koren Fast-Multiscale (Hanse, *et al*. 2011; Prell, 2012); (d) As categorias e subcategorias foram definidas de meneira mais detalhada nos Apêndices H e I.

Rede 5 - Rede temática da literatura em eficiência energética industrial



Fonte: Perroni *et al*. (2015b) - Apêndices H e I.

Nota: (a) Grupos categóricos - Esfera: Gestão/Eficiência Energética; Quadrado: Desempenho Quantitativo; Triângulo: Sustentabilidade Envolvendo Rede de Firmas. (b) Cor e tamanho dos vértices são proporcionais a centralidade auto vetorial [*eigenvector centrality*]; Espessura e opacidade das arestas são proporcionais ao peso da aresta. (c) Algoritmo utilizado para a distribuição: Harel-Koren Fast-Multiscale (Hanse, *et al*., 2011; Prell, 2012); (d) As categorias e subcategorias foram definidas de meneira mais detalhada nos Apêndices H e I.

Siglas: ANN - Artificial Neural Network; CED - Cumulative Energy Demand; CSC - Conservation Supply Curves; DM - Data Mining; DSR - Direct Secondary Reuse; EBM - Environmentally Benign Manufacturing; EEMs - Energy Efficiency Measures; EETs - Energy Efficient Technologies; EIO - Economics Input Output; EPE - Energy Product Embodied; IAC-ISA - Industrial Assessment Centers-industrial Saving Assessment; IDA - Index Decomposition Analysis; LCA - Life Cycle Analysis; LCI-Life Cycle Inventory; LMDI; Logarithmic Mean Divisia index; REM - Resource Efficiency Manufacturing; SFA- Stochastic Frontier Analysis; SMEs - Small and Medium-sized Enterprises; SNA – Social Network Analysis.

3.3 CONTRIBUIÇÃO DOS GRUPOS DA REVISÃO SISTEMÁTICA DA LITERATURA EM EFICIÊNCIA ENERGÉTICA INDUSTRIAL

O objetivo da seção 3.2 foi responder ao conjunto de perguntas definidas *ex-ante*: quem são os autores mais citados? Os autores são de quais países, institutos de pesquisa e departamentos? Quais as principais revistas? Quais são os principais temas e palavras-chaves identificados? Quais são os métodos e as técnicas utilizados pelos trabalhos? Quais grupos podem ser identificados? A análise dos questionamentos levantados *ex-ante* auxilia no mapeamento analítico categórico formando grupos de similaridade.

Uma questão que emerge é sobre a discussão dos grupos identificados nos 104 artigos do *corpus*, além das citações relevantes feitas pelos autores desses grupos. A estratégia para a apresentação da discussão dos grupos categóricos, identificados na seção 3.2, deu-se com base no painel de conteúdo construído bem como consultas adicionais aos artigos do *corpus* ou artigos e relatórios de organismos relevantes identificados na Figura 7 e Rede 4. Os termos a seguir, grupos categóricos e categorias, serão utilizados como sinônimos.

A principal categoria refere-se aos trabalhos da eficiência e gestão energética, sendo este o grupo mais denso ao se considerar as cocitações. Os vértices desse grupo são representados por esferas nas Redes 4 e 5. Para facilitar a apresentação, a categoria gestão e eficiência energética foi codificada em cinco subcategorias: eficiência energética, poupança de energia/medidas para a eficiência energética [*Energy Efficiency Measures* (EEMs)], gestão de energia, política energética e outros fatores relacionados à eficiência energética. A segunda categoria refere-se aos artigos que trabalham com o desempenho quantitativo da energia. Seus vértices são identificados por quadrados nas Redes 4 e 5. O grupo da sustentabilidade envolvendo rede de firmas é o terceiro a ser apresentado, e está representado por triângulos nos vértices das mesmas redes.

Para orientar a discussão dos grupos categóricos uma série de questões *ex-post* foram elaboradas e apresentadas no Quadro 2. Uma vez que cada artigo do *corpus* apresenta, no mínimo, uma pergunta de pesquisa, esta tese terá, pelo menos, 104 perguntas de pesquisa. Embora muitas perguntas de pesquisa possam ser semelhantes como a investigação das barreiras em eficiência energética, por exemplo, a aplicação das pesquisas ocorre em contextos distintos. As questões *ex-post* definidas são representativas das questões dos artigos, orientadas pelos grupos identificados. O objetivo proposto não é solucionar de forma definitiva ou completa as questões levantadas *ex-post*, mas sim ajudar na interpretação e análise da literatura.

Quadro 2 - Questões *ex-post* (QEP) representativas do *corpus*

•	***Gestão/Eficiência Energética***
QEP1	✓ *Por que estudar eficiência Energética?*
QEP2	✓ *Quais os principais determinantes e limitadores da eficiência energética?*
QEP3	✓ *Quais tipos de medidas podem ser adotados?*
QEP4	✓ *O que é gestão de energia?*
QEP5	✓ *Que tipos de prática de gestão de energias estão sendo investigados e quais as dificuldades?*
QEP6	✓ *Que tipo de frameworks tem sido proposto para a gestão de energia?*
QEP7	✓ *Quais tipos de políticas podem ser adotados pelos governos?*
QEP8	✓ *As ações de política energética têm dado o resultado esperado?*
•	***Desempenho Quantitativo***
QEP9	✓ *O que é eficiência energética?*
QEP10	✓ *O que é desempenho energético?*
QEP11	✓ *Como o desempenho energético está sendo medido?*
•	***Sustentabilidade Envolvendo Rede de Firmas***
QEP12	✓ *Quais tipos de conceitos e técnicas têm sido utilizados para o estudo da eficiência energética quando mais de um ator (inter-relação entre empresas) está envolvido?*
QEP13	✓ *O relacionamento entre empresas tem obtido sucesso na eficiência de energia?*

Fonte: o autor, 2016 - Apêndices H e I.

É importante destacar que a análise da revisão sistemática da literatura, feita de maneira *ex-post*, deve contribuir para a resolução do problema de pesquisa levantado. Em relação a presente tese, o problema refere-se à medição e controle do desempenho energético. As perguntas elaboradas, a cada um dos três grupos identificados na literatura, contribuirão com a resolução do problema de pesquisa. Vale ressaltar que essa análise não é uma ciência exata, portanto, se o objetivo deste trabalho fosse outro, provavelmente, outras questões surgiriam.

As próximas seções apresentarão, com mais detalhes, as contribuições de cada um dos três grupos identificados, orientados pelas respostas das questões *ex-post* propostas no Quadro 2.

3.3.1 Eficiência e gestão energética

Os 66 artigos deste grupo foram classificados em 13 temas, de acordo com o problema de pesquisa que os artigos procuram resolver, nos quais os autores e temas podem ser vistos na Figura 9. Posteriormente, a categoria foi dividida em cinco subcategorias para facilitar a apresentação (eficiência energética, poupança de energia/EEMs, gestão de energia, política energética e outros fatores relacionados à eficiência energética). Um dado notório, referente a esse grupo, é o fato de somente quatro artigos serem anteriores ao ano 2000 e, aproximadamente, 70% dos artigos são de 2010 ou superiores a esse ano.

3.3.1.1 Eficiência energética

As questões *ex-post* definidas para essa subcategoria foram: por que estudar eficiência Energética? Quais os principais determinantes e limitadores? A principal justificativa dos artigos, em relação ao primeiro questionamento, está associada a dois temas: escassez dos recursos não renováveis e seus impactos no meio ambiente, condizente com o que foi apresentado no capítulo 2. A Figura 8 salienta que as 50 palavras mais frequentes na justificativa dos artigos estão relacionadas a esses dois temas, destacando-se, de um lado, o consumo industrial de energia e, de outro, as emissões.

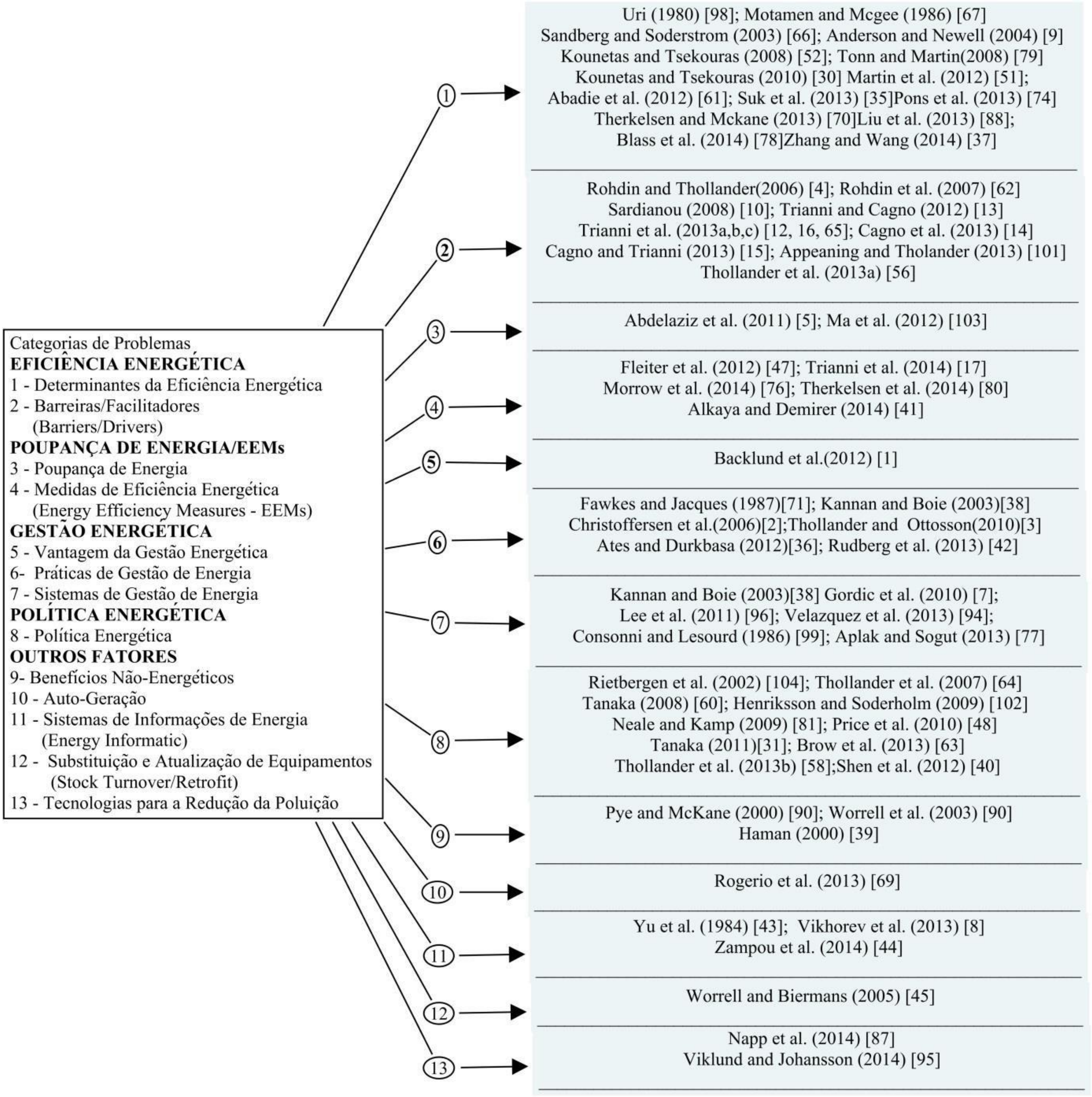
Existe ainda, o fato de a literatura reconhecer o chamado *energy efficiency gap* desde a década de 80. De acordo com Jaffe e Stavins (1994), autores mais citados na Figura 7 e cocitados na rede 4, o *gap* diz respeito à discrepância entre as adoções em eficiência energética, identificadas como ótimas e as realmente realizadas. O trabalho de DeCanio (1998) também aparece como um dos mais citados e cocitados nas mesmas ilustrações, cuja principal contribuição foi a constatação de que um paradoxo continuava existindo, uma vez que muitas empresas têm a oportunidade de maximizar os resultados, por meio de investimentos em eficiência energética, mas o fazem.

Devido ao cenário exposto, juntamente, com o fato das pressões governamentais e de lideranças políticas sociais, o tema eficiência energética passou a ser investigado com mais veemência a partir do final da primeira década do século XXI.

Uma das primeiras questões apresentadas está relacionada aos determinantes e limitações para a eficiência energética. Os autores apresentados na Figura 9, os quais foram categorizados como os que estudam os determinantes da adoção de práticas em eficiência energética, adotam, em geral, metodologias estatísticas/econométricas, as quais podem ser observadas no Gráfico 6. De acordo com o mesmo gráfico, os autores que discutem as limitações [*Barriers/Drivers*] adotam metodologias qualitativas, principalmente, o estudo de caso.

Nos estudos acerca dos determinantes da eficiência energética, trabalha-se com as mais variadas hipóteses para estabelecer um relacionamento entre o menor uso de energia e outros diversos fatores. Para Uri (1980), a eficiência energética é afetada pela inovação tecnológica, acesso ao capital, variação na capacidade de utilização e aumento no preço da energia. Segundo Motamen e Mcgee (1986), faltavam projetos de conservação de energia, e as discussões que seguem apresentam indícios de que esse ainda é o caso.

Figura 9 - Subcategorias do grupo da eficiência e gestão de energia



Fonte: Perroni *et al*. 2016b - Apêndices H e I.

Nas identificações feitas por Sandberg e Soderstrom (2003), a eficiência energética pode ser promovida por diferentes meios: informações aos envolvidos, apoio governamental, auditorias [*energy audit*], boas práticas [*housekeeping*], investimentos de capital, monitoramento do fluxo de energia, *benchmarking* e conexão com outros investimentos.

Por meio de uma análise das auditorias em eficiência energética, para pequenas e médias empresas nos Estados Unidos, vários autores (ANDERSON; NEWELL, 2004; ABADIE *et al*., 2012; THERKELSEN; MCKANE, 2013) constataram que aproximadamente 50% dos projetos são implementados e as adoções são guiadas por métricas de custo (menor custo, menor *payback* e maior preço da energia). Tonn e Martin (2008) identificaram que as auditorias tiveram uma correlação positiva com investimentos posteriores. No trabalho de Blass *et al*. (2014) também investigado com as informações das auditorias Americanas, o envolvimento dos gestores de operações é fundamental para a melhoria da taxa de adoção de práticas para a eficiência energética. A adoção mais provável é para firmas que receberam mais subsídios, firmas com maior intensidade energética e com capital fixo mais elevado.

Quanto ao relacionamento entre as tecnologias energeticamente mais eficientes [*energy efficiency Technologies*] (EETs) e a eficiência empresarial, Kounetas e Tesoukas (2010) identificaram que as tecnologias afetam positivamente a eficiência técnica das empresas.

Ao considerar os fatores políticos e ambientais, Suk *et al*. (2013), mesmo para empresas intensivas em energia, não encontraram uma relação entre regulação, competidores e associações, e a poupança de energia. A poupança de energia é determinada pelo suporte da alta gerência, incentivos econômicos e treinamentos. De acordo com Liu *et al*. (2013), a aceitação de taxas de carbono mais elevadas são determinadas por percepções subjetivas e automotivação devido, provavelmente, à falta de capacitação interna. Segundo Zhang e Wang (2014), a colaboração para redução da emissão de carbono por meio da Simbiose Industrial [*Industrial Symbiosis*] tem um relacionamento positivo com o desempenho econômico. Pons *et al*. (2013) não encontraram um relacionamento entre desempenho econômico e eficiência energética, mas identificaram um relacionamento positivo entre eficiência energética e desempenho ambiental.

Outro conjunto de autores investigou acerca da problemática existente, questionando diretamente as empresas industriais. Quais as principais limitações e fatores de difusão para uma maior eficiência energética? Uma síntese dos principais limitantes, as chamadas barreiras, é dada no trabalho de Cagno *et al*. (2013), na qual são identificadas uma série de barreiras internas (econômicas, comportamentais, organizacionais, competência/consciência) e barreiras externas (mercado, governo/políticas, tecnologia/serviços, projeto e desenvolvedores de tecnologias, disponibilidade de capital).

Por meio de técnicas qualitativas como entrevistas e questionários semiestruturados, diversos trabalhos investigaram tanto barreiras quanto facilitadores [*drivers*]. Dentre as principais barreiras empíricas, tanto nas indústrias não intensivas, quanto nas intensivas em energia, destacam-se: (i) custo e risco da parada de produção, (ii) falta de tempo, (iii) outras prioridades, (iv) custo da obtenção da informação do consumo de energia dos equipamentos comprados, (v) outras prioridades para o investimento de capital, (vi) falta de submedidores,

(vii) divisão de incentivos com Empresas de Serviços de Conservação de Energia (ESCOs) (ROHDIN; THOLLANDER 2006; ROHDIN *et al*., 2007; TRIANNI; CAGNO, 2012).

Sardianou (2008) identificou que nas indústrias gregas, os investimentos em energia não são prioridade. Cerca de 70% das firmas não estavam informadas a respeito das novas tecnologias, mas consideraram que se os competidores fizerem, elas estariam dispostas a fazer também. Investigando o *framework* de Cagno *et al*. (2013) para 48 manufaturas da Itália, Trianni *et al*. (2013a) identificaram as principais barreiras econômicas (alto custo dos investimentos, custos ocultos, intervenção não suficientes rentáveis), informação (informações sobre contrato de energia, informações não claras pelos ofertantes de tecnologias, informação sobre custo benefício), sendo que a conclusão é que a gestão de energia é marginal nas firmas investigadas. Trianni *et al*. (213b) identificaram em 65 fundições da Europa que as empresas estavam preocupadas com a garantia da continuidade do negócio, além da preocupação com os riscos. Posteriormente, para a indústria metal mecânica, Trianni *et al*. (2013c) identificaram ainda a falta de interesse em eficiência energética devido ao fato de as empresas se julgarem eficientes. Apeaning e Thollander (2013) identificaram, em uma grande área industrial, a falta de profissional qualificado para avaliar o desempenho das tecnologias de eficiência energéticas (EETs).

Dentre os facilitadores [*drivers*] identificam-se: estratégias de longo prazo, aumento do preço da energia, necessidade de pessoal com ambição real (ROHDIN; THOLLANDER, 2006; ROHDIN *et al*., 2007; APPEANNING; THOLANDER, 2013). Também são identificados como *drivers*: abonos ou financiamentos públicos, pressão externa, benefício de longo prazo, redução de custo e apoio dos altos gestores (CAGNO; TRIANNI 2013; THOLLANDER *et al*., 2013a).

3.3.1.2 Poupança de energia e medidas de eficiência energética

Outra questão pertinente é: quais tipos de medidas podem ser identificados? Em uma revisão de literatura, Abdelaziz *et al*. (2011) identificam que a poupança de energia ocorre de três formas: (i) gestão de energia (análise dos dados históricos, auditorias energéticas, análises de engenharia, informação/treinamento), (ii) por meio das tecnologias eficientes (EETs) (controladores de velocidade [*variable speed drive*], recuperação de calor, motores mais eficientes, prevenção de vazamentos em compressores de ar), (iii) política energética (regulações, política fiscal, acordos e metas).

Segundo Fleiter *et al*. (2012), as medidas (EEMs) dependem de três fatores, sendo a vantagem relativa (taxa interna de retorno, *payback*, gasto inicial, benefícios não energéticos), contexto técnico (distância do processo central, tipo de modificação, escopo do impacto, tempo de vida) e contexto da informação (custo de transação, conhecimento para o planejamento/implementação, progresso de difusão, aplicabilidade setorial).

Diversas vantagens indiretas da aplicação das medias (EEMs) são levantadas: melhoria do ambiente interno, redução de barulho, poupança de trabalho/tempo, melhoria do controle do processo, melhoria da comodidade, poupança de água, minimização de resíduos, benefícios da miniaturização dos equipamentos, redução de emissões, menor necessidade de manutenção, aumento da produtividade (TRIANNI *et al*., 2014).

Conforme apresentado por Abdelaziz *et al*. (2011), assim como no relatório do Departamento de Energia dos Estados Unidos DOE-IAC (2007), o qual tem aproximadamente 700 práticas relacionadas à gestão de energia, a identificação das medidas é caso específico. Com base na literatura, alguns trabalhos procuram identificar as medidas para casos específicos, Morrow *et al*. (2014) identificam 22 medidas para a indústria de cimento Indiana, Therkelsen *et al*. (2014) apontam 23 medidas para o setor de panificação, enquanto Alkaya e Demirer (2014) destacam 5 medidas gerais para uma fábrica têxtil na Turquia. O que atrai a atenção nessa fábrica têxtil é o fato de mesmo com um *payback* de investimentos de 1,5 meses, o consumo de água e de energia caiu 43% e 13.5%, respectivamente.

3.3.1.3 Gestão de energia

Em relação à subcategoria da gestão de energia, algumas questões podem ser respondidas, com base na literatura: o que é gestão de energia? Que tipos de práticas estão sendo investigadas e quais as dificuldades? Quais tipos de *frameworks* têm sido propostos para a gestão de energia?

Conforme denotado em Backlund *et al*. (2012), não existe uma definição precisa do que venha a ser gestão de energia. Para Amundsen (2000), ela não difere de outros sistemas de gerenciamento e pode ser integrada facilmente com os mesmos. Os autores Christoffersen *et al*. (2006) e Ates e Durakbasa (2012) associam a gestão de energia a certos procedimentos para a poupança de energia (treinamentos, controles, metas, planos, estimações, comunicações, avaliações entre outras) que as empresas podem adotar. Para Kannan e Boie (2003), bem como para Lee *et al*. (2011) o gerenciamento de energia é por natureza multidisciplinar com envolvimento das áreas de engenharias e de administração, no qual seu objetivo é maximizar a eficiência energética em prol de melhorias contínuas no desempenho competitivo. Segundo Gordic *et al*. (2010), a gestão de energia é um sistema de melhoria contínua, com a utilização de procedimentos planejados, revisados periodicamente. Conforme Bunse *et al*. (2011), ela está relacionada às atividades de controle, monitoramento e melhoria da eficiência energética.

Uma definição que contradiz o sentido de Amundsen (2000) é dada por Vikhorev *et al*. (2013), na qual a gestão industrial de energia é contexto específico, dependendo de fatores locais como desenho do produto, escolha do processo, matriz energética nacional, entre outros fatores. Essa última constatação apoiada principalmente nos trabalhos desenvolvidos por Kannan e Boie (2003) e Gordic *et al*. (2010) demonstra que é difícil reproduzir soluções tanto para indústrias, quanto para locais diferentes, requerendo abordagens *plan-do-chek-act* (PDCA).

Quais tipos de práticas de gestão são investigados e quais são as dificuldades? Os autores Fawkes e Jacques (1987) estudam a gestão de energia em termos dos intervalos de monitoramento do consumo, existência de metas e controle por centros de custo. Dentre as 49 empresas de bebidas, 11 praticavam a gestão de energia. O trabalho de Christofersen *et al*. (2006), por meio de um *survey*, investigou 304 empresas industriais na Dinamarca, chegando a conclusão de que entre 3% e 14% praticam gestão energética. Com relação aos motivos, 76% são motivados pelo custo. Para serem praticantes de gestão de energia, as empresas teriam que empregar os seguintes requisitos: (i) colocar em prática a política energética; (ii) estabelecer metas quantitativas para a gestão de energia ou preocupações objetivas com a implementação de projetos de poupança de energia, (iii) implementar projetos de poupança de energia específicos originados da gestão de energia. As empresas também precisariam empregar, pelos menos, um dos requisitos: (a) ter procedimentos específicos para as compras [*energy efficient purchase*]; (b) organizar as atividades de energia alocando claramente responsabilidades e tarefas; (c) envolver os funcionários na poupança de energia informando, motivando e educando.

Na pesquisa desenvolvida por Thollander e Ottosson (2010), acerca das indústrias intensivas de papel/celulose e fundição na Suécia, identificou-se que a gestão de energia não é uma atividade de destaque neste setor. Encontrou um critério de *payback* de até três anos. Os fatores de sucesso para a gestão de energia são: apoio dos altos gestores, abordagem estratégica, auditoria inicial, monitoramento do uso de energia, política energética, acompanhamento dos projetos de gestão de energia, treinamento e motivação da equipe de apoio. No trabalho de Ates e Durkbasa (2012) destaca-se que apenas 40% das empresas estudadas têm uma política energética formal, concluindo que 24% das empresas praticam gestão de energia. O grande problema identificado é a posição e a tarefa do gestor de energia que, geralmente, ocupa uma posição administrativa. Mesmo para empresas intensivas, a gestão de energia não é planejada em nível estratégico (ATES; DURKBASA, 2012; RUDBERG *et al*., 2013).

Quais tipos de *frameworks* têm sido propostos para a gestão de energia? Conforme o trabalho de Bunse *et al*. (2011) existe a necessidade de desenvolvimento de *frameworks* para a tomada de decisão. Os *frameworks* na área de energia são escassos. O trabalho de Consonni e Lesourd (1986) estava preocupado em desenvolver um sistema contábil para revelar os custos e as vantagens da poupança de energia. Aplak e Sogut (2013) utilizam uma abordagem da teoria dos jogos considerando indústria e meio ambiente como concorrentes. Velazquez *et al*. (2013) aplicam a abordagem de mineração de dados no desenvolvimento de um sistema de gestão energética com a utilização de diagramas de fluxo, análise discriminante e análise de regressão. A indústria de TI Lee *et al*. (2011) identificou que 80% das 66 empresas careciam de funções apropriadas de gestão de energia. Os autores propõem um sistema de monitoramento em tempo real.

Tanto a proposta de Kannan e Boie (2003), quanto Gordic *et al*. (2010) desenvolveram um processo de melhoria contínua para a gestão de energia. Segundo Kannan e Boie (2003), existem quatro fases: auditoria energética, identificação das medidas (EEMs), implementação das EEMs e avaliação/monitoramento. Aplicando o processo mencionado, em uma panificadora na Alemanha, a redução do consumo de energia esperado foi de 6%. Conforme Gordic *et al*. (2010), o sistema inicia-se com a definição de uma política de gestão de energia explícita, realização de uma auditoria energética, plano de ações, implementação e avaliação do desempenho. A melhora ocorre em seis pilares da matriz de gestão de energia: política empresarial, estrutura organizacional, motivação, monitoramento, consciência e investimento. Após a implantação do sistema na fábrica de automóveis Zastava na Sérvia, houve aproximadamente 25% de redução no consumo de energia no período 2005-2008.

3.3.1.4 Política energética

Quais tipos de políticas podem ser adotados pelos governos? As ações de política energética têm dado o resultado esperado? A necessidade de uma política energética industrial surge, principalmente, devido à presença de ineficiências e assimetrias de informação (HENRIKSSON; SODERHOLM, 2009). Com base em Tanaka (2011), conforme discutido no capítulo 2, a política para a eficiência e gestão energética industrial é apresentada em três grupos: prescritiva (regulação da eficiência do equipamento, regulação da configuração e eficiência do processo, regulação por gestão energética, acordos negociados); econômicos (taxas de energia, taxas para a redução direta do consumo de energia, incentivos financeiros diretos, contratos para emissões, discriminação do preço da energia) e de suporte (identificação de oportunidades de eficiência energética, medidas cooperativas, treinamento e capacitação). Outra questão levantada por Tanaka (2008) é se não forem definidas as fronteiras para a atuação das políticas energéticas, poderá ocorrer divergências na medição dos resultados.

O resultado das políticas energéticas nem sempre é simples de avaliar devido aos efeitos diretos (diminuição do consumo de energia esperado) e dos efeitos indiretos (benefícios não energéticos como a melhoria da produtividade). No estudo de Rietbergen *et al*. (2002) para a Holanda, entre um quarto e a metade da poupança de energia é atribuída aos acordos de longo prazo. Apesar do baixo nível de prioridade nas pequenas e médias empresas, o programa Highland teve uma adoção de 40% na Suécia.

Alguns trabalhos analisam os potenciais e lacunas de programas específicos em vários países. No programa da Nova Zelândia, para os sistemas de ar comprimido, Neale e Kamp (2009) encontram alguns *gaps*: instrumentos e procedimentos novos para análise do fluxo de ar, detecção de vazamentos de ar, capacitação para análise de dados e detecção de oportunidades de poupança de energia.

Com relação ao potencial do programa chinês para redução do consumo de energia das 1000 maiores empresas na China, Price *et al*. (2010) levantam que a estimação era de 148 *Mega Tonnes of Coal Equivalent* (MTCE) (4,3 Exajoule - EJ) que em termos de CO2 é equivalente as emissões da Polônia. Avaliando os programas de auditoria energética na China, Shen *et al*. (2012) identificam lacunas que precisam ser melhoradas: mecanismos de política de longo prazo, organização a nível nacional, motivação das empresas, escopo técnico limitado, análise de viabilidade econômica, incentivos adequados, padronização, ferramentas para avaliação de energia, capacitação e treinamento. Brow *et al*. (2013) identificam que uma política de estímulo fiscal ao CHP [*Combined Heat and Power* (CHP)] poderia gerar um retorno muito superior ao investimento feito nos Estados Unidos.

A meta Europeia é reduzir o consumo de energia em 20% até 2020. Essa meta foi analisada por Thollander *et al*. (2013b), considerando o setor industrial da Suécia, concluindo que as medidas adotadas (acordos voluntários, acordos de longo prazo, programas de auditorias energéticas) não seriam suficientes para que o país cumprisse o propósito desejado.

Segundo os autores, a meta pode ser alcançada por meio de três fatores: gestão energética, tecnologias eficientes em energia (EETs) e medidas de oferta de energia.

3.3.1.5 Outros fatores relacionados à eficiência energética

Os trabalhos de Pye e McKane (2000), Haman (2000), Worrell *et al.* (2003) identificam os benefícios não energéticos da eficiência energética, relacionados ao aumento da produtividade, redução da poluição, redução de custos, entre outros. O trabalho desenvolvido por Rogerio *et al.* (2014) analisa a auto geração para a indústria de alumínio no Brasil, a qual foi identificada sendo uma estratégia competitiva viável. O conjunto de três trabalhos, Yu *et al.*, (1984), Vikhorev *et al.* (2013) e Zampou *et al.* (2014), propõe sistemas informatizados para o monitoramento do consumo e eficiência energética.

Com relação às tecnologias, Worrell e Biermans (2005) partem do princípio que a intensidade energética pode ser reduzida tanto pela substituição de equipamentos, quanto por meio de atualizações da tecnologia [*retrofit*]. Napp *et al.* (2014) e Viklund e Johansson (2014) fazem um levantamento das tecnologias para a redução de emissão de CO2 e utilização dos resíduos.

3.3.2 Medição quantitativa do desempenho

O que é eficiência energética? O que é desempenho energético? Como o desempenho energético está sendo medido? Basicamente, entende-se por desempenho energético à medição da eficiência energética, utilizando-se de indicadores para isso. Vale ressaltar que a eficiência energética não é a única variável a ser controlada na medição do desempenho energético, fundamentado por trabalhos da revisão sistemática da literatura (KANNAN; BOIE, 2003; ANDERSON; NEWELL, 2004; GORDIC *et al.*, 2010; VIKHOREV *et al.*, 2013), além dos artigos desenvolvidos por esta tese (Apêndices F ao M), a gestão industrial de energia é contexto específico. Neste contexto, será necessário e viável medir o desempenho dos chamados uso dos recursos associados como: água, utilização de materiais intensivos em energia, emissões de poluentes, além de muitos outros, dependendo das condições locais de produção e processos escolhidos. De acordo com Soytas e Sari (2007), o relacionamento entre produção e energia nem sempre foi claro devido à marginalização deste *input* como fator de produção.

A primeira indagação diz respeito à definição de eficiência energética. Segundo Patterson (1996), que aparece entre as principais citações e cocitações apresentadas na Figura 7 e Rede 4, a eficiência energética é um termo genérico e não existe uma forma quantitativa capaz de medi-la sem incorrer em algum tipo de suposição. Em geral, a maior eficiência energética está associada ao menor uso de energia para produzir a mesma quantidade do bem ou serviço. A eficiência energética pode ser medida como a razão saída/entrada [*useful output of process/energy input into a process*]. A pesquisa de Patterson (1996) indica que a seleção das variáveis que compõem o indicador pode ser classificada em quatro tipos de indicadores: termodinâmico, físico termodinâmico, econômico-termodinâmico e econômico. Para Phylipsen *et al*. (1997), o indicador também consiste na relação numerador e denominador, denotando a existência de dois tipos de indicadores: econômicos e físicos. Os autores reconhecem que dois indicadores comumente utilizados são: (i) intensidade energética, [*Energy Intensity,* (EI)], na qual o numerador é uma variável energética medida em termos termodinâmicos (Joule, Quilocaloria, entre outras) e o denominador é uma variável de produção medida em termos econômicos; (ii) consumo específico de energia, [*Specific Energy Consumption,* (SEC)] em que o numerador também é uma variável energética termodinâmica, sendo o denominador medido em termos da produção física (toneladas, KM, entre outras). Phylipsen *et al*. (1997) reconhecem que esses indicadores medem o inverso da eficiência na prática, pois a situação ideal se dá com a queda do indicador.

Os relatórios da Agência Internacional de Energia (IEA) estão entre os mais citados, conforme Figura 7. Alguns pontos ainda necessitam de esclarecimentos, devido às dúvidas sobre os indicadores em eficiência energética. A primeira questão é que o desempenho energético tem várias dimensões, em que podem ser criados indicadores de um processo específico ao sistema industrial como um todo. Conforme a IEA (2014a), o montante de energia consumida, dividida pela atividade ou produto é um indicador de intensidade energética, geralmente, o valor da variável - atividade ou produto - é dado em valores monetários. Essa definição está de acordo com Patterson (1996) e Phylipsen *et al*. (1997), com a ressalva de que quanto mais um indicador de intensidade energética é agregado (vários setores) mais o indicador se torna um aproximador da eficiência energética, porque outros fatores vão se tornando relevantes (estrutura da economia, tipo da indústria, taxas de conversão/trocas, acessibilidade dos serviços de energia, tamanho do país, clima e comportamento). Considerando os indicadores em nível agregado, a IEA utiliza-se de índices de decomposição para o consumo de energia, separado geralmente em três efeitos: atividade (atividade econômica), estrutura (mix de atividades/processos dentro de um setor) e intensidade energética (eficiência energética) (IEA, 2014a). O algoritmo de decomposição mais conhecido é o [*Logaritmic Mean Divisia índex* (LMDI)], desenvolvido por Ang (2012), e também aparece entre os mais citados da Figura 7.

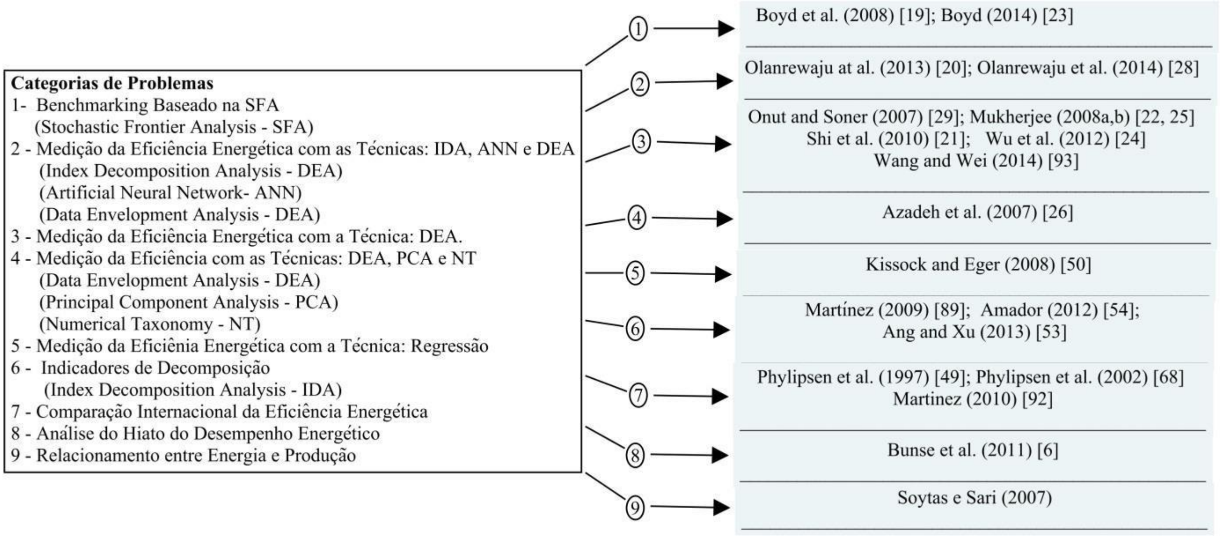
Outra diferenciação que também causa confusão entre os autores é a diferença entre eficiência energética e conservação de energia. Esta remete a uma mudança no estilo de vida, normalmente, deixando de consumir determinado produto/serviço, enquanto aquela está relacionada ao consumo do mesmo produto/serviço economizando energia, ou seja, ao uso das medidas (EEMs) para a eficiência energética (tecnologia, gestão de energia, política energética) (ABDELAZIZ *et al*., 2011; IEA, 2014a).

Diversos trabalhos de revisão sistemática procuram desenvolver formas para a medição do desempenho energético, formando uma categoria particular, que se preocupa com as formas de mensuração. Os autores e a categorização de temas podem ser visualizados na Figura 10.

Os trabalhos de Boyd *et al*. (2008) e Boyd (2014) fazem a estimação empírica do melhor desempenho observado, ou [*best practice*], ou seja, uma distribuição empírica da eficiência, baseado nas diferenças entre a melhor prática estimada e a observada (como cada planta está distante da fronteira). A estimação da fronteira nesse modelo é feita pela fronteira estocástica [*Stochastic Frontier Analysis,* (SFA)], e duas formas de melhorias são possíveis: tecnologia [*best-practice*] e mudança na eficiência. O modelo de Boyd (2008) cria um indicador de desempenho energético para comparar plantas industriais nos EUA, no qual é dado o selo *Energy Star* para as plantas mais eficientes.

Para a análise energética setorial, Olanrewaju *et al*. (2013) e Olanrewaju *et al*. (2014) integram métodos de decomposição [*Index Decomposition Analysis- Logaritmic Mean Divisia índex*, IDA-LMDI], análise de neurônios artificiais (ANN) e análise envoltória de dados (DEA). A ideia do modelo é usar o DEA para comparar o consumo de energia esperado (vindo dos efeitos da decomposição estimado pela ANN) com o consumo observado. O trabalho realizado por Azadeh *et al*. (2007) apresenta uma abordagem baseado no DEA, análise de componentes principais [*principal component analysis*, PCA] e taxonomia numérica [*numerical taxonomy*, (NT)] para avaliação da eficiência energética total. A aplicação é feita no Irã e em mais alguns países da Organização para a Cooperação e Desenvolvimento Econômico (OECD) utilizando dados agregados. Kissock e Eger (2008) apresentam um método para a medição da poupança de energia baseado na regressão, usando variáveis de temperatura, produção e uso de energia.

Figura 10 - Categoria do desempenho quantitativo



Fonte: Perroni *et al*. 2016b - Apêndices H e I.

Diversos trabalhos da RSL empregam o DEA para análise da eficiência energética. Onut e Soner (2007) fazem a estimativa da eficiência de empresas médias na Turquia (50-250 funcionários), utilizando o DEA. A principal dificuldade encontrada foi no levantamento dos dados (eletricidade, gás, óleo e LPG e vendas anuais), feito por meio de um questionário. Mukherjee (2008a) e Mukherjee (2008b) utilizam o DEA para medir a eficiência energética das manufaturas dos EUA e da Índia ao longo dos seus estados. A fronteira intertemporal também foi analisada. O trabalho de Shi *et al*. (2010) e Wu *et al*. (2012) utilizam o DEA com saídas [*output*] indesejadas (emissões de C02) para regiões da China. Por último, Wang e Wei (2014) aplicam o DEA para avaliar a poupança de energia, bem como a eficiência das emissões do setor industrial das 30 maiores cidades chinesas.

A abordagem de decomposição IDA-LMDI citada, anteriormente, foi utilizada por Martínez (2009) para avaliar os efeitos: conteúdo, estrutura e intensidade comparando a Alemanha com a Colômbia. Na comparação do conteúdo energético das exportações de 30 países industrializados e em desenvolvimento, Amador (2012) utiliza tanto as matrizes insumo-produto [*Economic Input Output* (EIO)] quanto à abordagem IDA.

Nos trabalhos de Phylipsen *et al*. (1997), Phylipsen *et al*. (2002) e Martinez (2010) o objetivo foi ainda mais amplo, o qual é comparar a eficiência energética entre os países. Phylipsen *et al*. (2002) apresentam uma metodologia que elimina o problema estrutural (mix de atividades e produtos dentro de um setor) entre países para a comparação de indicadores de eficiência energética.

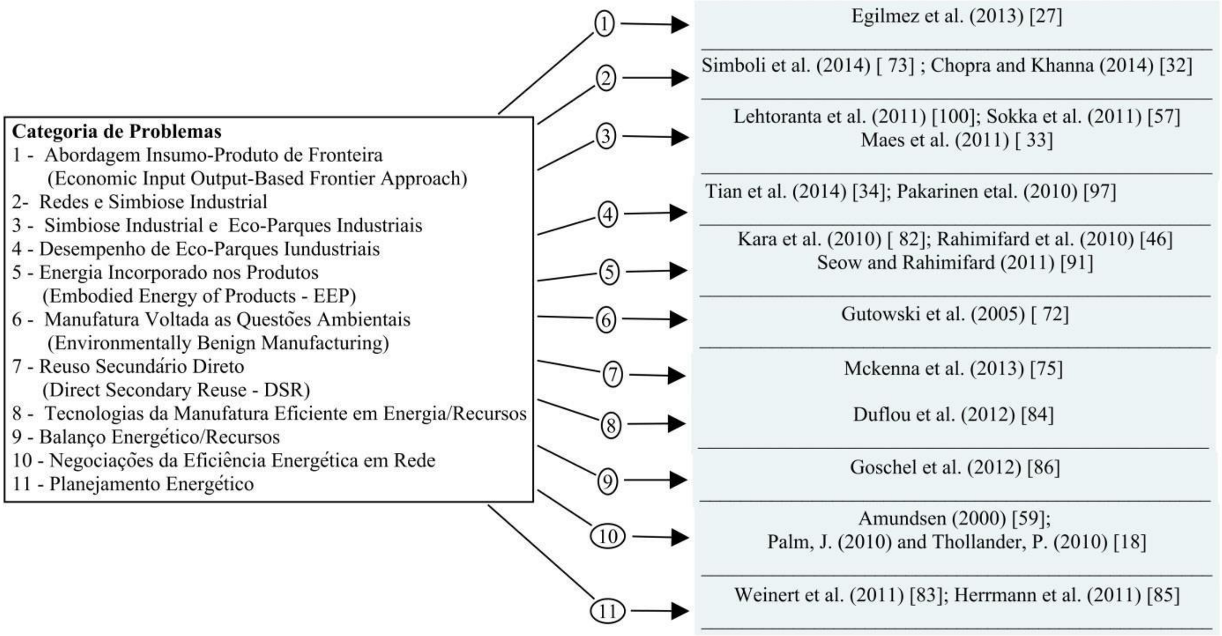
A revisão de Bunse *et al*. (2011) investiga o desempenho energético na gestão da produção, constatando que a existência de indicadores de eficiência energética está limitada ao nível nacional e setorial. O setor industrial necessita de métricas de eficiência energética padronizadas no nível das máquinas, processos e plantas (parte de baixo da pirâmide de indicadores da eficiência energética na Figura 5). Faltam também sistemas para *benchmarking*, tecnologias de medições contínuas do processo, *frameworks* conceituais, mecanismos de visualização computacional para os indicadores.

3.3.3 Sustentabilidade envolvendo rede de firmas

A justificativa de grande parte dos artigos que estudam eficiência energética, tendo a gestão de energia como foco, está relacionada direta ou indiretamente aos três pilares da sustentabilidade (econômica, ambiental, social). O que qualifica a categoria sustentabilidade envolvendo rede de firmas, [*Sustainable Inter-Firm Relations*], no qual os principais autores e temas de pesquisa podem ser observados na Figura 11, é o entendimento de que o problema da eficiência ou gestão de energia, não é um problema individual de uma empresa, e que o desempenho energético pode ser maior em um processo colaborativo sustentável, envolvendo vários participantes com interesses similares como a redução do consumo de energia, emissões, aumento da eficiência, entre outros (AMUNDSEN, 2000). A conclusão de Gutowski *et al*. (2005) foi a de que grandes empresas mundiais como Sony, Toyota, Hitachi, Volvo, Daimler, Chrsler, IBM, Motorola, Ford e Dupond estão se preocupando realmente com a questão ambiental, na qual a conservação de energia, emissões, eliminação de resíduos, uso da água estão entre as preocupações centrais. As perguntas que ressaltam são: quais tipos de conceitos e técnicas têm sido utilizados para o estudo da eficiência energética por essa categoria de pesquisa? Em quais casos essas técnicas têm obtido sucesso?

Os conceitos apresentados remetem ao relacionamento de mais de uma empresa, seja em cadeia, ou grupo de empresas trabalhando em sintonia. A ideia geral é que a complexidade aumenta, uma vez que cada participante dessa categoria tem os mesmos problemas identificados nas categorias anteriores. O levantamento de Duflou *et al*. (2012) identificou as tecnologias e metodologias para redução do impacto ambiental em quatro níveis: (i) processo unitário/máquinas (redesenho de máquinas, controle seletivo, otimização), multimáquinas (reuso de energia, controle de pico), (ii) nível da fábrica (sistema de simulação para prever o fluxo de energia, layout, normas construtivas, instalações), (iii) multifábrica (co-localização/ Simbiose industrial, [*Industrial Symbiosis,* (IS)], uso de análise insumo-produto, [*economic* *input output* (EIO)]), (iv) cadeia de suprimentos (geração de energia regional, localização, condições climáticas, uso de análise de ciclo de vida [*Life Cycle Analysis* (LCA)]).

Figura 11 - Categoria da sustentabilidade envolvendo rede de firmas



Fonte: Perroni *et al*. 2016b - Apêndices H e I.

O primeiro conceito que surge é o da simbiose industrial. Sendo um conceito da Ecologia Industrial, utiliza-se de uma abordagem sistêmica para estudar os fluxos físicos de materiais e energia de um sistema industrial local. Outro conceito similar é o de parques eco-industriais [*Eco-Industrial Parques* (EIP)], em que possui as mesmas proposições, mas com conceito mais amplo, podendo envolver prestadores de serviços (LEHTORANTA *et al*., 2011, TIAN *et al*., 2014).

Duas técnicas usadas e reconhecidas por vários autores para analisar os dados de energia são: a análise de ciclo de vida [*Life Cycle Analysis (*LCA*)*] e o modelo insumo-produto [*Economic Input-Output* (EIO)] ou análise insumo-produto [*Input-Output Analysis*, IOA]. A LCA, segundo a ISO 14040, é uma compilação e avaliação dos inputs/outputs e do impacto ambiental potencial do sistema produtivo no seu ciclo de vida. A IOA é uma abordagem matricial desenvolvida por Leontief (1936, 1966) para o planejamento econômico.

Na literatura, alguns trabalhos trataram especificamente da simbiose industrial (IS) e dos parques eco-industriais (EIP) em conjunto. Na análise de uma indústria de motocicletas na Itália, envolvendo uma grande empresa, e outras 18 de pequeno e médio porte, Simboli *et al*. (2014) mostraram que sem o desenvolvimento da simbiose industrial (IS), ineficiências em resíduos, máquinas obsoletas e gestão dos *scraps* estariam presentes. Um dos exemplos mais citados de EIP é o Kalundborg na Dinamarca, que opera como um sistema IS. Utilizando uma abordagem de redes sociais, procurando investigar a resiliência: capacidade de um sistema de absorver rupturas enquanto mantém sua estrutura e funcionalidade, Chopra e Khanna (2014) constataram que o Kalundborg tem aumentado sua resiliência ao longo do tempo. Outro EIP é o Kymenlaakso na Finlândia estudado por Pakarinen *et al*. (2010) e Sokka *et al*. (2011). Pakarinen *et al*. (2010) desenvolveram uma análise histórica no período entre 1890-2005, constatando uma crescente sustentabilidade por meio do aumento do consumo de recursos renováveis, reciclagem e utilização de resíduos. O estudo de Sokka *et al*. (2011), utilizando a LCA, analisa o uso de combustíveis e energia constatando que o parque o Kymenlaakso não é neutro em carbono, uma vez que a maioria das emissões vem de fora do sistema. Na Bélgica, Maes *et al*. (2011) analisaram um EIP experimental formado por 92 empresas de pequeno e médio porte, o qual tem um sistema de compartilhamento da produção de energia. Na China, Tian *et al*. (2014) estudaram o desempenho de 17 EIPs nos períodos de (2005-2009/2007-2011). Constataram que tanto o desempenho econômico quanto o ambiental apresentaram melhoras e todos os parques prosperaram em relação ao consumo de recursos e intensidade energética, contudo, existe a possibilidade de melhorias no uso da água e resíduos (sólido-líquidos). Embora a intensidade energética tenha melhorado, a quantidade total do uso de energia aumentou de 13.62 milhões de tces [*tons of coal equivalente*] para 16.39 milhões.

Outro conceito estudado, envolvendo mais de uma empresa, é o da energia incorporada de produtos/serviços [*Embodied Energy of Products,* (EEP)]. Um modelo, para avaliar o impacto da manufatura global, na energia incorporada no ciclo de vida do produto, é apresentado por Kara *et al*. (2010). A análise insumo-produto (IOA) foi utilizada para modelar a energia incorporada para cada cadeia de suprimentos da manufatura. Os fatores que afetam a energia incorporada são: peso da matéria prima; energia usada para extrair e processar a matéria prima, distância do local da extração para a manufatura, meio de transporte utilizado. Os trabalho de Rahimifard *et al*. (2010) e Seow e Rahimifard (2011) desenvolvem uma abordagem representando o total de energia requerido para manufaturar uma unidade do produto. Utiliza-se de simulações para tomar decisões sobre o consumo de energia no ciclo de vida do produto. A diferenciação que esses autores fazem é em relação à energia direta (energia usada pelos vários processos para manufaturar um produto) e energia indireta (energia consumida pelas atividades para manter o ambiente de produção em funcionamento como sistemas de ventilação, iluminação, entre outras). Os autores reconhecem que a abordagem realmente não mostra quanta energia é requerida para manufaturar uma unidade do produto, mas ajuda na análise identificando os fatores para minimização do uso de energia.

Outro conceito utilizado é o de reuso secundário direto [*Direct Secondary Reuse* (DSR)]. McKenna *et al*. (2013) definem a DSR como o reuso do produto no final do seu ciclo de vida sem destruir a estrutura básica do produto. Os autores concluem que na indústria automobilística da Alemanha, com a prática DSR, a economia de energia seria de aproximadamente 3% a 6%.

Baseado em um sistema de detecção sistemático do fluxo de materiais e energia, um método matemático foi desenvolvido por Goschel *et al*. (2012) para o balanço de energia e recursos. Weinert *et al*. (2011) apresentam um esquema de planejamento energético para o ciclo de vida da planta, dos equipamentos e da cadeia de valor. Herrmann *et al*. (2011) desenvolvem um modelo de simulação para o sistema da manufatura que inclui o fluxo de energia e seus subsistemas. Com uma abordagem setorial, Egilmez *et al*. (2013) fazem uma combinação entre a abordagem EIO-LCA e o DEA para analisar o desempenho sustentável do setor manufatureiro americano, criando um indicador de ecoeficiência.

Uma visão sociotécnica contextual é oferecida por Palm e Thollander (2010), na qual a eficiência energética não depende apenas de questões tecnológicas ou práticas específicas, mas também de discussões, negociações e acordos desenvolvidos em rede.

3.4 DISCUSSÃO DA REVISÃO SISTEMÁTICA DA LITERATURA

Conforme Tranfield (2003), o objetivo de uma Revisão Sistemática é apresentar respostas às várias perguntas definidas *ex-ante* que servirão de guia para futuras pesquisas: quem são os autores mais citados? Os autores são de quais institutos de pesquisa e departamentos? Quais são os principais temas e palavras-chaves identificados? Quais métodos e técnicas são utilizados pelos trabalhos? A seção 3.2 apresentou as respostas por meio de análise gráfica, e a seção 3.3 mostra as principais contribuições e os resultados de cada grupo categórico.

O primeiro ponto a ser discutido é: a eficiência energética industrial realmente representa um campo de pesquisa? A Rede 4 tem estatística de densidade de 34%, isso significa que as conexões representam um terço do máximo possível entre os 100 autores mais citados. Dúvidas poderiam surgir quanto à eficiência energética industrial ser um campo de pesquisa se a densidade da rede fosse próxima de zero.

Algumas constatações em relação à revisão sistemática podem ser destacadas, considerando o Apêndice I (Artigo 4): (i) multiplicidade de abordagens de pesquisa e técnicas; (ii) número de instituições que os autores e coautores declaram pertencer é maior do que o número de artigos do *corpus*, 107 contra 104, (iii) os autores pertencem a 83 departamentos diferentes, sendo os mais centrais vindos das Engenharias, Gestão e Sustentabilidade. Pode-se concluir que, embora a existência de algumas áreas centrais como: Engenharia Mecânica e Gestão, o campo eficiência energética industrial é por natureza multidisciplinar.

A seção 3.3 apresentou as contribuições e resultados dos 104 artigos identificados da RSL. Uma série de questões *ex-post*, representativas, foram idealizadas para orientar na apresentação da revisão sistemática. O propósito da elaboração do Quadro 2 foi identificar questões que são analisadas pelos grupos das Figuras 9, 10 e 11 que podem auxiliar na resolução do problema da pesquisa.

A categoria eficiência e gestão energética foi agrupada em cinco subcategorias como pode ser visto na Figura 9. O Quadro 3 sintetiza as respostas das questões colocadas para representar essa categoria. Na análise destas subcategorias pode ser destacado que os principais motivos para o estudo da eficiência energética são os fatores ambientais (Figura 8). Devido ao chamado "*energy efficiency gap*" de Jaffe e Stavins (1994) e o "*energy paradox*" de DeCanio (1998), uma série de estudos empíricos levantaram os principais determinantes e limitantes da eficiência energética. Em resumo, os principais determinantes identificados nos estudos empíricos são: *payback*, custo, preço da energia, subsídios e o suporte de altos gestores ou gestores de operações (ANDERSON; NEWELL, 2004; ABADIE *et al*. 2012; SUK *et al*. 2013). O relacionamento entre os fatores ambientais e o desempenho energético geralmente são positivos, embora o relacionamento entre eficiência energética e desempenho econômico pode ser negativo (PONS *et al*. 2013; ZHANG; WANG 2014). Essa última informação pode ser confirmada no trabalho de Eccles e Serafeim (2013) que, embora não pertença ao escopo da RSL, constataram divergências entre o desempenho econômico e a sustentabilidade.

Os autores dos vários artigos que estudaram as limitações da eficiência energética, por meio das barreias, chegaram a semelhantes conclusões, identificando como principais barreiras: custo e risco da parada de produção, falta de tempo, outras prioridades, custo da obtenção da informação do consumo de energia dos equipamentos comprados, outras prioridades para o investimento de capital, falta de sub medidores, divisão de incentivos com ESCOs (ROHDIN; THOLLANDER, 2006, ROHDIN *et al*., 2007; TRIANNI; CAGNO, 2012). Três fatores bastante enfatizados são: a falta de interesse em eficiência energética, o risco e a necessidade de apoio da alta gerência (SARDINOU, 2008; ROHDIN et la. 2007; TRIANNI *et al*., 2013a, 2013b).

Alguns determinantes [*drivers*] também são identificados por meio dos estudos de casos, não contradizendo os resultados encontrados por meio de *surveys*: preço da energia, necessidade de pessoal com ambição real, apoio dos atos gestores, subsídios, entre outros (ROHDIN; THOLLANDER 2006; ROHDIN *et al*. 2007; APPEANNING; THOLANDER, 2013).

Com relação às medidas para a eficiência energética [*Energy Efficiency Measures* (EEMs)], o trabalho de Abdelaziz *et al*. (2010) merece destaque. Nele os autores indicam que as EEMs podem ocorrer de três formas distintas: tecnologias, gestão de energia e política energética. As duas primeiras formas estão sob o poder de decisão da empresa, mas a última não.

Com relação à subcategoria gestão de energia, procurou-se estabelecer uma definição para tal. Afinal, diferentes autores possuem diferentes concepções e um conceito associado que em essência não contradiz essa revisão sistemática e pode ser utilizado é: a gestão de energia é por natureza multidisciplinar envolvendo áreas das engenharias e de gestão em contextos específicos, tendo a função de controlar, monitorar e promover melhorias da eficiência energética (LEE *et al*., 2011; BUNSE *et al*., 2011; VIKHOREV *et al*., 2013).

Os autores dos artigos que procuraram investigar a gestão energética empiricamente, mesmo com escopo estreito do que venha a ser gestão energética, assim como a categoria da eficiência energética, encontraram resultados muito abaixo do esperado, com um número baixo de empresas praticantes de gestão de energia. Na pesquisa de Christofersen *et al*. (2006) esse número não passa de 14% (THOLLANDER; OTTOSSON 2010; ATES; DURKBASA 2012).

Na revisão de literatura feita por Bunse *et al*. (2011), os *frameworks* de gestão de energia são escassos. Com relação a essa revisão sistemática da literatura, o resultado apresentado pode ser confirmado, acrescido o fato de que os *frameworks*, que estão sendo propostos, estão baseados no PDCA (KANNAN; BOIE 2003; GORDIC *et al*., 2010). (KANNAN; BOIE 2003; GORDIC *et al*., 2010). Um fator relevante é que em algum momento do PDCA entra o *energy audit*. Este por sua vez é um procedimento reconhecido por diversos autores (KANNA; BOIE 2003; GORDIC *et al*., 2010; BUNSE *et al*., 2010; LEE *et al*., 2011).

Quadro 3 - Questões *ex-post* - grupo da eficiência e gestão de energia

QEP1	• ***Por que estudar eficiência Energética?*** *Escassez dos recursos não renováveis, impactos ambientais, implementações de práticas ótimas versus realizada, barreiras, drivers (Jaffe e Stavins 1994; DeCanio, 1998; Cagno et al. 2013).*
QEP2	• ***Quais os principais determinantes ou limitadores da eficiência energética?*** *Inovação tecnológica, acesso ao capital, preço da energia, custo do projeto, custos ocultos, custo da obtenção da informação, payback, projetos de conservação, apoio governamental, energy audit, housekeeping, monitoramento do fluxo de energia, bechmarking, subsídios, suporte da alta gerência, treinamentos, percepções subjetivas, automotivação, falta de capacitação, risco da parada de produção, falta de sub medidores, divisão de incentivos, intervenção não rentável, continuidade do negócio, estratégia de longo prazo, ambição real (Uri, 1980; Motamen e Mcgee, 1986; Sandberg e Soderstrom, 2003; Anderson e Newell, 2004; Rohdin e Thollander, 2006; Trianni e Cagno, 2012; Therkelsen e Mckane; 2013; Suk et al., 2013; Trianni et al., 2013c).*
QEP3	• ***Quais tipos de medidas podem ser adotados?*** *Gestão de energia, Energy efficiency Technologies/Energy Efficiency Measures (EETs/EEMs) e Política Energética (DOE-IAC, 2007; Abdelaziz et al., 2011; Fleiter et al., 2012).*
QEP4	• ***O que é gestão de energia?*** *Não existe uma definição precisa de gestão de energia. A gestão de energia pode ser integrada facilmente a outros sistemas de gestão. Associada a procedimentos para a poupança de energia. É multidisciplinar com envolvimento das áreas de engenharias e de gestão na qual seu objetivo é maximizar a eficiência energética em prol de melhorias contínuas. É um sistema de melhoria contínua, com a utilização de procedimentos planejados, revisados periodicamente. Está relacionada às atividades de controle, monitoramento e melhoria da eficiência energética. É contexto específico, dependendo de fatores locais como desenho do produto, escolha do processo, matriz energética nacional, entre outros fatores (Amundsen, 2000; Kannan e Boie 2003; Christoffersen et al., 2006; Gordic et al., 2010; Bunse et al., 2011; Lee et al., 2011; Backlund et al., 2012; Ates e Durakbasa 2012; Vikhorev et al., 2013).*
QEP5	• ***Quais tipos de prática de gestão de energias estão sendo investigados?*** *Monitoramento do consumo, critério de payback, energy audit, papel do gestor de energia, estratégia energética, metas quantitativas para a gestão de energia, controle por centros de custo, política energética empresarial, preocupações objetivas com a implementação de projetos de poupança, energy efficient purchase, alocação de responsabilidades, treinamento de funcionários. (Fawkes e Jacques 1987;* Christofersen *et al.*, 2006; Ates e Durkbasa, 2012; Thollander e Ottosson, 2010; Rudberg *et al.*, 2013).
	• ***Quais as dificuldades?*** *3% e 14% das empresas industriais praticam gestão energética, além de 76% serem motivadas pelo custo. A gestão de energia não é uma atividade principal. Mesmo para empresas intensivas a gestão de energia não é pensada em um nível estratégico. Falta uma política energética formal. (Christofersen et al., 2006; Thollander e Ottosson 2010; Ate e Durkbasa, 2012; Rudberg et al., 2013)*
QEP6	• ***Quais tipos de frameworks têm sido propostos para a gestão de energia?*** *Os frameworks existentes são escassos. Sistema contábil para revelar os custos e as vantagens da poupança. Frameworks baseados em técnicas analíticas como teoria dos jogos e data mining. Framework de processo para melhoria contínua (Kannan e Boie, 2003; Bunse et al., 2011; Lee et al., 2011; Gordic et al., 2010; Aplak e Sogut, 2013; Velazquez et al., 2013).*
QEP7	• ***Quais tipos de políticas podem ser adotados pelos governos?*** *Prescritiva (regulação da eficiência do equipamento, regulação da configuração e eficiência do processo, regulação por gestão energética, acordos negociados), econômicas (taxas de energia, taxas para a redução direta do consumo de energia, incentivos financeiros diretos, cap and trade esquemas, discriminação do preço da energia), e Suportiva (identificação de oportunidades de eficiência energética, medidas cooperativas, treinamento e capacitação) (Tanaka 2011).*
QEP8	• ***As ações de política energética têm dado o resultado esperado?*** *Na Holanda, entre um quarto e a metade da poupança de energia é atribuída aos acordos de longo prazo. O programa Highland teve uma adoção de 40% na Suécia. Adoção de aproximadamente 50% no programa DOE-IAC. Muitos gaps de política energética podem ser encontrados como nos sistemas de ar comprimido, Combined Heat and Power, energy audit, entre outros (Rietbergen et al., 2002; Neale e Kamp, 2009; Price et al., 2010; Abadie et al., 2012; Brow et al., 2013; Thollander et al., 2013b).*

Fonte: Perroni *et al.* 2016b - Apêndices H e I.

Nota: As questões fazem parte do Quadro 2 e foram respondidas utilizando a discussão do grupo Gestão e Eficiência da Figura 9.

Uma questão pendente é: sendo o *energy audit* reconhecido por muitos autores, estes citados ao longo do trabalho, com a responsabilidade de identificar as EEMs, por que os trabalhos sobre como proceder para executar um *energy audit* estão escassos? Uma hipótese é devido à gestão de energia ser contexto específico e os procedimentos de *energy audit* seriam mais úteis para os casos específicos.

Segundo Abdelaziz *et al.* (2011), embora a política energética não faça parte da decisão de uma empresa isolada, ela é a terceira forma de se poupar energia. Tanaka (2011) está entre os autores mais citados e cocitados da Figura 7 e Rede 4, é um dos principais proponentes da política energética, identificando os facilitadores e formas de incentivos tanto macro, quanto micro políticas direcionadas a um segmento específico. Ações de política energética são divulgadas pelas pesquisas de Rietbergem *et al*. (2002), informando que na Holanda entre um quarto e a metade da poupança de energia é atribuída aos acordos de longo prazo. O programa *Highland* na Suécia teve adoção de 40% para empresas pequenas e médias. Embora alocado para a categoria da eficiência energética, o trabalho de Anderson e Newell (2004) também chegou ao número aproximado de 50% de adoção para o programa DOE-IAC nos Estados Unidos. Os trabalhos de Price *et al.* (2010); Shen *et al.* (2012); Brow *et al.* 2013; Thollander *et al.* (2013b) identificam *gaps* da política energética para China, EUA e Suécia, ou seja, constatam que a política energética pode e muito ser aprimorada.

Na categoria do desempenho quantitativo, procurou-se esclarecer o conceito de eficiência energética, desempenho energético, intensidade energética e consumo de energia específica. As questões *ex-post* para essa categoria podem ser visualizadas no Quadro 4. Os indicadores de eficiência energética, levantados pelos artigos (PATTERSON 1996; PHYLIPSEN *et al*. 1997; IEA, 2014a), são vistos pela literatura de eficiência empresarial como [*Key performance Indicators* (KPI)] (BOGETOFT; OTTO, 2010).

Alguns trabalhos da categoria do desempenho energético procuram desenvolver modelos mais sofisticados para a medição do desempenho energético que vão além da medição de KPI. Duas técnicas sofisticadas utilizadas pela literatura são: a análise de fronteira estocástica [*Stochastic Frontier Analysis* (SFA)] (Boyd 2008) e a análise envoltória de dados (DEA). Vale ressaltar que a análise envoltória de dados [*Data Envelopment Analysis* (DEA)] é utilizada e integrada juntamente com outras técnicas em vários trabalhos (ONUT; SONER 2007; AZADEH *et al*. 2007; MUKHERJEE 2008a; SHI *et al.* 2010; WU *et al*. 2012; OLANREWAJU *et al*. 2013; WANG; WEI 2014). O Gráfico 6 e a Rede 3 revelam que a preferência pelo DEA para medir a eficiência ou desempenho energético não é por acaso, uma vez que a palavra DEA aparece entre as mais importantes, e um dos de seus proponentes, Charnes, *et al*. (1978) aparece entre os autores mais citados e cocitados da Figura 7 e Rede 4.

Quadro 4 - Questões *ex-post* - grupo desempenho quantitativo

QEP9	• ***O que é eficiência energética?*** *Não existe uma forma quantitativa de medir a eficiência energética sem incorrer em algum tipo de suposição. Uma maior eficiência energética está associada ao menor uso de energia para produzir a mesma quantidade do bem ou serviço, podendo ser medida pela razão (useful output of process/energy input into a process) (Patterson, 1996; Phylipsen et al., 1997; OECD/IEA, 2014a).*
QEP10	• ***O que é desempenho energético?*** *No desempenho energético, o indicador de eficiência energética não é a única variável a ser controlada, pode ser necessário medir o desempenho dos chamados uso dos recursos associados como: água, utilização de materiais intensivos em energia, emissões de poluentes, além de muitos outros (Vikhorev et al., 2013).*
QEP11	• ***Como o desempenho energético está sendo medido?*** *Energy Intensity (EI), Specific Energy Consumption (SEC), Stochastic Frontier Analysis (SFA), Data Envelopment Analysis (DEA). Logaritmic Mean Divisia Index (LMDI). Técnicas mais aplicadas em nível nacional ou setorial. (Phylipsen et al., 1997; Azadeh et al., 2007; Boyd et al., 2008; Ang, 2012; IEA, 2014a)*

Fonte: Perroni *et al*. 2016b - Apêndices H e I.
Nota: As questões fazem parte do Quadro 2 e foram respondidas utilizando a discussão do grupo do Desempenho Quantitativo da Figura 10.

Outro fator a ser considerado na medição do desempenho energético é o desenvolvimento de índices de decomposição [*Index Decomposition Analysis* (IDA)] como o algoritmo [*Logarithmic Mean Divisia Index* (LMDI)] desenvolvido por Ang, (2012) que tem citações e cocitações expressivas na Figura 7 e Rede 4. O LMDI foi desenvolvido para separar os efeitos: estrutura, conteúdo e atividade. Logo é aplicado em um nível setorial ou multissetorial, semelhante à técnica apresentada em Phylipsen *et al*. (2002) para comparar a eficiência energética entre países.

Em síntese, na categoria de desempenho energético, quase todos os trabalhos aplicam ou desenvolvem técnicas para utilizar dados agregados em níveis setoriais ou nacionais. Apenas os trabalhos de Onut e Soner (2007) e Boyd (2008) aplicam a análise de desempenho energético de forma desagregada, mesmo assim, uma das principais limitações identificadas por Onut e Soner (2007) foi na coleta de dados, tendo que elaborar um questionário para tal.

Uma questão fundamental é que a energia não é utilizada isoladamente por uma fábrica ou planta. Alguns trabalhos foram categorizados como pertencentes à Sustentabilidade Envolvendo Rede de Firmas [*Sustainable Inter-Firm Relations*], apresentado na Figura 11, em que as questões *ex-post* podem ser vistas no Quadro 5. O que diferencia essa categoria é o desenvolvimento ou utilização de conceitos e técnicas envolvendo mais de uma empresa. A ideia subjacente nesse grupo categórico é que os interesses comuns, manifestados nas interrelações das partes, são capazes de produzir uma sinergia com melhor benefício ou desempenho do que em condição de individualidade.

Quadro 5 - Questões *ex-post* - sustentabilidade envolvendo rede de firmas

QEP12	• ***Quais tipos de conceitos e técnicas têm sido utilizados para o estudo da eficiência energética quando mais de um ator (inter-relação entre empresas) está envolvido?*** *Industrial Symbiosis (IS), Life Cycle Analysis(LCA), Eco-Industrial Parques (EIP), Input-Output Analysis (IOA) Embodied Energy of Products (EEP); Direct Secondary Reuse (DSR) (Lehtoranta et al., 2011;* Kara *et al*., 2010; Sokka *et al*., 2011; *Duflou et al., 2012; McKenna et al., 2013).*
QEP13	• ***O relacionamento entre empresas tem obtido sucesso na eficiência de energia?*** *Sem o desenvolvimento da Industrial Symbiosis, ineficiências em resíduos, máquinas obsoletas e gestão dos scraps estariam presentes. Aumento da resiliência ao longo do tempo, crescente sustentabilidade por meio do aumento do consumo de recursos renováveis, reciclagem e utilização de resíduos. Melhora do desempenho econômico e ambiental (Pakarinen et al., 2010; McKenna et al., 2013; Simboli et al., 2014; Chopra e Khanna, 2014; Tian et al., 2014).*

Fonte: Perroni *et al*. 2016b - Apêndices H e I.
Nota: As questões fazem parte do Quadro 2 e foram respondidas utilizando a discussão do grupo Sustentabilidade Envolvendo Rede de Firmas da Figura 11.

As principais concepções envolvendo um conjunto de participantes, quando se trata de energia, são: da Simbiose Industrial e EIPs (PAKARINEN *et al*., 2010; SOKKA *et al*., 2011; TIAN *et al*., 2014), a energia incorporados de produtos [*Embodied Energy of Products* (EEP)] (KARA *et al*., 2010 RAHIMIFARD *et al*., 2010; SEOW; RAHIMIFARD 2011) e o reuso de materiais [*Direct Secondary Reuse* (DSR)] (McKENNA *et al*., 2013). Os resultados dos trabalhos que analisam as IS e os EIP confirmam a poupança de energia, além de outros recursos, mas com potenciais a serem desenvolvidos. Outra questão levantada é que os estudos principalmente de energia relacionados aos [*Eco-Industrial Parks* (EIPs)] parecem se limitar a poucos casos como: o Kakundborg e Kymenlaakso, com exceção, talvez, aos casos da China identificados por Tian *et al*. (2014). O conceito [*Direct Secondary Reuse* (DSR)] foi considerado viável, uma vez que foi constatada a possibilidade de redução do consumo de energia de até 6% na Alemanha (MCKENNA *et al*., 2013).

Basicamente, duas técnicas podem ser destacadas como as principais para a análise do desempenho energético integrado nessa categoria: a análise insumo-produto [*Input-Output Analysis* (IOA)] (WEINERT *et al*., 2011; DUFLOU *et al*., 2012; KARA *et al*., 2010) e a do ciclo de vida [*Life Cycle Analysis* (LCA)] (SOKKA *et al*., 2011; DUFLOU *et al*., 2012), as quais podem ser utilizadas em conjunto.

4 REPRESENTAÇÃO DA MEDIÇÃO E CONTROLE DO DESEMPENHO ENERGÉTICO

A representação do desempenho energético, desenvolvida pela presente tese, utiliza as contribuições dos três grupos identificados na revisão sistemática da literatura, apresentados no capítulo 3 e nos Apêndices H e I (PERRONI *et al.*, 2015b; PERRONI *et al.*, 2016b). A estrutura na qual o desempenho energético ocorre, na sua forma integrada, é estudada pelo grupo Sustentabilidade Envolvendo Rede de Firmas. A dinâmica dos determinantes do desempenho energético é estudada pelo grupo de Gestão e Eficiência. E, por sua vez, as formas de se medir quantitativamente o desempenho energético é estudado pelo grupo do Desempenho Quantitativo.

Com base nas discussões metodológicas da Figura 2 e mapa da tese da Figura 3, o objetivo deste capítulo é fazer a representação do desempenho energético, do ponto de vista da gestão de energia. Essa representação tem origem em quatro artigos do projeto de pesquisa expostos nos Apêndices J ao M (PERRONI *et al.*, 2014; PERRONI *et al.*, 2016c; PERRONI *et al.*, 2016d; PERRONI *et al.*, 2017). A seção 4.1 apresenta o *framework* de processos para a medição do desempenho energético integrado. A seção 4.2 desenvolve um mapa dos indicadores de eficiência energética de processos. A seção 4.3 adapta um modelo insumo-produto de processos longitudinal para a medição contínua do desempenho energético.

4.1 *FRAMEWORK* DE PROCESSOS PARA A MEDIÇÃO DO DESEMPENHO ENERGÉTICO INTEGRADO

No contexto desta tese, a palavra processo refere-se a processos de produção, sendo este o mecanismo responsável pela transformação dos insumos [*input*] em produtos/serviços [*output*] (ALBINO *et al.*, 2003; SLACK *et al.*, 2007; KUHTZ *et al.*, 2010). Conforme o primeiro capítulo, um processo pode ser definido como "*uma abordagem para atingir os objetivos gerenciais por meio da transformação de insumos em produtos*" (SHEHABUDDEN, *et al.*, 1999, p. 14). A definição nesse formato torna mais fácil a hierarquização do sistema produtivo, afinal uma máquina que transforma matéria prima (insumo) em algum tipo de produto (recurso intermediário) está dentro do escopo da definição. Considerando uma empresa ou uma cadeia, como um conjunto de processos responsáveis pela transformação de insumos em produtos/serviços, o processo de produção pode ser composto em diferentes níveis de agregação. O conjunto de processos pode formar uma rede, com produtos intermediários e produtos finais (SLACK *et al*. 2007; KUHTZ *et al*., 2010).

Vale ressaltar que, diferentemente, de outros recursos, a energia é utilizada em praticamente todos os processos de produção. Desta forma, o desempenho energético pode ser avaliado dentro desses processos (PATTERSON, 1996).

A revisão sistemática da literatura identificou três grupos categóricos na área de Eficiência Energética Industrial: gestão/eficiência, desempenho quantitativo e sustentabilidade envolvendo rede de firmas. A indagação fundamental está relacionada a como integrar a discussão desses grupos em uma abordagem de processos, identificando a contribuição de cada um ao desempenho energético. O grupo da gestão/eficiência oferece o conteúdo da identificação de fatores facilitadores ou inibidores do desempenho energético tanto no ambiente interno, quanto externo da empresa. O grupo do desempenho indica maneiras diferentes de se criar indicadores para o desempenho energético capaz de revelar a efetividade do sistema de gestão energética. O grupo da sustentabilidade envolvendo rede de firmas, fornece evidências da estrutura mais completa em que o desempenho energético ocorre.

O intuito dessa seção é propor um *framework* de processos para a medição do desempenho energético integrado. O *framework* é montado em dois blocos, sendo o primeiro, conforme Figura 12(A), destinado a representar a dinâmica do desempenho energético e, o segundo 12(B) representa a estrutura do desempenho energético. Conforme discussões metodológicas da Figura 2, o *framework* tem nível conceitual mais elevado suportando o entendimento, a comunicação da estrutura e o relacionamento de forma que fique mais clara a evolução na Figura 12(A), e a estrutura do desempenho energético na Figura 12(B) (SHEHABUDDEN, *et al*., 1999, p. 9).

A Figura 12(A) apresenta um *framework* estrutural adaptado de Bititci *et al*. (2000) que tem a função de auxiliar na representação da dinâmica do desempenho energético industrial, uma vez que o modelo de Bititci *et al*. (2000) descreve o que um sistema de medição do desempenho deve ter, sendo um *framework* normativo (PERRONI *et al*., 2014).

Segundo Bititci *et al*. (2000), um sistema de medição de desempenho é composto por quatro sistemas auxiliares: monitoramento externo, monitoramento interno, revisão e implementação. Estes sistemas interagem em um loop contínuo de melhoria [*Plan-Do-Study-Act* (PDCS)] gerando *feedback* entre a base operacional (monitoramento/controle) e o nível estratégico (objetivos principais por meio do planejamento). Esse sistema não é isolado para um processo específico, uma vez que quando se agregam vários processos (rede de processos), os mesmo mecanismos podem estar em operação.

A integração feita por Bititci *et al.* (2000) é similar à lógica da pirâmide da eficiência energética da Figura 5 no capítulo 2. Adaptada para o desempenho energético a hierarquia pode ser integrada utilizando uma rede de processos na Empresa Estendida, conforme Figuras 12(A) e 12(B). Um exemplo de rede de processos intersetoriais é o modelo insumo-produto de Leontief (1936), apresentado na Rede 1.

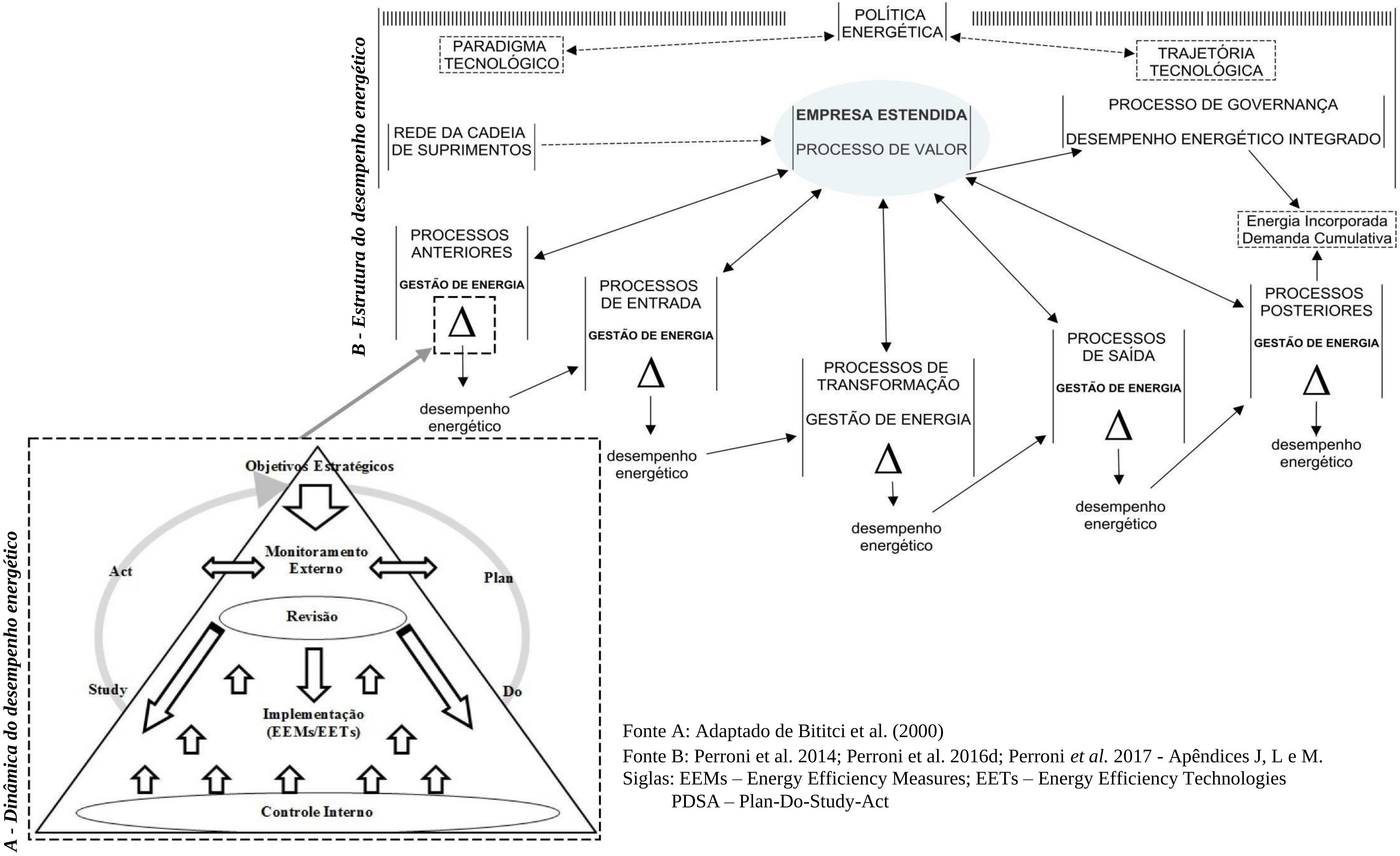
Basicamente, entende-se que o desempenho energético está relacionado à medição da eficiência energética, sendo que ela está relacionada de certa forma ao menor uso de energia por unidade de produção. Vale ressaltar que, independentemente, de qualquer tipo de medição ou controle, dado nível de desempenho energético existe e ocorre em um ambiente complexo, envolvendo a interação de múltiplos participantes (PALM; THOLLANDER, 2010).

Tomando como base a discussão do grupo eficiência e gestão energética industrial diversos trabalhos estudaram a importância dos quatro sistemas levantados por Bititci *et al.* (2000), reconhecendo a importância do apoio dos altos gestores ou nível estratégico, sistema de revisão [*energy audit* ou *energy survey*] com a responsabilidade de identificar as tecnologias [*Energy Efficiency Technologies* (EETs)] e as medidas [*Energy Efficiency Measures* (EEMs)] com o objetivo da implementação, além do reconhecimento do monitoramento e controle (FAWKES; JACQUES 1987; KANNAN; BOIE 2003; SANDBERG; SODERSTROM, 2003; GORDIC *et al.*, 2010; THOLLANDER; OTTOSSON 2010; ABDELAZIZ *et al.*, 2011; ATES; DURKBASA, 2012; SUK *et al.*, 2013; RUDBERG *et al.*, 2013; BLASS *et al.*, 2014). Vários trabalhos do grupo gestão e eficiência energética da revisão sistemática da literatura reconhecem implícita ou explicitamente, que é possível identificar tanto medidas, quanto tecnologias para poupança de energia. Segundo Caffal (1995), as indústrias que adotarem práticas de gestão de energia podem poupar até 40% do consumo total. A pesquisa de Morrow *et al.* (2014) analisaram 22 medidas de eficiência energética para a indústria indiana de cimento e 25 medidas para a indústria de aço, entre os períodos de 2010-2030. Após aplicação das medidas, a estimativa seria obter uma poupança de energia de 83.000 GWh em energia elétrica e 285.833 GWh em combustíveis. A título de comparação, baseado em Perroni *et al.* (2015a), a economia de eletricidade no programa PROCEL, tomando como base o ano de 2013, foi de 9 GWh. Therkelsen *et al.* (2014) identificaram 23 medidas para o setor de panificação com possibilidade de poupança variando entre 1% e 75%. O trabalho de Alkaya e Demirer (2014) identifica 5 medidas gerais para uma fábrica têxtil na Turquia, sendo possível obter uma redução de 20% do consumo de gás natural. Gordic *et al*. (2010), no período 2005-2008, aplicando 10 medidas em uma manufatura automotiva, obtiveram uma redução de 25% no consumo de energia. Grande parte das informações organizadas de forma sistemática vem de um projeto nos Estados Unidos realizado pelo DOE-IAC [*Department of Energy - Industrial Assessment Centers*]. As informações de auditorias de energia do programa DOE-IAC contêm 17.566 casos com mais de 130.000 recomendações desde 1981. Empresas de todos os setores manufatureiros da subdivisão SIC [*Standard Industrial Classification*] já participaram desse projeto, que oferece consultoria em identificação de medidas para a eficiência energética por meio de uma avaliação - [*energy survey*] ou [*energy audit*] - às pequenas e médias manufaturas dos Estados Unidos (DOE-IAC-2011; PERRONI *et al*., 2016c). As medidas e tecnologias, voltadas à eficiência energética, identificadas pelo programa DOE-IAC (2011), são recomendações do ponto de vista técnico-econômicas, mas as manufaturas têm a liberdade de implementá-las ou não. Em relação à revisão sistemática da literatura alguns trabalhos (TONN; MARTIN, 2000; ANDERSON; NEWELL; 2004; ABADIE *et al*., 2012; THERKELSEN; MCKANE 2013; BLASS *et al*., 2014) utilizaram as informações para verificar principalmente como variáveis: custo, preço, tamanho das empresas, entre outras, influenciam na taxa de adoção das medidas (PERRONI *et al*., 2016c).

Com base na discussão proposta, duas questões podem ser levantadas: como organizar o ambiente complexo do desempenho energético? Quais fatores afetam o desempenho energético dos processos? Na revisão sistemática da literatura, Abdelaziz *et al*. (2011) identificaram que a poupança de energia pode ocorrer por meio de três formas: na gestão de energia (análise dos dados históricos, auditorias energéticas, análises de engenharia, informação/treinamento), por meio das tecnologias eficientes [EETs] (controladores de velocidade [*variable speed drive*], recuperação de calor, motores mais eficientes, prevenção de vazamentos em compressores de ar) e na política energética (regulações, política fiscal, acordos e metas). Por sua vez, Cagno *et al*. (2013) desenvolveram um modelo dos fatores limitantes para a eficiência energética industrial tendo origem no ambiente interno e externo.

O trabalho de Abdelaziz *et al*. (2011) mostra que o desempenho energético pode ser melhorado por meio da gestão, tecnologia, e política energética. Inversamente, Cagno *et al*. (2013) levantaram os condicionantes tanto internos quanto externos que limitam o desempenho energético. Os fatores internos e externos que limitam o desempenho energético podem ser classificados de acordo com as formas de poupança de energia (PERRONI *et al*., 2016b).

Figura 12 - *Framework* de processos para a medição do desempenho energético integrado



Fonte A: Adaptado de Bititci et al. (2000)

Fonte B: Perroni et al. 2014; Perroni et al. 2016d; Perroni *et al.* 2017 - Apêndices J, L e M.

Siglas: EEMs – Energy Efficiency Measures; EETs – Energy Efficiency Technologies
PDSA – Plan-Do-Study-Act

Em cada processo o responsável pelos objetivos estratégicos tem que lidar com os condicionantes internos (disponibilidade de capital, custos não percebíveis, risco relacionado à intervenção, falta de interesse, outras prioridades, inércia, critério de avaliação imperfeita, falta de partilha dos objetivos, baixo status da eficiência energética, interesse divergente, cadeia de decisão complexa, falta de tempo, falta de controle interno, identificação de ineficiências, implementação da intervenção e falta de consciência) (CAGNO *et al*., 2013).

Os condicionantes mencionados, anteriormente, podem ser interpretados como condicionantes internos à gestão do desempenho energético. Os limitadores externos ao desempenho energético podem ser classificados em relação às tecnologias eficientes (EETs), gestão de energia e política energética: (i) EETs (baixa difusão de tecnologias, falta de interesse em eficiência energética pelos fornecedores de tecnologias, tecnologias desatualizadas, características técnicas não adequadas, falha na comunicação e custo inicial alto); (ii) Gestão de Energia (baixa difusão de informações, dificuldade de obter mão de obra qualificada, custo para o investimento de capital indisponível e dificuldades de identificar a qualidade do investimento); (iii) Política Energética (distorção do preço da energia, risco de mercado, distorção da política fiscal, falta de regulação apropriada, distorção da política energética, falha de comunicação, falta de interesse em eficiência energética por parte das empresas de energia) (ABDELAZIZ *et al*., 2011; CAGNO *et al*., 2013).

A complexidade destacada torna difícil reproduzir soluções específicas para casos mais gerais (VIKHOREV *et al*., 2013), uma vez que tanto as formas de melhorias (gestão, tecnologia e política) quanto as limitações (internas e externas) podem ser diferentes entre os processos, requerendo abordagens de melhoria contínua *plan-do-chek-act* (PDCA) (KANNAN; BOIE, 2003; GORDIC *et al*., 2010), como a *plan-do-study-act* (PDSA) da Figura 12(A) (BITITCI *et al*., 2000).

O grupo da literatura sustentabilidade envolvendo rede de firmas, assume que o desempenho energético pode ser ampliado se vários participantes (processos) operarem de forma colaborativa. A Figura 12(B), adaptada de Perroni *et al*. (2014), apresenta o *framework* de processos para a gestão do desempenho energético integrado, utilizando-se o conceito de Empresa Estendida (EE). Os trabalhos de Beamon (1998) e Folan e Brown (2005) pressupõem também que a gestão do desempenho na sua forma completa ocorre nos processos da Empresa Estendida. Tradicionalmente a cadeia de suprimentos se preocupava com o fluxo de matérias e informações. Gradativamente está sendo incluída nessa cadeia: logística reversa, recuperação de resíduos, reuso e a remanufatura (BEAMON, 1998). Outro fluxo que pode ser incluído é o estudo do fluxo de energia (KARA *et al*., 2010, RAHIMIFARD *et al*., 2010).

Conforme as Figuras 12(A) e 12(B), cada processo da Empresa Estendida pode adotar um sistema de gestão do desempenho em energia, baseado na melhoria contínua, *plan-do-study-act* (PDSA) (BITITCI *et al*., 2000; KANNAN; BOIE, 2003; GORDIC *et al*., 2010). Pelo *framework* de processos da Figura 12(B) o desempenho energético da Empresa Estendida pode ser avaliado pelos conceitos de energia incorporada de produtos [*embodied energy of products*] (RAHIMIFARD *et al*. 2010) ou pelo conceito similar da demanda energética cumulativa [*cumulative energy demamd]* (PATEL, 2003). O desempenho energético da EE não está em um ambiente isolado, dependendo da rede de fornecedores [*supply chain network*], bem como das tecnologias existentes (paradigmas e trajetórias tecnológicas) na área de energia (WORRELL; BIERMANS 2005) ou fontes alternativas para a oferta de energia (WEE *et al*., 2012).

A política energética tem um papel fundamental no *framework* de processos da Figura 12(B), uma vez que ela pode influenciar tanto a oferta (gerenciamento direto da matriz de energia) quanto a demanda de energia (política energética voltada à eficiência) conforme discutido na análise do aspecto macro energético no capítulo 2. Baseado na Figura 5, a política energética pode interferir em todos os níveis hierárquicos da produção: equipamentos, processos, empresa, cadeia, indústria e economia (TANAKA *et al*., 2011).

4.2 MAPA DOS INDICADORES DE EFICIÊNCIA ENERGÉTICA DE PROCESSOS

Uma vez discutido o contexto dinâmico do desempenho energético, bem como a estrutura em que ele pode ser integrado, outra questão refere-se às medidas ou indicadores de eficiência energética para representar o desempenho energético dos processos da Empresa Estendida. O grupo do Desempenho Quantitativo em energia apresenta diversas formas de medir o desempenho energético. Existe neste grupo, incluindo os relatórios da Agência Internacional de Energia (IEA, 2014a), uma preocupação em como medir o resultado alcançado com as ações de poupança ou gestão de energia. Durante o processo de revisão sistemática da literatura uma série de termos apareceu, como: eficiência energética, produtividade energética, conteúdo energético, intensidade energética, consumo específico de energia e eficiência relativa (PATTERSON, 1996; PHYLIPSESEN *et al*., 1997; IEA, 2014a).

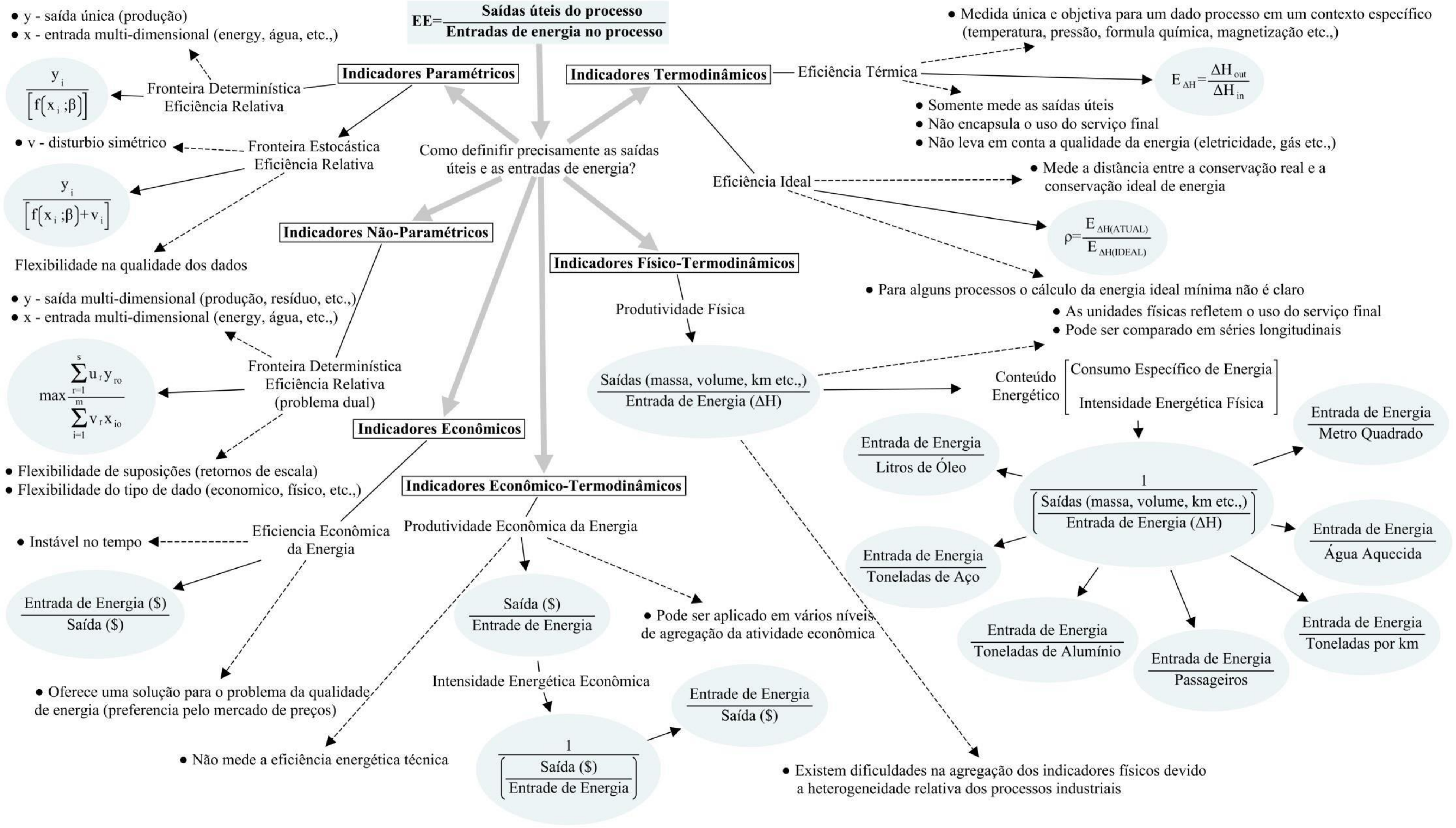
Baseado em Patterson (1996), não existe uma forma quantitativa de medir a eficiência energética sem incorrer em algum tipo de suposição. Utilizando o indicador de eficiência definido em Patterson (1996) [*useful output of a process/energy input into a process*], pela análise dos trabalhos representados no grupo do desempenho quantitativo da literatura (PERRONI *et al*., 2016b), a Figura 13 apresenta um mapa de ramificação da composição do numerador e do denominador do indicador, indo dos chamados *key performance indicators* (KPIs) (PHYLIPSESEN *et al*., 1997; PATTERSON, 1996; IEA, 2014a) aos indicadores de fronteira paramétricos como a análise de fronteira estocástica (SFA) (AIGNER *et al*., 1977, BOYD *et al*., 2008) e não paramétricos como a análise envoltória (DEA) (CHARNES *et al*., 1978, AZADEH *et al*., 2007), sendo possível classificar seis categorias de indicadores: termodinâmico, físico-termodinâmico, econômico-termodinâmico, econômico, fronteira paramétrica e fronteira não paramétrica (PATTERSON, 1996, PERRONI *et al*., 2016d). Conforme discussão metodológica, no primeiro capítulo, um mapa suporta o entendimento do relacionamento estático entre os diversos indicadores que podem ser criados, oferecendo um sistema de referência ou posicionamento para os indicadores (SHEHABUDDEN, *et al*., 1999, p. 11).

No mapa da Figura 13, dois indicadores termodinâmicos são identificados: o indicador de eficiência térmica e o de eficiência ideal. O primeiro indicador é fundamentado na lei de conservação de energia da termodinâmica e mede a eficiência em termos do conteúdo calorífico das entradas [*input*] e saídas [*output*] dos processos. Esse indicador oferece uma medida única para dado processo e ambiente específico considerando: a temperatura, pressão, fórmula química, entre outras variáveis (PATTERSON, 1996). Sua principal desvantagem, no contexto desta tese, é que ele não encapsula adequadamente o uso final do serviço. O indicador de eficiência ideal indica como a conservação real de energia está distante da conservação ideal, uma vez que é a razão de eficiências térmicas. A principal limitação desse indicador está na complexidade que possuiu em determinar a energia mínima ideal para dado processo (PATTERSON, 1996, PERRONI *et al*., 2016d).

Os indicadores físico-termodinâmicos podem ser divididos em dois grupos: produtividade física e conteúdo energético (este também pode ser chamado de intensidade energética física ou consumo específico de energia).

O indicador de produtividade mede a produtividade do fator energia, em outras palavras, o quanto uma unidade de energia (BTU, Joule, Caloria) consegue produzir em determinado processo. Quanto mais saídas são geradas por unidade de energia, diz-se que a produtividade energética é maior.

Figura 13 - Mapa dos indicadores de eficiência energética de processos



Fonte: Perroni *et al.* 2016d; Perroni *et al.* 2017 – Apêndices L e M.

Os indicadores de conteúdo energético, por sua vez, medem a quantidade de energia contida em uma unidade física de produção (toneladas, quilômetros, litros, entre muitos outros), sendo o inverso do indicador de produtividade (PATTERSON, 1996; PHYLIPSESEN *et al*., 1997).

As principais vantagens dos indicadores físico-termodinâmicos são: refletir acerca do uso final de bens e serviços, demandados pelos consumidores, e a possibilidade de comparação em séries longitudinais. A principal desvantagem desse tipo de indicador é a dificuldade de agregação devido à heterogeneidade dos processos de produção (PATTERSON, 1996; PHYLIPSESEN *et al*., 1997).

Os indicadores econômico-termodinâmicos podem ser divididos em: indicadores de produtividade econômica da energia e intensidade energética econômica (conteúdo energético para cada valor monetário), uma vez que medem o valor da produção em valores monetários. Esses indicadores são úteis quando se deseja comparar setores (como no caso do Gráfico 3 do capítulo 2), uma vez que é fácil a agregação em todos os níveis: processos, rede de processos, cadeias, setores industriais ou economia. Na medida em que variáveis econômicas são utilizadas para avaliar a eficiência energética, a grande limitação é que se distancia da eficiência energética técnica. Em níveis agregados é comum a utilização de números índices para separar os efeitos da atividade e da estrutura da eficiência energética, como o algoritmo de divisão [*Logarithmic Mean Divisia index* (LMDI)] (PATTERSON, 1996; ANG, 2012; IEA, 2014a).

Dois outros conjuntos de indicadores retirados da revisão sistemática da literatura são: os indicadores de eficiência relativa de origem paramétrica (estatística) e não paramétrica (programação matemática). São chamados indicadores de eficiência relativa, porque comparam o desempenho de uma entidade (processo) com outra (intraorganizacional ou interorganizacional). Essa comparação é feita baseada na relação de quanto uma dada entidade está distante de uma fronteira calculada. É possível também fazer comparações de uma mesma entidade (processo) ao longo do tempo em abordagens longitudinais ou dinâmicas (BOGETOFT; OTTO; 2010, PERRONI *et al*., 2016d).

Na revisão sistemática da literatura a construção de indicadores que mais se destaca é a dos não paramétricos, baseados na programação matemática utilizando o *Data Envelopment Analysis* (DEA). A principal vantagem do DEA é que múltiplas entradas [*input*] e múltiplas saídas [*output*] podem ser utilizadas, além de poder misturar dados econômicos e físicos. A razão representada no mapa da Figura 13 é o chamado problema dual ou multiplicador[8], enquanto o problema primal é chamado de modelo envelope. O problema dual é mais fácil de interpretar porque pode ser escrito como a razão saídas/entradas. A modelagem DEA pode ser construída sob diferentes perspectivas de retorno de escala, medição de eficiência cruzada, inclusão de entradas ou saídas indesejadas, inclusão de variáveis categóricas, modelo de preferências, dados imprecisos, entre outras possibilidades (CHARNES *et al.*, 1978; BOGETOFT; OTTO; 2010; ZHU, 2014).

Os indicadores paramétricos podem ser divididos entre: determinístico [*Corrected Ordinary Least Squares* (COLS)] e estocástico [*Stochastic Frontier Analysis* (SFA)] (PERRONI *et al.*, 2016c). Na abordagem determinística é assumida a hipótese de que os desvios da fronteira são sempre ineficiências. A abordagem estocástica assume que outros fatores aleatórios afetam a fronteira de produção. A principal desvantagem desses indicadores está no fato de conseguir tratar de apenas uma saída [*output*]. A vantagem está na escolha da composição das entradas [*input*], uma vez que várias técnicas estão disponíveis para avaliar a qualidade dos resultados (AIGNER *et al*., 1977; BOGETOFT; OTTO; 2010).

Segundo Neely *et al*. (1995), o sistema de medição do desempenho pode ser definido como um conjunto de métricas que quantifica a eficiência e a eficácia, enquanto a medição do desempenho está relacionada ao processo dessa quantificação. Os indicadores do mapa da Figura 13 podem ser entendidos como métricas usadas para quantificar a eficiência e/ou a efetividade das ações de gestão de energia (NEELY *et al*., 1995).

4.3 MODELO INSUMO-PRODUTO DE PROCESSOS LONGITUDINAL

Uma vez apresentada a dinâmica e a estrutura do desempenho energético, bem como a composição dos indicadores, esta seção tem por objetivo propor um modelo insumo-produto de processos longitudinal para a medição contínua do desempenho energético. Este modelo pode ser visto como uma arquitetura capaz de representar o desempenho energético da Empresa Estendida da Figura 12(B). Em seu estágio mais evoluído, conforme Figura 12(A), essa arquitetura pode encapsular um sistema de medição do desempenho energético. O estágio mais evoluído refere-se ao fato de que a gestão de energia pode ter estágios de maturidade diferentes, reconhecido pela literatura (GORDIC *et al*., 2010; NEGAI *et al*., 2013; PERRONI *et al*., 2014).

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[8] Essa razão não inclui as restrições usuais do problema dual. A montagem do problema pode ser visto na equação 7.

O modelo insumo-produto foi desenvolvido durante as pesquisas de Leontief (1936/1966) - Prêmio Nobel de Economia. Baseado em Leontief (1966), a análise de insumo-produto é uma extensão prática da teoria clássica de interdependência geral que vê toda a economia (empresas, região, país, mundo) como um sistema interdependente de transações entre as empresas/setores (ver Rede 1). A ideia central da análise insumo-produto é que existe vínculo fundamental entre o volume de produção de uma indústria/empresa e o vulto de insumos que ela absorve. A relação descrita acima é linear entre a quantidade de insumos e a quantidade a ser produzida de produtos e serviços. O modelo insumo-produto tem procedimentos e técnicas específicas como a elaboração das tabelas insumo-produto e o cálculo dos coeficientes direto-indiretos. As tabelas insumo-produto descrevem o fluxo de bens e serviços entre todos os setores em um período específico de tempo. Os coeficientes diretos são coeficientes técnicos de produção que mostram a relação entre os insumos e os produtos/serviços. Os coeficientes indiretos também são conhecidos como a matriz de Leontief, e mostram a relação direta e indireta entre insumos e produtos/serviços. A relação direta é a necessidade direta de insumos para o produto/serviço, semelhante ao exemplo dado no capítulo 2, em que é necessária mais energia para a produção do aço (energia direta). Por outro lado, a relação indireta é a necessidade indireta de insumos, como a energia para a produção do pneu do caminhão que transportou o aço (energia indireta). Uma vez que a coleta de dados para as tabelas insumo-insumo produto de todas as transações entre empresas seria praticamente impossível (nos tempos de Leontief), a solução encontrada foi a agregação das empresas em setores, demonstrando o relacionamento existente entre os mesmos (ver Rede 1) (LEONTIEFF, 1936; LEONTIEF, 1966[9]).

O trabalho desenvolvido pela orientanda de doutorado de Leontief, Karen Rosel Polenske, reorganizou as tabelas insumo-produto, de forma que pudesse ser utilizado com processos empresariais, sendo uma abordagem de processos do modelo insumo-produto. Essa abordagem é conhecida como modelo insumo-produto de processo ou modelo insumo-produto empresarial (LIN; POLENSKE, 1998 ALBINO *et al.*, 2003). A justificativa dos autores está na inadequação dos sistemas contábeis de lidar com fatores como: suporte à estratégia operacional, flexibilidade, qualidade, divisibilidade do desempenho, impactos

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[9] "A Academia Real Sueca de Ciências concedeu o prêmio de 1973 em Ciência Econômica em memória de Alfred Nobel ao professor Wassily Leontief pelo desenvolvimento do método *input-output* e pela sua aplicação em problemas econômicos importantes. O método encontrou uso extensivo especialmente na previsão e planejamento, tanto no curto como no longo prazo. A grande utilidade da técnica *input-output* está no fato de ser usada na previsão e planejamento em sistemas econômicos bastante diferentes - economias de mercado descentralizadas, principalmente com empresas privadas, assim como economias de planejamento centralizadas dominadas pela propriedade pública." http://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/1973/press.html (acessado em Outubro 2016).

diretos e indiretos, além do desempenho de longo prazo. Na literatura que estuda e propõe soluções alternativas de desempenho existe uma concordância referente a esses mesmos princípios (NEELY *et al.*, 1995; GUALAYINE *et al.*, 1996, BOURNE *et al.*, 2000).

Como pode ser observado na revisão sistemática da literatura, o modelo insumo-produto [*input-output*] está entre os principais utilizados pelo grupo da sustentabilidade envolvendo rede de firmas, justamente pela sua flexibilidade em lidar com critérios de desempenho múltiplos relacionados ao desempenho energético e ambiental, no qual os processos são por natureza heterogêneos, gerando tabelas esparsas (DUFLOU *et al.*, 2012).

As principais matrizes (tabelas) do modelo insumo-produto de processos podem ser observadas na Tabela 2, sendo uma abordagem insumo-produto [*input-output*], baseada em processos de produção.

Tabela 2 - Matrizes do modelo insumo-produto de processos

$Matrizes$	$Processos$					$Demanda$
		1	2	3	n	
$Produto\ Principal$	1	Z_{11}	Z_{12}	Z_{13}	Z_{1n}	Y_1
	2	Z_{21}	Z_{22}	Z_{23}	Z_{2n}	Y_2
	3	Z_{31}	Z_{32}	Z_{33}	Z_{3n}	Y_3
	n	Z_{n1}	Z_{n2}	Z_{n3}	Z_{nn}	Y_n
–	–	–	–	–	–	–
$Energia$	1	$\mathbf{E_{11}}$	$\mathbf{E_{12}}$	$\mathbf{E_{13}}$	$\mathbf{E_{1n}}$	$\mathbf{X_1^E}$
	2	$\boldsymbol{E}_{\mathbf{21}}$	$\mathbf{E_{22}}$	$\mathbf{E_{23}}$	$\mathbf{E_{2n}}$	$\mathbf{X_2^E}$
	3	$\mathbf{E_{31}}$	$\mathbf{E_{32}}$	$\mathbf{E_{33}}$	$\mathbf{E_{3n}}$	$\mathbf{X_3^E}$
	n	$\mathbf{E_{n1}}$	$\mathbf{E_{n2}}$	$\mathbf{E_{n3}}$	$\mathbf{E_{nn}}$	$\mathbf{X_n^E}$
–	–	–	–	–	–	–
$Insumos\ primários$	1	P_{11}	P_{12}	P_{13}	P_{1n}	X_1^P
	2	P_{21}	P_{22}	P_{23}	P_{2n}	X_2^P
	3	P_{31}	P_{32}	P_{33}	P_{3n}	X_3^P
	n	P_{n1}	P_{n2}	P_{n3}	P_{nn}	X_n^P
–	–	–	–	–	–	–
$Resíduos$	1	W_{11}	W_{12}	W_{13}	W_{1n}	X_1^w
	2	W_{21}	W_{22}	W_{23}	W_{2n}	X_2^w
	3	W_{31}	W_{32}	W_{33}	W_{3n}	X_3^w
	n	W_{n1}	W_{n2}	W_{n3}	W_{nn}	X_n^w
–	–	–	–	–	–	–
$Subprodutos$	1	B_{11}	B_{12}	B_{13}	B_{1n}	X_1^B
	2	B_{21}	B_{22}	B_{23}	B_{2n}	X_2^B
	3	B_{31}	B_{32}	B_{33}	B_{3n}	X_3^B
	n	B_{n1}	B_{n2}	B_{n3}	B_{nn}	X_n^B
–	–	–	–	–	–	–
$Produto\ principal$		$X_1^{Z_{11}}$	$X_2^{Z_{22}}$	$X_3^{Z_{33}}$	$X_n^{Z_{nn}}$	

Fonte: Lin e Polenske, 1998.

Nota: Z – Matriz de processos e produto principal; Y – Matriz da produção final dos produtos principais; E - matriz de energia; X^E Matriz do uso total de energia; P- Matriz das entradas primárias; X^P- Matriz das entradas primárias totais; W- Matriz de resíduos; X^W- Matriz da geração total de resíduos; B- Matriz de subprodutos; X^B – Matriz da produção total de subprodutos; X^z- Matriz da produção bruta do produto principal (diagonal principal da matriz de processos).

Na Tabela 2, as matrizes componentes do modelo são: processos (Z), energia (E), insumos primários (P), resíduos (W) e subprodutos (B). Cada processo da matriz (Z) transforma i*nputs* em *outputs*, no qual o *output* principal de um processo é o *input* do processo seguinte, sendo que o *output* final é o produto/serviço vendido fora do sistema (ALBINO *et al*., 2003). Cada processo de produção exige uma quantidade de materiais e energia, sendo que após o processamento, além do *output* principal, são gerados resíduos e subprodutos (LIN; POLENSKE, 1998, ALBINO *et al*., 2003, KUHTZ *et al*., 2010). São necessárias duas hipóteses básicas para operacionalizar o modelo: (i) cada processo só pode gerar um produto principal (diagonal principal da matriz Z); (ii) o produto principal de um processo não pode ser consumido por ele mesmo (WANG; JIA, 2012).

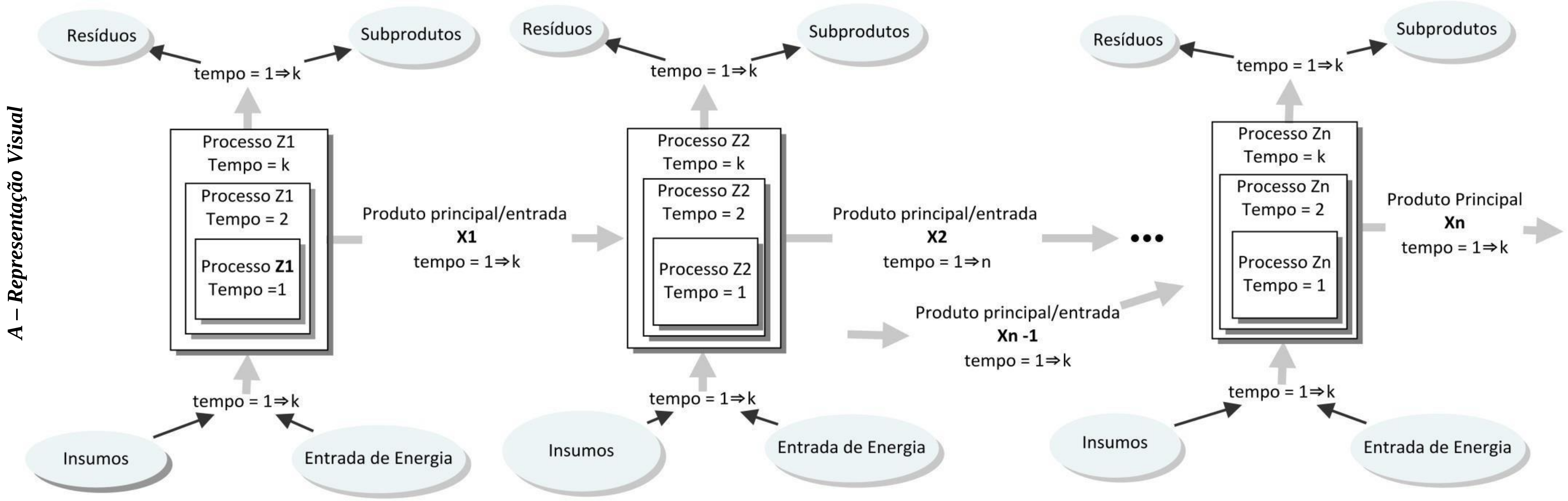
O modelo insumo-produto de processo foi aplicado nos processos de uma Empresa Estendida ou parte dela, por exemplo, nos processos de fabricação de aço (LIN; POLENSKE, 1998), produção de Coke (POLENSKE; MCMICHAEL 2002), construção de estofados (ALBINO *et al*., 2002, ALBINO *et al*., 2003, ALBINO *et al*., 2008), manufatura de telhas (ALBINO; KUHTZ 2004, KUHTZ *et al*., 2010) e produção do biodiesel de segunda geração (YAZAN *et al*., 2012) possuindo as características técnicas para representar o desempenho energético da Empresa Estendida da Figura 12(A) e 12(B). O modelo pode ser utilizado como ferramenta de planejamento/controle para elaborar cenários para verificar o impacto de mudanças nos *inputs/outputs*, estudar o fluxo de materiais e energia, analisar as ligações internas e externas da cadeia, quantificar a demanda de recursos, monitorar a geração/utilização de resíduos/poluição, entender o processo de desmaterialização, entre outros (LIN; POLENSKE 1998, ALBINO *et al*., 2003, KUHTZ *et al*., 2010).

A Figura 14(A) representa um modelo insumo-produto de processos longitudinal, apresentando um esquema simplificado em que é acrescentada a variável tempo no modelo original. No modelo longitudinal, a divisibilidade dos processos também é recortada com relação ao tempo, sendo que a análise pode ser processada após o término do ciclo de produção.

Cada novo ciclo de produção (tempo t de 1 até k na Figura 14(A)) pode produzir novos resultados (derivados da gestão de energia, por exemplo) que precisam ser analisados e comparados.

Com relação à hierarquia do modelo insumo-produto, a unidade principal de análise é a dos processos de produção (transformação dos *inputs* em *outputs* por meio do arranjo de recursos) (SHEHABUDDEN, *et al*., 1999).

Figura 14 - Modelo insumo-produto de processos longitudinal



B – Representação Matemática

	B1 – Coeficiente Diretos	**B2 – Matriz**	**B3 – Demanda/Produção**	**B4 – Coeficientes Indiretos**
1 –	$\lvert Processos \rightarrow A = a_{ij} = \frac{Z_{ij}}{X_j} = Z\hat{X}^{-1} \rvert$	$\lvert Processos \rightarrow Z = A\hat{X} \rvert$	$\lvert Produto \rightarrow Y = AX^T \rvert$	$\lvert Processos \rightarrow A^{-1} \rvert$
2 –	$\lvert \boldsymbol{ENERGIA \rightarrow EDC = e_{ij} = \frac{E_{ij}}{X_j} = E\hat{X}^{-1}} \rvert$	$\lvert \boldsymbol{ENERGIA = EDC\hat{X}} \rvert$	$\lvert \boldsymbol{ENERGIA = EDCX^T} \rvert$	$\lvert \boldsymbol{ENERGIA = EDCA^{-1}} \rvert$
3 –	$\lvert Insumos \rightarrow PIDC = p_{ij} = \frac{P_{ij}}{X_j} = P\hat{X}^{-1} \rvert$	$\lvert Insumos = PIDC\hat{X} \rvert$	$\lvert Insumos = PIDCX^T \rvert$	$\lvert Insumos = PIDCA^{-1} \rvert$
4 –	$\lvert Resíduos \rightarrow WDC = w_{ij} = \frac{W_{ij}}{X_j} = W\hat{X}^{-1} \rvert$	$\lvert Resíduos = WDC\hat{X} \rvert$	$\lvert Resíduos = WDCX^T \rvert$	$\lvert Resíduos = WDCA^{-1} \rvert$
5 –	$\lvert Subprodutos \rightarrow BDC = b_{ij} = \frac{B_{ij}}{X_j} = B\hat{X}^{-1} \rvert$	$\lvert Subprodutos = BDC\hat{X} \rvert$	$\lvert Subprodutos = BDCX^T \rvert$	$\lvert Subprodutos = BDCA^{-1} \rvert$

Fonte: Adaptado de Lin e Polenske, 1998; Kuhtz *et al*. 2010 [10]; Perroni *et al*. 2016d ; Perroni *et al*. 2017- Apêndices D, L e M.
Nota: (a) EDC – Coeficientes diretos de energia; E – Matriz de energia; X – Matriz de saídas; A^{-1} – Equivalente a inversa de Leontief.
(b) Representação matemática considerando t=1.

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[10] O chapéu em X denota a diagonal da matriz

Uma sequência ordenada de processos de produção é definida como ciclo de produção. O ciclo pertence a uma rede de processos de produção [*network of production process*] que pode estar localizada em um cluster local ou em uma cadeia global [*global supply-chain*] (ALBINO *et al*., 2002; KUHTZ *et al*., 2010). A Figura 14(A) representa de uma forma mais simplificada, um ciclo de produção, afinal não existem mecanismos de *feedback* (sendo um modelo *one-way*) (ALBINO *et al*., 2003).

A Figura 14(B) apresenta as equações matriciais do modelo para as matrizes dos processos (Z), produtos principais (X), energia (E), entradas primárias (P), resíduos (W) e subprodutos (B), de acordo com a Tabela 2. O objetivo desta tese está diretamente relacionado às matrizes de coeficientes energéticos tanto diretos quanto indiretos na representação matemática da Figura 14(B), uma vez que estas medem o desempenho energético. As duas matrizes de indicadores de energia gerados pelo modelo são: a matriz dos coeficientes diretos ($E\hat{X}^{-1}$) e a matriz dos coeficientes indiretos ($EDCA^{-1}$), em que: (i) E é a matriz de energia, (ii) $\hat{X}^{-1}$ é a matriz de saídas, na qual a diagonal principal recebe o vetor inverso de saídas, sendo os outros elementos iguais a zero, (iii) e EDC é a matriz de coeficientes diretos, (iv) A^{-1} é equivalente a inversa de Leontief (um exemplo numérico será apresentado no próximo capítulo). A matriz de coeficientes diretos é o inverso do indicador de produtividade do fator energia (quanto uma unidade de energia consegue produzir), em outras palavras, mede o conteúdo energético do processo (quanto uma unidade de produção consome de energia no respectivo processo). Para tal, ver mapa de indicadores da Figura 13. Dependendo da escolha para a composição dos dados (alterando o numerador e/ou o denominador conforme mapa da Figura 13), a matriz de coeficientes diretos do modelo pode representar um indicador físico-termodinâmico, econômico-termodinâmico e econômico.

A matriz de coeficientes indiretos é o fluxo de energia, medindo a energia incorporada no produto/serviço final [*cumulative energy demand*] conforme especificado no modelo de processos da Empresa Estendida da Figura 12(B).

Interpretado de forma analítica, a principal contribuição do modelo insumo-produto é a geração de duas matrizes de desempenho energéticas: uma direta e outra indireta, sendo nesta última acrescentada à conexão com outros processos. As matrizes de desempenho podem ser interpretadas como matrizes de multiplicadores, sendo uma espécie de receita para a produção. A matriz de multiplicadores informa as quantidades unitárias de recursos diretos e indiretos para produzir uma unidade do produto ou serviço. O próximo capítulo faz novas interpretações das matrizes de desempenho, considerando a transformação longitudinal feita na Figura 14(A).

4.4 RELACIONAMENTO ENTRE O *FRAMEWORK*, MAPA E O MODELO

Para concluir o encerramento desta seção, algo a destacar é o relacionamento entre o framework de processos, mapa de indicadores e o modelo insumo-produto. O framework propõe que cada processo tem o seu desempenho energético específico. Quando o escopo da organização é a Empresa Estendida, esse desempenho pode ser avaliado de forma integrado. O framework da Figura 12(A) também leva em conta que as escolhas das medidas e tecnologias ocorrem em um sistema de melhoria contínua, ligando as operações com a estratégia. Uma vez que a criação de indicadores não é trivial, a função do mapa de indicadores é mostrar as várias formas de se gerar e interpretar os indicadores. Basicamente, dois tipos de indicadores são possíveis: conteúdo e produtividade energética. O modelo insumo-produto de processo gera matrizes de desempenho (conteúdo energético), possibilitando a intepretação individualizada ou integrada dos indicadores. Dentro do escopo desse modelo, novos indicadores podem ser propostos, considerando as opções apresentadas no mapa.

5 ABORDAGEM PARA A MEDIÇÃO E CONTROLE DO DESEMPENHO ENERGÉTICO

Conforme descrito no mapa da tese da Figura 3, este capítulo tem o objetivo de apresentar a lógica de aplicação da abordagem de processos para o monitoramento contínuo do desempenho energético. Essa abordagem tem origem em quatro artigos do projeto de pesquisa expostos nos Apêndices J ao M (PERRONI *et al.*, 2014; PERRONI *et al.*, 2016c; PERRONI *et al.*, 2016d; PERRONI *et al.*, 2017).

Com base na literatura, o *framework* estrutural (Figura 12(A)) assume que o desempenho energético pode ser melhorado de forma contínua. A representação desenvolvida no capítulo anterior requer a identificação de medidas operacionais que levem à melhoria. Assumiu-se na discussão do problema de pesquisa, no primeiro capítulo, que a hipótese da eficiência energética faz parte do cinturão protetor do núcleo/paradigma da sustentabilidade (KHUN, 1962; LAKATOS, 1978, WCED, 1987; KPMG, 2012; MACHADO, 2015). Essa hipótese é reforçada pela revisão sistemática da literatura, uma vez que quase todos os artigos mais recentes (posterior ao ano 2000) relacionam a eficiência energética com algum aspecto da sustentabilidade, sendo o fator mais relevante os danos causados ao meio ambiente, principalmente, a emissão de CO2. A pesquisa também assume a hipótese *ad hoc* de que é possível identificar tanto medidas, quanto tecnologias, e a partir de sua implementação o desempenho energético possa ser melhor.

Fundamentado na metodologia da representação/abordagem da Figura 2, a operacionalização da representação envolve processos, procedimentos, técnicas e ferramentas (SHEHABUDDEN, *et al.*, 1999). A representação identifica procedimentos e técnicas que podem ser utilizadas como: construção das tabelas insumo-produto, cálculos matriciais, elaboração de indicadores de eficiência, formas de visualização, entre outras. Este capítulo visa integrar algumas dessas técnicas, sendo por natureza baseada no dedutivismo, atendendo aos objetivos específicos. Apoiado na área de eficiência empresarial, a seção 5.1 propõe indicadores para acompanhar continuamente o desempenho energético. A partir de uma estrutura real de processos, a seção 5.2 desenvolve uma abordagem de simulação para alimentar o modelo na sua forma longitudinal. Uma abordagem para visualização multidimensional dos indicadores é construída na seção 5.3.

5.1 INDICADORES BASEADOS NA EFICIÊNCIA EMPRESARIAL

Um indicador de eficiência vem da razão de dois indicadores de desempenho (PERRONI *et al.*, 2016c). Adaptado de Bogetoft e Otto (2010) e Perroni *et al.* (2016c) a eficiência, ineficiência e a efetividade empresarial podem ser representadas como:

$$INEFICIÊNCIA = \frac{DESEMPENHO\ ATUAL - DESEMPENHO\ MÍNIMO}{DESEMPENHO\ ATUAL} \qquad (1)$$

$$EFICIÊNCIA = \frac{DESEMPENHO\ MÍNIMO}{DESEMPENHO\ ATUAL} = 1 - INEFICIÊNCIA \qquad (2)$$

$$EFETIVIDADE = \frac{DESEMPENHO\ ATUAL}{DESEMPENHO\ IDEAL} \cong \frac{DESEMPENHO\ ATUAL}{DESEMPENHO\ MÁXIMO} \qquad (3)$$

Normalmente o que se almeja é um desempenho melhor ou máximo. O desempenho mínimo, nas Equação 1 e 2, pode ser explicado porque o desejado é reduzir a quantidade de energia por unidade de produção, ou seja, diminuir o conteúdo energético conforme mapa da Figura 13. Quando o desempenho atual se aproximar do desempenho mínimo, a ineficiência estará próxima de zero (0), e a eficiência próxima de um (1). O desempenho máximo, na Equação 3, está relacionado ao indicador de produtividade energética do mapa da Figura 13, uma vez que o desejado é maximizar a produção por unidade de energia, neste caso, quando o desempenho atual se aproximar do desempenho máximo, a efetividade se aproximará da unidade (1). As propriedades dos indicadores das Equações 1, 2 e 3 podem ser visualizadas com um exemplo hipotético na Tabela 3.

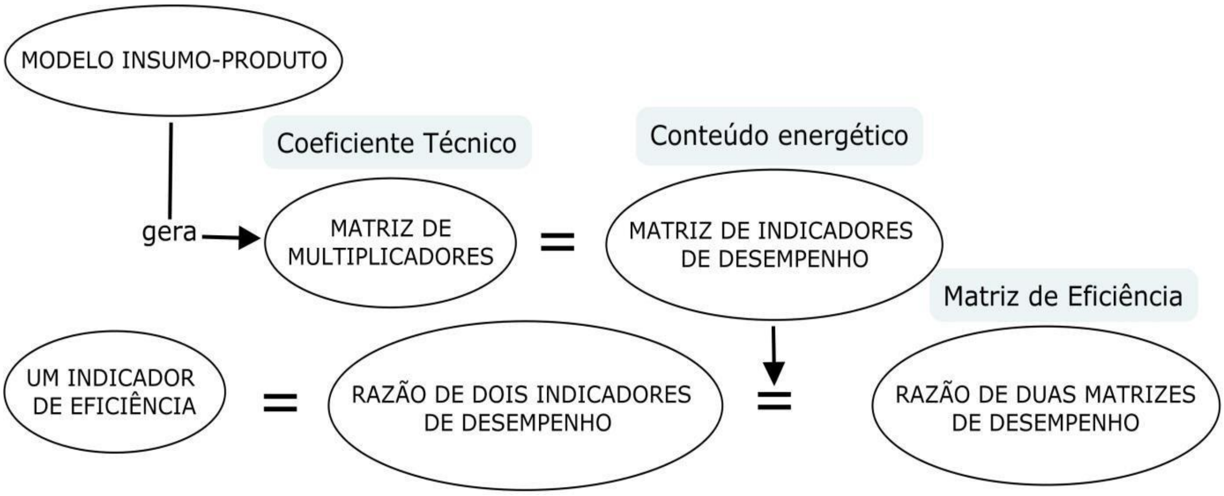
Tabela 3 - Relacionamento entre indicadores de desempenho, eficiência, ineficiência e efetividade

Tempo	1 trim	2 trim	3 trim	4 trim	5 trim	6 trim	7 trim	8 trim	9 trim	10 trim	11 trim	12 trim
Desempenho	105666	70355	73865	112670	81670	65258	110318	69820	57230	103387	98331	53048
Ineficiência	0,50	0,25	0,28	0,53	0,35	0,19	0,52	0,24	0,07	0,49	0,46	0,00
Eficiência	0,50	0,75	0,72	0,47	0,65	0,81	0,48	0,76	0,93	0,51	0,54	**1,00**
Efetividade	0,94	0,62	0,66	**1,00**	0,72	0,58	0,98	0,62	0,51	0,92	0,87	0,47

Nota: (a) Para o cálculo da eficiência, assume-se o desempenho como um indicador de conteúdo energético; (b) para a efetividade relaciona-se o desempenho à produtividade energética; (c) o valor sombreado um (1,00) para a eficiência significa que ela ocorre quando se consumiu o mínimo de recursos energéticos, por sua vez para a efetividade o valor um (1,00) significa que se produziu o máximo de produtos/serviços dado um nível de energia estabelecido como base.

Com base na Equação 2, um indicador de eficiência energética pode ser obtido da razão de dois indicadores de conteúdo energético ou produtividade energética (BOGETOFT; OTTO, 2011; PERRONI *et al.*, 2016c). A Figura 15 mostra o relacionamento entre o (i) modelo insumo-produto, (ii) indicador de desempenho e (iii) indicador de eficiência.

Figura 15 - Relacionamento entre o modelo insumo-produto, indicador de desempenho e indicador de eficiência



Fonte: o autor, 2016.

Conforme exposto na Figura 15, um indicador de eficiência energética pode vir da razão de duas matrizes de desempenho energético, geradas no modelo insumo-produto longitudinal, de forma que a matriz resultante é uma matriz de eficiência.

De acordo com o mapa de indicadores da Figura 13, no modelo insumo-produto longitudinal da Figura 14(A) e nos relacionamentos da Figura 15, é possível criar indicadores para a medição do desempenho energético. É importante ressaltar que a base matemática para criação dos indicadores vem da teoria dos números índices, que possui a mesma ramificação dos índices de decomposição [*Index decomposition analysis* (IDA)] (LIU, 2004; FARIAS; LAURENCEL, 2005; FEIJÓ; RAMOS, 2013) e da análise de decomposição estrutural [*Structural Decomposition Analysis* (SDA)]. A SDA teve origem nas tabelas insumo-produto de Leontief (LIU, 2004).

A primeira matriz de indicadores (Equação 4) pode ser obtida pela razão “desempenho mínimo/desempenho atual”, fazendo a divisão da matriz do conteúdo energético mínimo de cada processo pela matriz de conteúdo energético atual. De acordo com a representação matemática da Figura 14(B), a variável E é a matriz de energia, e $\hat{X}^{-1}$ é a matriz de saídas, em que a diagonal principal recebe o vetor inverso de saídas, sendo os outros elementos iguais a zero. Conforme o mapa de indicadores da Figura 13, o conteúdo energético também é chamado de consumo específico de energia ou intensidade energética (PERRONI *et al.*, 2016d). Esse indicador faz uma comparação entre a energia direta mínima por unidade de produção gasta no processo, com a energia direta por unidade de produção gasta em um período específico do tempo. O indicador será nomeado como eficiência energética direta (EED).

$$EED = \frac{\min\limits_{t=1\to k}\left[\hat{\boldsymbol{E}}\boldsymbol{X}^{1}\right]_{t}}{\left[\hat{\boldsymbol{E}}\boldsymbol{X}^{1}\right]_{t}} \equiv \left|\frac{\min\limits_{t=1\to k}\left[\frac{E_{ij}}{X_{j}}\right]_{t}}{\left[\frac{E_{ij}}{X_{j}}\right]_{t}}\right| = \frac{\begin{matrix}Conteúdo\ energético\ direto\\ mínimo\ do\ proceso\end{matrix}}{\begin{matrix}Conteúdo\ energético\ direto\\ atual\ do\ processo\end{matrix}} \qquad (4)$$

O segundo indicador proposto é o da mudança na eficiência energética direta (MEE) (Equação 5), em que reflete a mudança na eficiência energética direta, dividindo a matriz de conteúdo energético do período atual pela matriz do período anterior, revelando oscilações de curto prazo, porque é um relativo com base móvel. É chamado relativo porque está associado à variação entre dois períodos de uma única variável, e a base tem que ser móvel para poder comparar o período atual com o período anterior (FARIAS; LAURENCEL, 2005; FEIJÓ; RAMOS, 2013).

$$MEE = \left\{\frac{\left[\hat{\boldsymbol{E}}\boldsymbol{X}^{1}\right]_{t}}{\left[\hat{\boldsymbol{E}}\boldsymbol{X}^{1}\right]_{t-1}} - 1\right\} \equiv \left\{\frac{\left[\frac{E_{ij}}{X_{j}}\right]_{t}}{\left[\frac{E_{ij}}{X_{j}}\right]_{t-1}} - 1\right\} = \frac{\begin{matrix}Conteúdo\ energético\ direto\\ atual\ do\ processo\end{matrix}}{\begin{matrix}Conteúdo\ energético\ direto\\ anterior\ do\ processo\end{matrix}} \qquad (5)$$

O terceiro indicador é o da Eficiência Energética Indireta (EEI), apresentado na Equação 6, obtido pela razão da matriz de coeficientes indiretos, do modelo insumo-produto de processo longitudinal (matriz de multiplicadores indiretos), levando em conta a energia direta incorporada no processo, mais a energia indireta de todos os processos relacionados. A operacionalização desse indicador pode ser feita pela razão do consumo direto e indireto mínimo pelo consumo direto e indireto em um dado período de tempo. Conforme representação matemática da Figura 14(B), a variável EDC é a matriz de coeficientes diretos (desempenho direto) e A^{-1} é equivalente a inversa de Leontief. Esse indicador é mais robusto do que o anterior, porque funciona em qualquer nível de relacionamento entre os processos, o qual é à base do modelo de Leontief (1936-1966).

$$EEI = \left| \frac{\min\limits_{t=1 \to k} [\boldsymbol{EDCA}^{-1}]_t}{[\boldsymbol{EDCA}^{-1}]_t} \right| = \frac{\begin{matrix} Conteúdo\ energético\ indireto \\ mínimo\ do\ proceso \end{matrix}}{\begin{matrix} Conteúdo\ energético\ indireto \\ atual\ do\ processo \end{matrix}} \tag{6}$$

O papel desse indicador é medir o desempenho do que a literatura denomina de energia incorporada de produtos [*embodied energy of products*] (KARA *et al.*, 2010; RAHIMIFARD *et al.*, 2010) ou a demanda energética cumulativa [*cumulative energy demamd*] (PATEL, 2003). No caso específico do modelo insumo-produto de processos, energia incorporada nos processos. No último processo (Z*n*) do modelo-insumo produto longitudinal da Figura 14(A), o cálculo da eficiência indireta mede a eficiência energética global se todas as fontes energéticas forem agregadas para computar o indicador, em outras palavras, no processo (Z*n*) o indicador pode medir a eficiência conjunta (todos os processos e todas as fontes energéticas).

O problema de um indicador de efetividade é conhecer antecipadamente o valor do desempenho ideal. A solução é uma aproximação conforme Equação 3, substituindo o desempenho ideal pelo desempenho máximo que possa ser alcançado. A maneira de superar esse problema tem sido por meio da aplicação do conceito de eficiência, chamada eficiência de Farrel (1957), movendo o foco da efetividade para a eficiência relativa. Conforme mapa da Figura 13 existem duas abordagens para a construção da eficiência relativa: a paramétrica e a não paramétrica. A revisão sistemática da literatura indica que a abordagem mais utilizada tem sido a não paramétrica, desenvolvida nas pesquisas de Charnes *et al*. (1978). Os dados para a construção de um indicador de eficiência relativa podem vir diretamente das tabelas insumo-produto. Considerando que o modelo de processos da Figura 14(A) é longitudinal - envolvendo períodos de tempos diferentes - o indicador de eficiência relativa leva em conta a fronteira intertemporal, existindo a possibilidade de agregação de várias entradas [*inputs*] (fontes energéticas diferentes ou outras entradas primárias) e várias saídas [*outputs*] (além da produção do processo podem ser utilizadas variáveis de subprodutos e resíduos). A solução para esse indicador é obtida com a programação matemática, denominado na Equação 7 de Eficiência Energética Relativa (EER). Esse problema é conhecido na literatura de eficiência empresarial como modelo multiplicador [*multiplier model*] (CHARNES *et al.*, 1978; BOGETOFT; OTTO; 2010; ZHU, 2014).

$$EER = \left|\begin{array}{lll} max\,\dfrac{\sum_{r=1}^{s} u_r\boldsymbol{X}_{ro}}{\sum_{i=1}^{m} v_i\boldsymbol{E}_{ro}} = & max\,\dfrac{Saídas\ do\ processo}{Entradas\ do\ processo\ (energia)} \equiv & Produtividade\ energética \\ st: & & \\ \dfrac{\sum_{r=1}^{s} u_r X_{rt}}{\sum_{i=1}^{m} v_i E_{it}} \leq 1 & t = 1, \ldots, k. & \\ u_{r,}\ v_i \geq 0 & r = 1, \ldots, s & i = 1, \ldots, m \end{array}\right| \qquad (7)$$

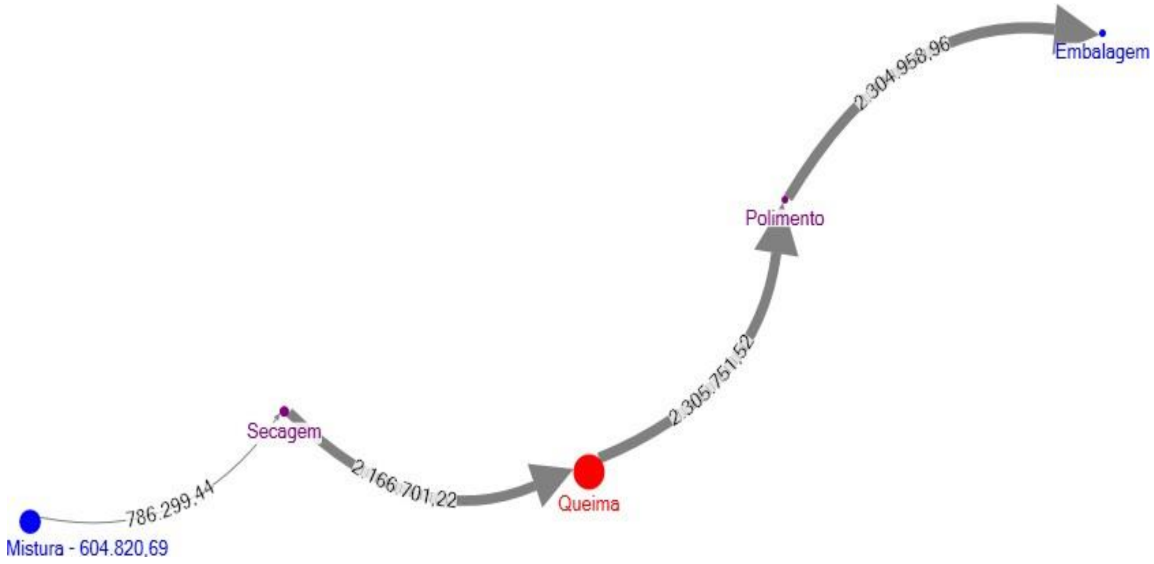
Os indicadores *EED, MEE e EEI* são construídos a partir da Equação 2, tendo como referência o conteúdo energético. O indicador de eficiência relativa (EER) é baseado na maximização da produtividade energética, na qual a medida da eficiência é obtida pela produtividade máxima da energia, similar a Equação 3. Na Equação 7 a saída (X_{ro}) e a entrada (E_{ro}) recebem os pesos (u_r) e (v_i) respectivamente. Esse modelo de programação matemática presume que a produtividade definida da mesma forma em outros períodos de tempo $(X_{rt}\ e\ E_{it})$ é menor ou igual à unidade (CHARNES *et al.*, 1978). A implementação pode ser feita pela solução do multiplicador [*multiplier model*] ou do *modelo envelope* [*envelopment model*] (BOGETOFT; OTTO, 2011; ZHU, 2014; PERRONI *et al.*, 2016c). De acordo com o mapa da Figura 13, os indicadores de fronteira paramétricos também são fundamentados na relação de produtividade, uma vez que a ineficiência configura-se por estar abaixo da fronteira, quando comparada com o desempenho máximo, conforme Equação 3.

5.2 ABORDAGEM DE SIMULAÇÃO DA ESTRUTURA DO MODELO INSUMO-PRODUTO DE PROCESSOS LONGITUDINAL

Uma vez que o modelo insumo-produto de processos longitudinal incorpora a estrutura (*framework*) em que o desempenho energético ocorre, bem como os indicadores relevantes (baseado no mapa de indicadores da Figura 13), o funcionamento contínuo da abordagem pode ser descrito por meio de um sistema. Baseado na metodologia da representação/abordagem da Figura 2, sistema é "*um conjunto de elementos inter-relacionados delimitados com propriedades emergentes sendo representado dentro do contexto do paradigma*" (SHEHABUDDEN, *et al.*, 1999 p.8). Como o modelo insumo-produto de processos longitudinal é matemático, uma das formas de demonstrar como ele poderia ser utilizado para monitorar o desempenho energético é por meio de ferramentas computacionais. Dentro da abordagem de processos proposta, o desempenho energético pode ser monitorado pelos indicadores criados com as técnicas insumo-produto, adaptadas para funcionar de forma longitudinal.

A Tabela 4 apresenta um caso simples, mas real, de processos para manufaturar telhas (ALBINO *et al*., 2004; KUHTZ *et al*., 2010). A melhoria do desempenho energético está relacionada à possibilidade de identificação tanto de tecnologias quanto medidas (ações) gerais de gestão de energia que possam ser aplicadas. Uma vez que o setor de fabricação de telhas pertence ao setor cerâmico, o Apêndice A organiza as informações oferecidas pelo Departamento de Energia Americano (DOE-IAC) demonstrando que podem ser identificadas tanto medidas, quanto tecnologias para a poupança de energia que contribuam para a melhoria do desempenho energético no setor cerâmico (PERRONI *et al*., 2016c). A manufatura de telhas foi dividida em cinco processos conforme Rede 6:

Rede 6 - Rede de processos para a manufatura de telhas: fluxo de energia



Fonte: Elaborado pelo autor com base nos dados de Kuhtz *et al*. 2010.
Nota: (a) Tamanho dos vértices: proporcional ao uso total de energia; (b) Cor dos vértices: centralidade auto vetorial; (c) Espessura das arestas: somatório das colunas dos coeficientes indiretos de energia (kcal por unidade de produção) da Tabela 6; (d) Algoritmo - Harel-Koren Fast Multiscale (Hansen, *et al*., 2011).

- **Processo de Mistura - M**: a argila, os resíduos reutilizáveis e outros materiais (que dependem do tipo de telha que está sendo produzida) são moídos e peneirados e, em seguida, misturados com água e o barro.

- **Processo de Prensagem e Secagem - N**: primeiro a mistura de argila é prensada e posteriormente enviada para a secagem.
- **Processo de Queima - O**: é um processo contínuo em que a telha passa pela queima para evaporar o restante da água. Faz parte desse processo: o pré-aquecimento, a queima e a refrigeração.
- **Processo de Polimento - P**: as telhas são polidas em duas etapas: primeira de forma grosseira e a segunda de forma mais refinada.
- **Processo de Seleção e Embalagem - Q**: as telhas são selecionadas de acordo com a cor e a qualidade, posteriormente são embaladas por máquinas automatizadas.

A Tabela 4 apresenta a matriz de processos (Z), matriz de energia (E) e o vetor de saídas (X), enquanto a Figura 16 expõe uma abordagem de simulação para gerar os dados do modelo. Na matriz de processos, todas as saídas da Mistura (M), até o Polimento (P), são consumidas pelos processos subsequentes, de forma que só há demanda (Y) para o produto embalado (Q). Essa tabela representa um ciclo de produção como o da Figura 14(A), sendo um modelo simples de caminho único (*one-way*), representando uma Empresa Estendida. Quando a matriz de processos (Z) for representada por uma rede, como a Rede 6, os vértices da diagonal principal são produção/autoprodução. Cada vértice fora da diagonal principal é ligado por uma aresta direcional, indicando as transações da rede (ALBINO *et al.*, 2003).

Tabela 4 - Matriz de processos e matriz de energia para uma manufatura de telhas

Produto		**Z** - Processos de produção					Demanda
	10^4	**M**	**N**	**O**	**P**	**Q**	**Y**
M – Mistura	**t**	16,300	-16,300	0	0	0	**0**
N – Secagem	**t**	0	15,600	-15,600	0	0	**0**
O – Queima	**t**	0	0	15,130	-15,130	0	**0**
P – Polimento	**t**	0	0	0	14,740	-14,740	**0**
Q – Embalagem	**t**	0	0	0	0	14,760	**14,760**
Energia	**10^4**	**E** – Matriz de Energia					
E- Eletricidade	**kcal**	1.084.129	0	955.066	1.204.588	34.416	3.278.200
T - Térmica	**kcal**	4.387.224	1.203.847	9.780.426	0	0	15.371.497
L - Óleo	**kcal**	4.387.224	0	0	0	0	4.387.224
D -Diesel	**kcal**	0	0	1.848.000	0	0	1.848.000
G -Gás natural	**kcal**	0	1.203.847	7.932.426	0	0	9.136.273
		X – Saída do produto principal do processo					
Saídas	**t**	16,300	15,600	15,130	14,740	14,760	

Fonte: Albino e Kuhtz 2004; Kuhtz *et al.* 2010; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices D, L e M.
Nota: (a) O produto do processo entra com sinal positivo na diagonal principal da matriz Z; (b) Os valores fora da diagonal principal recebem o sinal negativo porque representam o consumo de recursos oriundos de outros processos; (c) Cada processo só pode gerar um produto principal (diagonal principal da matriz Z); (d) O produto principal de um processo não pode ser consumido por ele mesmo.

Para o cálculo dos indicadores de desempenho diretos e indiretos é necessário a operacionalização das Equações das linhas 1 e 2, da representação matemática do modelo insumo-produto de processo da Figura 14(B) (KUHTZ *et al.*, 2010)[11]. Os coeficientes diretos e indiretos dos processos e energia podem ser vistos nas Tabelas 5 e 6.

Tabela 5 - Coeficientes intermediários dos processos e matriz inversa da produção

Coeficientes diretos dos processos $A = a_{ij} = \frac{Z_{ij}}{X_j} = Z\hat{X}^{-1}$						Coeficientes indiretos dos processos A^{-1}						Diagonal inversa da produção $\hat{X}^{-1}$					
	M	**N**	**O**	**P**	**Q**		**M**	**N**	**O**	**P**	**Q**		**M**	**N**	**O**	**P**	**Q**
M	1	-1,04	0	0	0	**M**	1	1,04	1,08	1,11	1,10	**E**	0,061	0	0	0	0
N	0	1	-1,03	0	0	**N**	0	1	1,03	1,06	1,06	**T**	0	0,064	0	0	0
O	0	0	1	-1,03	0	**O**	0	0	1	1,03	1,03	**L**	0	0	0,066	0	0
P	0	0	0	1	-1,00	**P**	0	0	0	1	1,00	**D**	0	0	0	0,068	0
Q	0	0	0	0	1	**Q**	0	0	0	0	1	**G**	0	0	0	0	0,068

Nota: (a) Processos: M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; (b) Fontes Energéticas: E - Eletricidade; T – Térmica; L – Óleo; D – Diesel; G - Gás natural

Os coeficientes diretos da Tabela 6 são indicadores de desempenho físico-termodinâmicos do mapa da Figura 13, medindo o conteúdo energético por unidade de produção do processo. O processo Q (Embalagem) requer 2.332 kcal de energia elétrica (2,71 kWh) para embalar cada tonelada de telha. Pela análise da matriz de desempenho direto (coeficientes diretos de energia), o processo Q (Embalagem) consome apenas energia elétrica. Os indicadores indiretos da Tabela 6 medem o fluxo de energia, ou de outra forma a energia acumulada/incorporada pelos processos de produção [*embodied energy of products*] (RAHIMIFARD *et al.*, 2010). O indicador no processo de Embalagem (Q) representa a energia total (direta mais indireta) necessária para manufaturar uma tonelada de telhas.

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[11] O trabalho de Kuhtz et al. (2010) organiza as tabelas e equações do modelo insumo-produto de processo de uma forma um pouco diferente do trabalhho original de Lin e Polenske (1998). Em Kuhtz et al. (2010) Z_0 é a matriz de processos, sendo que a entrada da diagonal principal é zero; f_0 é o vetor de demanda; x_0 é o vetor do produto principal; α representa o número de processos de produção; β é a quantidade de insumos primários agrupados na matriz R^u; λ são as fontes de energia agrupadas na matriz E^u e γ são os tipos de sub-produtos e resíduos produzidos agrupados na matriz W^u. Os coeficientes diretos dos insumos são definidos como: $\forall k = 1, \dots \beta, \ \forall j = 1, \dots \alpha \quad R^u_{kj} = R_{kj} x_j$, em que $R^u = [R^u_{kj}]$ é a matriz dos insumos primários; $R = [R_{kj}]$ é a matriz dos coeficientes técnicos diretos dos insumos primários. Para a matriz de energia: $\forall k = 1, \dots \lambda, \ \forall j = 1, \dots \alpha \quad E^u_{kj} = E_{kj} x_j$, em que $E^u = [E^u_{kj}]$ é a matriz de energia, $E = [E_{kj}]$ são os coeficientes técnicos diretos de energia e por último para a matriz de sub-proutos/resíduos: $\forall k = 1, \dots \gamma, \ \forall j = 1, \dots \alpha \quad W^u_{kj} = W_{kj} x_j$, em que $W^u = [W^u_{kj}]$ são as saídas de sub-produtos e resíduos, $W = [W_{kj}]$ são os coeficientes técnicos de saídas dos sub-produtos ou resíduos. A matriz de coeficientes intermediários A é representada pela equação $A_0 = Z_0 \hat{X}^{-1}{}_0$ O resultado pode ser representado por $x_0 = A x_0 + f_0 = (I - A)^{-1} f_0$. Uma mudança na demanda final induz um aumento do produto principal para $x_* = (I - A)^{-1} f_*$, dessa forma o insumo primário adicional pode ser representado por $r_* = R(I - A)^{-1} f_*$, a demanda de energia adicional será $e_* = E(I - A)^{-1} f_*$, já os resíduos e sub-produtos gerados ficarão em $w_* = W(I - A)^{-1} f_*$. Com a sutil reorganização feita por Kuhtz et al. (2010) o modelo insumo produto de processo fica em um formato semelhante ao modelo de Leontief (1966), conforme apêndice D. Colocado dessa forma o modelo insumo-produto de processo serve mais aos propósitos de planejamento.

Diferentemente da matriz de desempenho direto, a matriz de desempenho indireto (coeficientes indiretos de energia) considera o consumo de todos os tipos de energia. Para manufaturar uma tonelada de telhas são gastas 222.100 kcal de energia elétrica (0.25 MWh), 1.041.429 kcal de energia térmica (1,21 MWh), 297.237 kcal de Óleo (0,35 MWh), 125.203 kcal de diesel (0,15 MWh) e 618.989 kcal de gás natural (0,72 MWh) (KUHTZ *et al*., 2010).

Tabela 6 - Coeficientes diretos e indiretos das entradas de energia

Coeficientes diretos de energia Matriz de desempenho direto						Coeficientes indiretos de energia Matriz de desempenho indireto					
$EDC = e_{ij} = \frac{E_{ij}}{X_j} = E\hat{X}^{-1}$						$EDCA^{-1}$					
	M	**N**	**O**	**P**	**Q**		**M**	**N**	**O**	**P**	**Q**
E	66.511	0	63.124	81.722	2.332	**E**	66.511	69.495	134.778	220.067	222.100
T	269.155	77.170	646.426	0	0	**T**	269.155	358.402	1.015.961	1.042.842	1.041.429
L	269.155	0	0	0	0	**L**	269.155	281.232	289.969	297.641	297.237
D	0	0	122.141	0	0	**D**	0	0	122.141	125.373	125.203
G	0	77.170	524.285	0	0	**G**	0	77170	603.851	619.829	618.989

Nota: M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; E - Eletricidade; T – Térmica; L – Óleo; D – Diesel; G - Gás natural

As pesquisas de Albino *et al*. (2004) e Kuhtz *et al*. (2010) apresentam apenas um conjunto de tabelas insumo-produto para os processos de manufatura de telhas (processos da Empresa Estendida). O problema é que para representar o modelo insumo-produto longitudinal são necessárias mais de uma tabela, em períodos de tempo diferentes. Para gerar os dados em diferentes períodos de tempo foi elaborada uma abordagem de simulação, apresentada na Figura 16.

A abordagem de simulação da Figura 16, desenvolvida no R[12], gera os dados para operacionalizar os indicadores das Equações 4 a 7 (JONES *et al*., 2009). Ela funciona em quatro etapas: (a) geração dos dados insumo-produto; (b) cálculo dos indicadores das Equações (4 a 7); (c) construção do painel de indicadores; (d) visualização multidimensional dos indicadores.

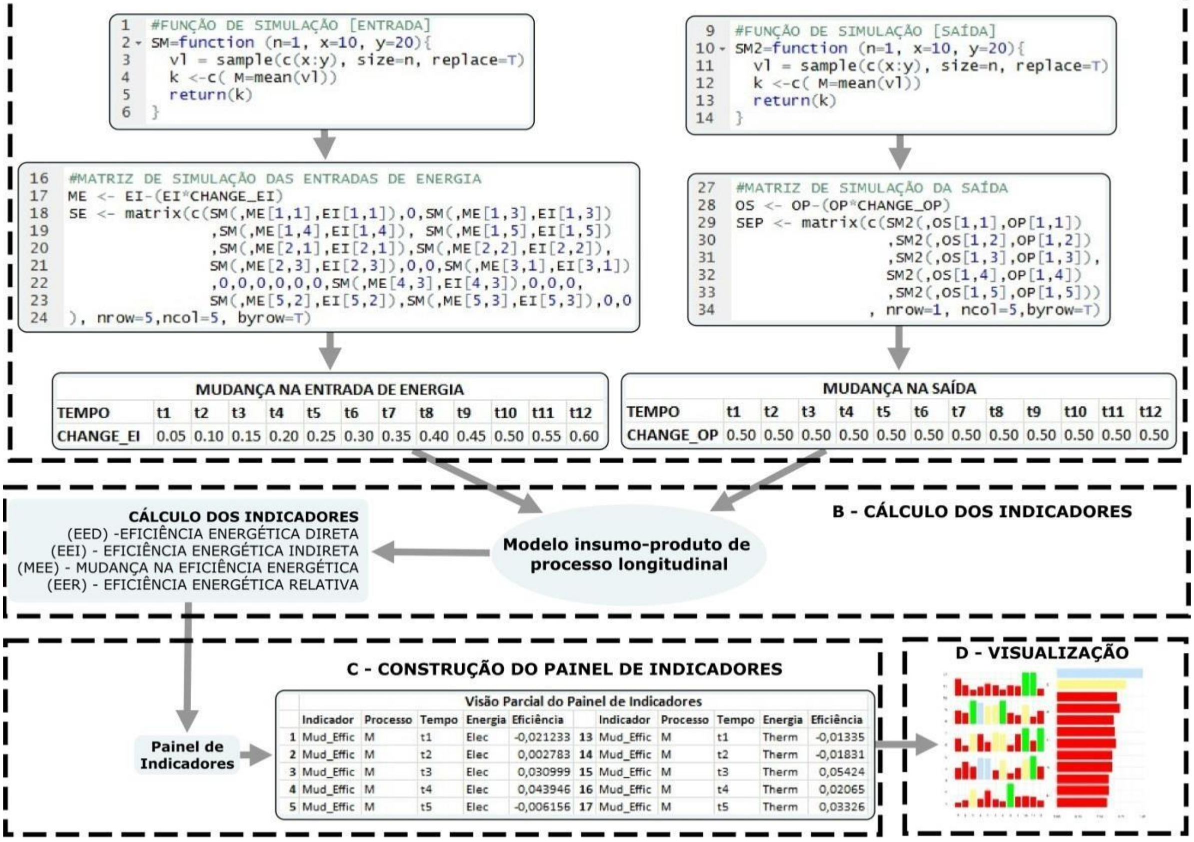
O ponto de partida para a geração dos dados insumo-produto vem dos processos da Tabela 4, mantendo a mesma estrutura da saída (matriz de simulação das saídas na Figura 16) e a mesma de energia (matriz de simulação de energia na Figura 16). A função de simulação tem o papel de gerar números aleatórios entre os valores reais do consumo de energia e produção de telhas da Tabela 6, e um segundo valor estabelecido por uma taxa de mudança, (ME=EI-EI*CHANGE_EI) em que: ME - é a nova matriz de energia, EI - é a original, CHANGE_EI - é uma taxa de mudança, e a mudança na saída (OS=OP-OP*CHANGE_OP)

---

[12] https://www.r-project.org

em que: OS - é o novo vetor de produção, OP - é o original e CHANGE_OP - é a taxa de mudança.

Figura 16 - Abordagem de simulação da estrutura do modelo insumo-produto de processos longitudinal



```r
#FUNÇÃO DE SIMULAÇÃO [ENTRADA]
SM=function (n=1, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))
  return(k)
}
```

```r
#FUNÇÃO DE SIMULAÇÃO [SAÍDA]
SM2=function (n=1, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))
  return(k)
}
```

```r
#MATRIZ DE SIMULAÇÃO DAS ENTRADAS DE ENERGIA
ME <- EI-(EI*CHANGE_EI)
SE <- matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3])
                ,SM(,ME[1,4],EI[1,4]), SM(,ME[1,5],EI[1,5])
                ,SM(,ME[2,1],EI[2,1]),SM(,ME[2,2],EI[2,2]),
                SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1])
                ,0,0,0,0,0,0,SM(,ME[4,3],EI[4,3]),0,0,0,
                SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0
), nrow=5,ncol=5, byrow=T)
```

```r
#MATRIZ DE SIMULAÇÃO DA SAÍDA
OS <- OP-(OP*CHANGE_OP)
SEP <- matrix(c(SM2(,OS[1,1],OP[1,1])
                ,SM2(,OS[1,2],OP[1,2])
                ,SM2(,OS[1,3],OP[1,3]),
                SM2(,OS[1,4],OP[1,4])
                ,SM2(,OS[1,5],OP[1,5]))
              , nrow=1, ncol=5,byrow=T)
```

MUDANÇA NA ENTRADA DE ENERGIA

TEMPO	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
CHANGE_EI	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60

MUDANÇA NA SAÍDA

TEMPO	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
CHANGE_OP	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Visão Parcial do Painel de Indicadores

	Indicador	Processo	Tempo	Energia	Eficiência		Indicador	Processo	Tempo	Energia	Eficiência
1	Mud_Effic	M	t1	Elec	-0,021233	13	Mud_Effic	M	t1	Therm	-0,01335
2	Mud_Effic	M	t2	Elec	0,002783	14	Mud_Effic	M	t2	Therm	-0,01831
3	Mud_Effic	M	t3	Elec	0,030999	15	Mud_Effic	M	t3	Therm	0,05424
4	Mud_Effic	M	t4	Elec	0,043946	16	Mud_Effic	M	t4	Therm	0,02065
5	Mud_Effic	M	t5	Elec	-0,006156	17	Mud_Effic	M	t5	Therm	0,03326

Fonte Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: No Apêndice B encontra-se a codificação R para a abordagem de simulação e no apêndice C o exemplo do painel de indicadores.

Para fins de testes dos indicadores, a abordagem de simulação, da Figura 16, presumiu uma redução no consumo de energia que pode variar de 0% a 5% para cada trimestre, ao longo de 12 trimestres (3 anos). Nesse sistema as saídas (toneladas de telhas) também podem ser reduzidas de 0% a 50% em todos os períodos. Quando o valor de (*n*), na função de simulação, assume o valor 1 (um) os dados de energia e produção assumem qualquer valor entre x e y, ou seja, entre os valores de energia e produção reais da Tabela 4 e um segundo valor determinado pela taxa de mudança (CHANG_EI, CHANGE_OP). Quando o valor de (*n*) assume um valor grande (por exemplo, 10.000.000) os dados gerados tendem a uma medida central (média). Esta constatação é sustentada pelo Teorema do Limite Central (JONES *et al*., 2009; ROBERT; CASELLA, 2010).

Aplicando os princípios do Teorema do Limite Central a interpretação para a aboradagem de similação pode ser feita da seguinte forma: quando o valor de (*n*) na função de simulação das entradas (energia) e saída [*output*] tender ao infinito, ocorrerá variação (redução crescente) apenas nas entradas de energia, sendo a variação (redução) máxima acumulada próxima de 30% no último trimestre (12) e a variação (redução) mínima de 2,5% no primeiro trimestre (1). Nessa condição as saídas (toneladas de telhas) permanecerão constantes. A partir dessa propriedade estatística do Teorema, será possível testar a capacidade dos indicadores, desenvolvidos na seção anterior, de representar a evolução contínua do desempenho energético.

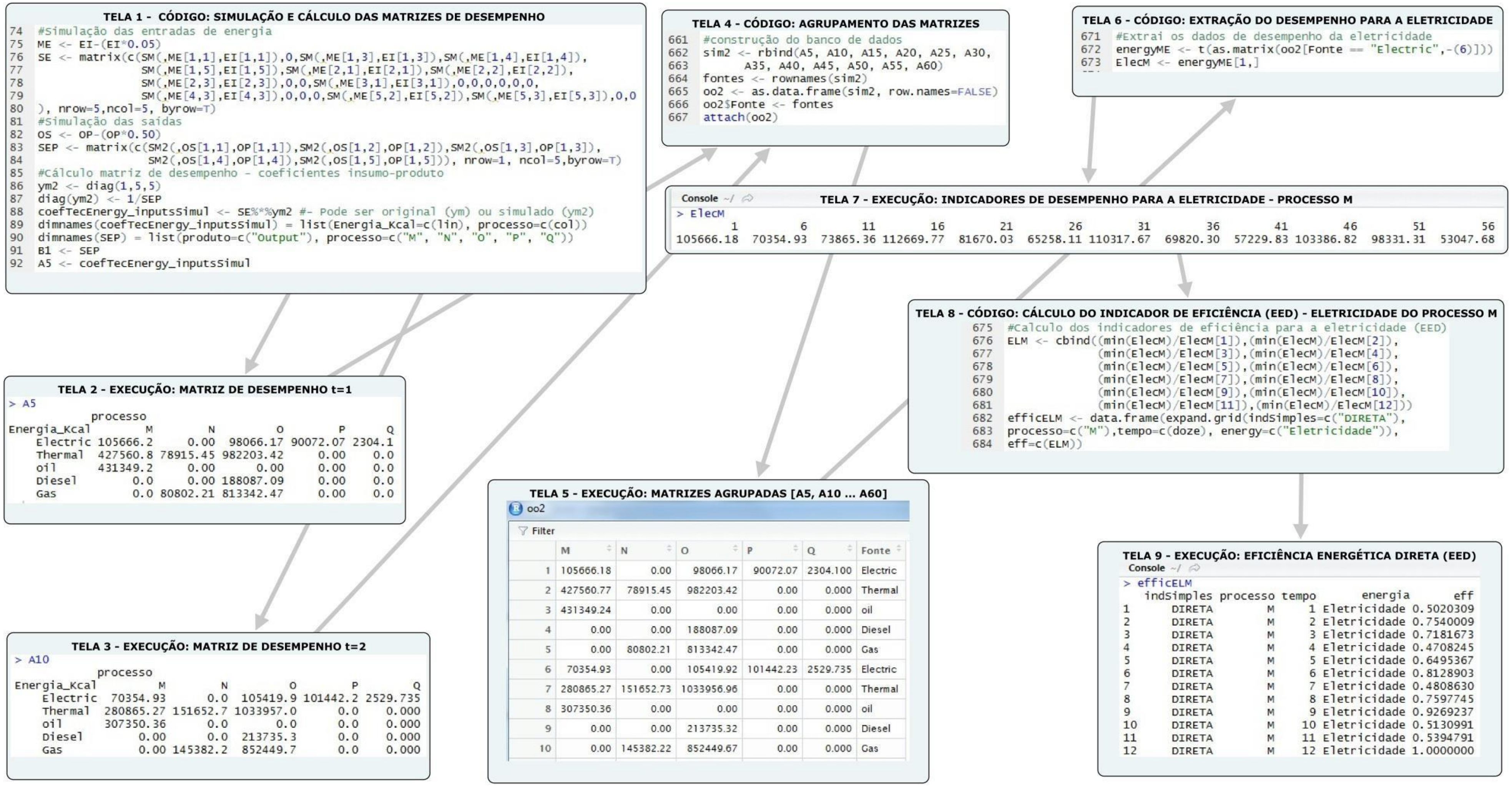
O período de tempo em casos reais dependerá dos processos em análise, não podendo ser menor do que a duração necessária para se concretizar o ciclo de produção (Figura 14(A)). Concluída essa regra, o período pode ser representado por semanas, meses, trimestres, entre outros.

O propósito da simulação não é fazer previsões, mas gerar os dados para representar o modelo insumo-produto longitudinal. O valor final de melhoria, adotado de 30% em 12 trimestres (3 anos), não está fora dos padrões do que a revisão sistemática da literatura tem encontrado para a eficiência energética industrial. Segundo Caffal (1995), as indústrias que adotarem práticas de gestão de energia podem poupar até 40% do consumo total. De acordo com Gordic et al. (2010), uma Indústria Automobilística, no período 2005-2008, obteve uma redução de 25% no consumo de energia, Alkaya e Demirer (2014) mencionam que em uma fábrica têxtil a poupança de Gás Natural foi de 20%.

O Apêndice A, na Tabela A2 apresenta uma lista com 127 medidas (EEMs) e tecnologias (EETs) em eficiência energética, recomendadas e implementadas no setor cerâmico. Tendo como exemplo as medidas reais, que podem contribuir com o caso de melhoria, simulado para a fábrica de telhas, é possível citar as três mais implementadas: (i) iluminação mais eficiente; (ii) uso de motores elétricos mais eficientes; (iii) eliminação de vazamentos de ar comprimido.

A Figura 16 não mostra como a abordagem de simulação funciona na prática. Por outro lado, a Figura 17 expõe o fluxo de execução da abordagem de simulação, desde a simulação até o cálculo do indicador; apresentando como exemplo a Eficiência Energética Direta (EED). A Tela 1 mostra o código para a simulação, além do procedimento em R equivalente a equação ($E\hat{X}^{-1}$) para o cálculo da matriz de desempenho (coeficientes diretos de energia). As Telas 2 e 3 apresentam as matrizes de desempenho (coeficientes diretos de energia) para os dois primeiros trimestres. Estes coeficientes representam o conteúdo energético, ou seja, a energia por unidade de produção.

Figura 17 - Fluxo de execução da abordagem de simulação



TELA 1 - CÓDIGO: SIMULAÇÃO E CÁLCULO DAS MATRIZES DE DESEMPENHO

```r
#Simulação das entradas de energia
ME <- EI-(EI*0.05)
SE <- matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),
               SM(,ME[1,5],EI[1,5]),SM(,ME[2,1],EI[2,1]),SM(,ME[2,2],EI[2,2]),
               SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0,0,0,
               SM(,ME[4,3],EI[4,3]),0,0,0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0
), nrow=5,ncol=5, byrow=T)
#Simulação das saídas
OS <- OP-(OP*0.50)
SEP <- matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),
                SM2(,OS[1,4],OP[1,4]),SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
#Cálculo matriz de desempenho - coeficientes insumo-produto
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"), processo=c("M", "N", "O", "P", "Q"))
B1 <- SEP
A5 <- coefTecEnergy_inputsSimul
```

TELA 2 - EXECUÇÃO: MATRIZ DE DESEMPENHO t=1

```
> A5
            processo
Energia_Kcal        M        N         O        P      Q
    Electric 105666.2     0.00  98066.17 90072.07 2304.1
    Thermal  427560.8 78915.45 982203.42     0.00    0.0
    oil      431349.2     0.00      0.00     0.00    0.0
    Diesel        0.0     0.00 188087.09     0.00    0.0
    Gas           0.0 80802.21 813342.47     0.00    0.0
```

TELA 3 - EXECUÇÃO: MATRIZ DE DESEMPENHO t=2

```
> A10
            processo
Energia_Kcal         M        N         O        P        Q
    Electric  70354.93      0.0  105419.9 101442.2 2529.735
    Thermal  280865.27 151652.7 1033957.0      0.0    0.000
    oil      307350.36      0.0       0.0      0.0    0.000
    Diesel        0.00      0.0  213735.3      0.0    0.000
    Gas           0.00 145382.2  852449.7      0.0    0.000
```

TELA 4 - CÓDIGO: AGRUPAMENTO DAS MATRIZES

```r
#construção do banco de dados
sim2 <- rbind(A5, A10, A15, A20, A25, A30,
      A35, A40, A45, A50, A55, A60)
fontes <- rownames(sim2)
oo2 <- as.data.frame(sim2, row.names=FALSE)
oo2$Fonte <- fontes
attach(oo2)
```

TELA 5 - EXECUÇÃO: MATRIZES AGRUPADAS [A5, A10 ... A60]

oo2

Filter

	M	N	O	P	Q	Fonte
1	105666.18	0.00	98066.17	90072.07	2304.100	Electric
2	427560.77	78915.45	982203.42	0.00	0.000	Thermal
3	431349.24	0.00	0.00	0.00	0.000	oil
4	0.00	0.00	188087.09	0.00	0.000	Diesel
5	0.00	80802.21	813342.47	0.00	0.000	Gas
6	70354.93	0.00	105419.92	101442.23	2529.735	Electric
7	280865.27	151652.73	1033956.96	0.00	0.000	Thermal
8	307350.36	0.00	0.00	0.00	0.000	oil
9	0.00	0.00	213735.32	0.00	0.000	Diesel
10	0.00	145382.22	852449.67	0.00	0.000	Gas

TELA 6 - CÓDIGO: EXTRAÇÃO DO DESEMPENHO PARA A ELETRICIDADE

```r
#Extrai os dados de desempenho da eletricidade
energyME <- t(as.matrix(oo2[Fonte == "Electric",-(6)]))
ElecM <- energyME[1,]
```

TELA 7 - EXECUÇÃO: INDICADORES DE DESEMPENHO PARA A ELETRICIDADE - PROCESSO M

```
> ElecM
        1         6        11        16        21        26        31        36        41        46        51        56
105666.18  70354.93  73865.36 112669.77  81670.03  65258.11 110317.67  69820.30  57229.83 103386.82  98331.31  53047.68
```

TELA 8 - CÓDIGO: CÁLCULO DO INDICADOR DE EFICIÊNCIA (EED) - ELETRICIDADE DO PROCESSO M

```r
#Calculo dos indicadores de eficiência para a eletricidade (EED)
ELM <- cbind((min(ElecM)/ElecM[1]),(min(ElecM)/ElecM[2]),
              (min(ElecM)/ElecM[3]),(min(ElecM)/ElecM[4]),
              (min(ElecM)/ElecM[5]),(min(ElecM)/ElecM[6]),
              (min(ElecM)/ElecM[7]),(min(ElecM)/ElecM[8]),
              (min(ElecM)/ElecM[9]),(min(ElecM)/ElecM[10]),
              (min(ElecM)/ElecM[11]),(min(ElecM)/ElecM[12]))
efficELM <- data.frame(expand.grid(indSimples=c("DIRETA"),
processo=c("M"),tempo=c(doze), energy=c("Eletricidade")),
eff=c(ELM))
```

TELA 9 - EXECUÇÃO: EFICIÊNCIA ENERGÉTICA DIRETA (EED)

```
> efficELM
   indSimples processo tempo      energia       eff
1      DIRETA        M     1 Eletricidade 0.5020309
2      DIRETA        M     2 Eletricidade 0.7540009
3      DIRETA        M     3 Eletricidade 0.7181673
4      DIRETA        M     4 Eletricidade 0.4708245
5      DIRETA        M     5 Eletricidade 0.6495367
6      DIRETA        M     6 Eletricidade 0.8128903
7      DIRETA        M     7 Eletricidade 0.4808630
8      DIRETA        M     8 Eletricidade 0.7597745
9      DIRETA        M     9 Eletricidade 0.9269237
10     DIRETA        M    10 Eletricidade 0.5130991
11     DIRETA        M    11 Eletricidade 0.5394791
12     DIRETA        M    12 Eletricidade 1.0000000
```

Fonte: o autor, 2016; Apêndice B.

Nota: (a) Fluxo de execução do código para o cálculo da Eficiência Energética Direta (EED) para a Eletricidade consumida no Processo M (Mistura) ; (b) A Tela 9 faz parte do Painel de Indicadores apresentado no Apêndice C.

As Telas 4 e 5 mostram o código e a execução parcial (2 trimestres) para os agrupamentos das matrizes de desempenho nos 12 trimestres, gravados em um banco de dados do R. A Tela 6 exibe o código para a extração do desempenho energético da eletricidade no processo M, enquanto a Tela 7 apresenta o indicador de desempenho propriamente dito, que é o conteúdo energético ou o consumo específico de energia, nos 12 trimestres. A variação do indicador de desempenho deve-se ao fato de nesse exemplo ser adotado o valor igual a um (1), na função de simulação da Figura 16.

As Telas 8 e 9 expõem o código e a execução do indicador de Eficiência Energética Direta (EED). A Tabela 7 mostra, com mais detalhes, os cálculos finais para o indicador EED.

Tabela 7 - Eficiência Energética Direta (EED) e Ineficiência (Processo M)

$Tempo$	$Eficiência - EED$	$Ineficiência$	$Eficiência + Ineficiência$
1	$53047{,}68/105666{,}18 = \mathbf{0,502}$	$(105666{,}18 - 53047{,}68)/105666{,}18 = \mathbf{0,498}$	**1**
2	$53047{,}68/70354{,}93 = \mathbf{0,754}$	$(70354{,}93 - 53047{,}68)/70354{,}93 = \mathbf{0,246}$	**1**
3	$53047{,}68/73865{,}36 = \mathbf{0,718}$	$(73865{,}36 - 53047{,}68)/73865{,}36 = \mathbf{0,282}$	**1**
4	$53047{,}68/112669{,}77 = \mathbf{0,471}$	$(112669{,}77 - 53047{,}68)/112669{,}77 = \mathbf{0,529}$	**1**
5	$53047{,}68/81670{,}03 = \mathbf{0,650}$	$(81670{,}03 - 53047{,}68)/81670{,}03 = \mathbf{0,350}$	**1**
6	$53047{,}68/65258{,}11 = \mathbf{0,813}$	$(65258{,}11 - 53047{,}68)/65258{,}11 = \mathbf{0,187}$	**1**
7	$53047{,}68/110317{,}67 = \mathbf{0,481}$	$(110317{,}67 - 53047{,}68)/110317{,}67 = \mathbf{0,519}$	**1**
8	$53047{,}68/69820{,}3 = \mathbf{0,760}$	$(69820{,}3 - 53047{,}68)/69820{,}3 = \mathbf{0,240}$	**1**
9	$53047{,}68/57229{,}83 = \mathbf{0,927}$	$(57229{,}83 - 53047{,}68)/57229{,}83 = \mathbf{0,073}$	**1**
10	$53047{,}68/103386{,}82 = \mathbf{0,513}$	$(103386{,}82 - 53047{,}68)/103386{,}82 = \mathbf{0,487}$	**1**
11	$53047{,}68/98331{,}31 = \mathbf{0,539}$	$(98331{,}31 - 53047{,}68)/98331{,}31 = \mathbf{0,461}$	**1**
12	$53047{,}68/53047{,}68 = \mathbf{1}$	$(53047{,}68 - 53047{,}68)/53047{,}688 = \mathbf{0,00}$	**1**

Fonte: O autor, 2016
Nota: Indicadores cálculos via abordagem de simulação conforme Tela 9 da Figura 17.

Observa-se na Tabela 7 que o indicador atende as propriedades das Equações 1 e 2, uma vez que, a eficiência pode ser obtida fazendo a operação: $eficiência = 1 - ineficiência.$

Os outros indicadores criados nas Equações 5, 6 e 7 seguem o mesmo fluxo da Figura 17. Eles foram calculados a partir das matrizes de desempenho, geradas na Tela 5. O cálculo na Mudança da Eficiência Energética (MEE) é similar ao apresentado na Tabela 7, comparando o desempenho do trimestre atual com o do trimestre anterior. A operacionalização da Eficiência Energética Indireta (EEI) é exatamente igual ao fluxo da Figura 17, mas utilizando a matriz de desempenho energético indireto (coeficientes indiretos de energia), semelhante aos apresentados na Tabela 6. A determinação da Eficiência Energética Relativa (EER) foi feita pelo modelo envelope utilizando o R (BOGETOFT; OTTO, 2014). O artigo do Apêndice K é mais detalhado em relação ao cálculo da Eficiência Energética Relativa (PERRONI *et al.*, 2016c). O trabalho de Zhu (2014) apresenta, de maneira didática, diversas formas para calcular a eficiência relativa, utilizando planilhas eletrônicas tanto do modelo envelope quanto do modelo multiplicador da Equação 7.

5.3 ABORDAGEM PARA VISUALIZAÇÃO MULTIDIMENSIONAL DOS INDICADORES DESENVOLVIDOS

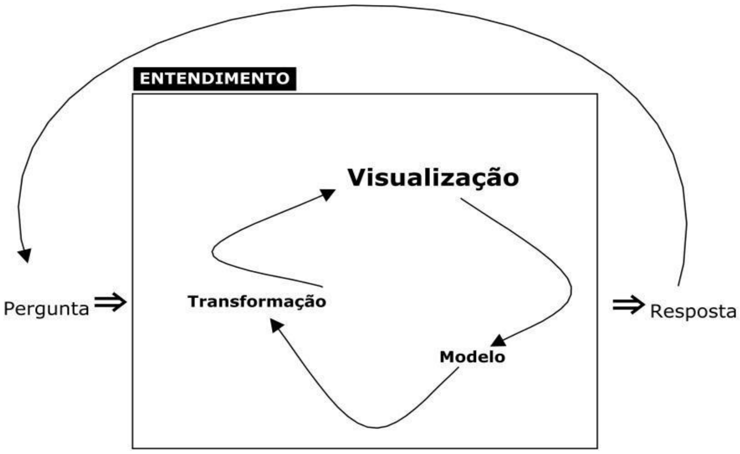
O último objetivo específico desta tese está relacionado em como fazer a análise das informações geradas por meio da abordagem de processos, para verificar a existência da melhoria do sistema ou não, dada a adoção de estratégias de poupança de energia, que pode ser realizada implementando medidas e tecnologias, algumas delas apresentadas no Apêndice A. A função da análise é testar o sucesso da implementação da estratégia de poupança de energia (BITITCI *et al.*, 2000; GORDIC *et al.*, 2010).

A análise de dados pode ser interpretada como um conjunto de procedimentos para construir o entendimento, assemelhando-se ao processo cognitivo conhecido como *sensemaking*, ou seja, procura por significado (GROLEMUND, 2012; GROLEMUND; WICKHAM, 2014b). Com os avanços das tecnologias de informação, a operacionalização da análise pode ser feita por softwares computacionais específicos. A visualização merece destaque, dado à quantidade de indicadores que podem ser criados com o modelo insumo-produto de processos longitudinal. A informação visual impõe menor carga cognitiva à memória do indivíduo do que uma informação não visual, facilitando a interpretação (WICKHAM, 2011; GROLEMUND; WICKHAM, 2014a). O relacionamento entre o modelo e visualização pode ser observado na Figura 18. A preparação dos dados para a visualização exige operações de transformações. Essas operações podem ser técnicas específicas para organizar as informações, como a criação do painel de indicadores na Figura 16 (WICKHAM, 2015).

O painel de indicadores da abordagem de simulação na Figura 16 é uma forma de organizar os dados para que sejam visualizados. A visualização contribui para o entendimento, uma vez que a grande quantidade de informações pode prejudicá-lo. O entendimento, de acordo com o contexto desta pesquisa, refere-se à avaliação da estratégia de poupança de energia (resultado da implementação de medidas e tecnologias (EEMs e EETs)).

Considerando 12 períodos na simulação e tendo como base a estrutura da Tabela 4, é possível criar 132 indicadores apenas para a eficiência energética direta (Equação 4). Duas técnicas capazes de fazer a visualização múltipla do modelo insumo-produto de processo longitudinal são: Gramática dos Gráficos em Camadas [*Layered Grammar of Graphics*] (WICKHAM, 2009, 2011) e *Framework* de Plotagem Estrutural [*Strucplot Framework*] (FRIENDLY 1994; MEYER *et al*., 2006).

Figura 18 - Ciclo da análise de dados



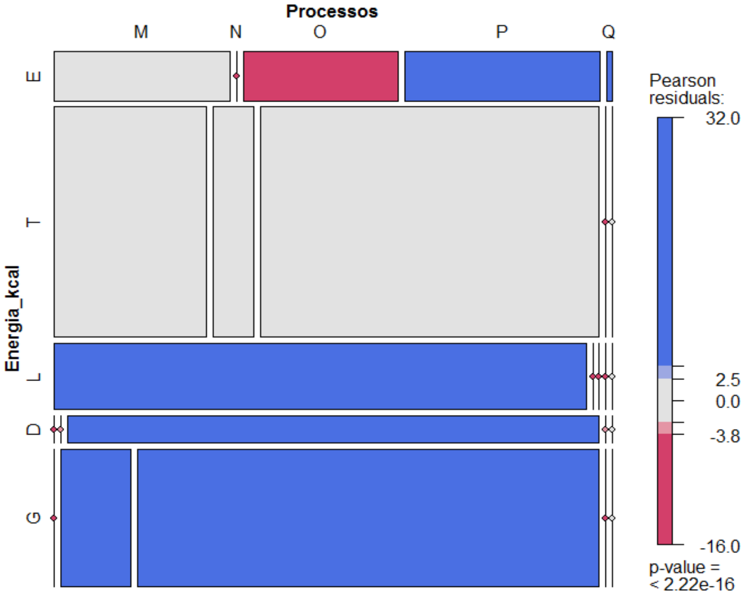
Fonte: Wickham (2011)

De acordo com a gramática dos gráficos, a palavra gráfico significa mapeamento de dados, utilizando-se de atributos estéticos (cor, forma, tamanho, entre outros) de objetos geométricos (barra, ponto, linha, entre outros). Ele é um mapeamento abstrato para a visualização dos dados, na qual uma série de componentes pode ser combinada para produzir imagens úteis (WICKHAM, 2009; GROLEMUND, 2012). A abordagem de plotagem estrutural foi criada para visualizar tabelas de contingência de múltiplas entradas [*multi-way contingency tables*], na qual a principal visualização é o gráfico mosaico. O gráfico mosaico é composto por uma série de retângulos que representam, proporcionalmente, cada célula de uma matriz de dados (FRIENDLY 1994; MEYER *et al*., 2006).

O processo de visualização é importante para o monitoramento do desempenho energético, identificando o resultado de possíveis ações de melhoria por meio da gestão de energia, envolvendo a implementação das medidas e tecnologias (EEMs e EETs). Entre outros fatores, a revisão da literatura realizada por Bunse *et al*. (2011) identificou a falta de mecanismos de visualização computacional para a representação dos indicadores. Conforme identificado por Wee *et al*. (2012), devido a uma futura decadência dos recursos energéticos tradicionais como petróleo, carvão e gás natural, as fontes renováveis como: biomassa, geotérmica, vento e solar tenderão a crescer na matriz energética da Empresa Estendida. Um sistema de visualização ajudará na comparação estrutural, identificando as mudanças da matriz energética da Empresa Estendida (EE). A visualização será útil para acompanhar a evolução dos indicadores dos processos da Empresa Estendida no modelo longitudinal.

O Gráfico 9 representa a matriz de energia da Tabela 4. Os comprimentos horizontais dos retângulos medem a participação do consumo de energia nos processos, e o comprimento vertical a participação das fontes energéticas. As linhas no Gráfico 9 demonstram que o processo não consome a energia específica.

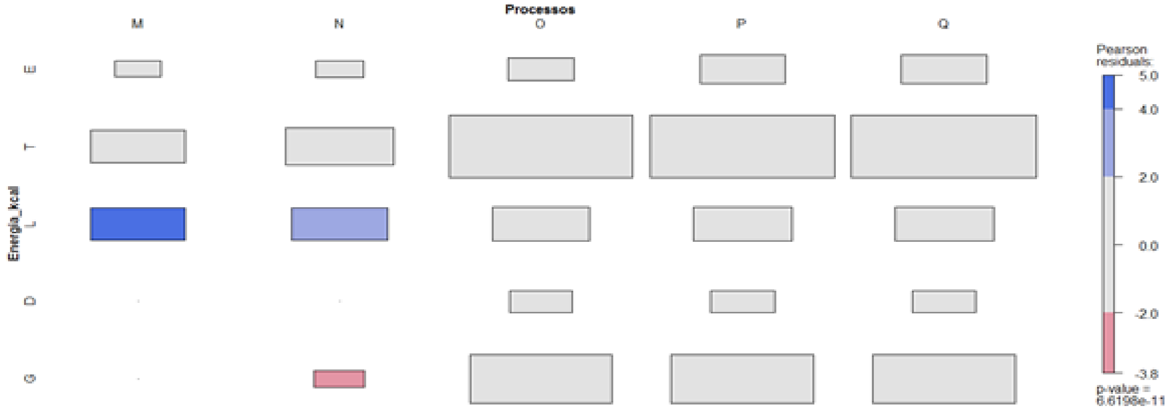
Gráfico 9 - Matriz de Energia



Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: (a) M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; E - Eletricidade; T – Térmica; L – Óleo; D – Diesel; G - Gás natural; (b) Produzido no pacote *vcd: Visualizing Categorical Data* do R, versão 1.4-1. Meyer *et al*. 2006.

O Gráfico 10 é um mosaico construído com a técnica [*tile plot*] (MEYER *et al*., 2006), utilizando os dados da matriz de desempenho indireto (coeficientes indiretos da Tabela 6, $EDCA^{-1}$ da representação matemática 14(B)). Ele revela a absorção direta e indireta de energia pelos processos, em outras palavras, o fluxo unitário de energia (desempenho/conteúdo energético até o processo sob análise), sendo os retângulos do processo Q (embalagem) proporcionais ao conteúdo energético unitário total da Empresa Estendida (ALBINO *et al*., 2002).

Gráfico 10 - Fluxo de Energia



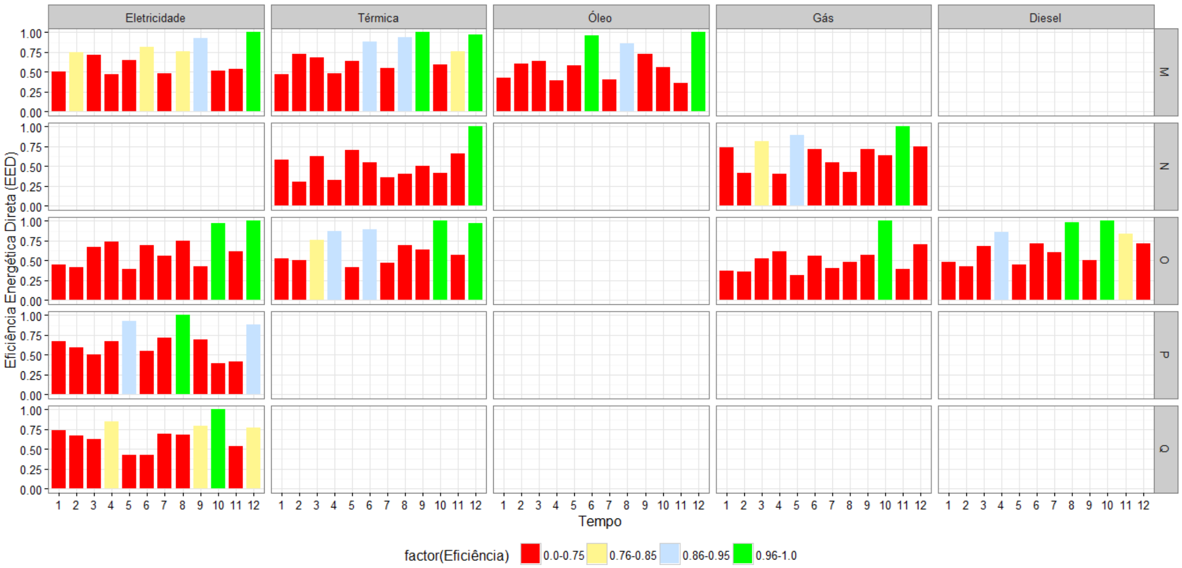
Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: (a) M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; E - Eletricidade; T – Térmica; L – Óleo; D – Diesel; G - Gás natural; (b) Produzido no pacote *vcd: Visualizing Categorical Data* do R, versão 1.4-1. Meyer *et al*. 2006.

As cores dos Gráficos 9 e 10 representam o consumo de energia: azul (acima do esperado) e vermelha (abaixo do esperado). As cores precisam ser analisadas com cuidado, uma vez que, não se pode comparar diretamente a energia gasta no processo de Embalagem (Q) com a energia gasta no processo de Queima (O), porque são processos independentes na utilização de energia. É possível interpretar as cores como processos que utilizam mais ou menos energia do ponto de vista relativo, ou seja, levando em conta tanto os processos como as fontes energéticas.

Os Gráficos 11 ao 15 foram elaborados com base no princípio da gramática dos gráficos (WICKHAM, 2009; GROLEMUND, 2012). O Gráfico 11 apresenta o painel do indicador de eficiência energética direta (Equação 4, EED), representando um total de 132 indicadores de eficiência, considerando todos os processos e fontes energéticas. Os valores do indicador EED da eletricidade no processo de Mistura (M) foram apresentados na Figura 17 e Tabela 7.

Esse mesmo gráfico teria potencial para representar 300 indicadores, uma vez que os espaços em branco indicam que o processo não consome a fonte de energia específica. As cores podem ser programadas para mostrar uma escala de eficiência, sendo os períodos menos eficientes (vermelha) ou mais eficientes (verde). A possibilidade de comparação entre os indicadores vem do fato de que os indicadores criados são adimensionais, estando no intervalo entre (0 e 1) como é de praxe nos indicadores de eficiência.

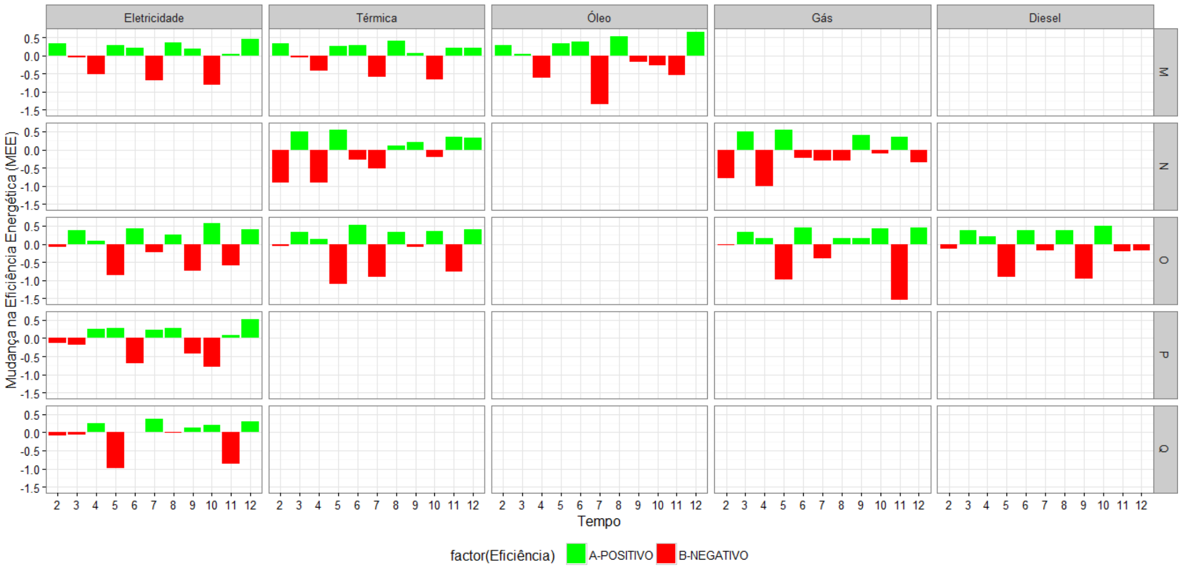
Gráfico 11 - Eficiência Energética Direta



Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: (a) M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; (b) (n=1) na função de simulação da Figura 16; (c) Simulação considerando um período de 12 trimestres; (d) Produzido no pacote *ggplot2* do R, Wickham, 2009.

O Gráfico 12 representa a mudança na eficiência energética em relação ao Gráfico 11 (Equação 5, MEE), tornando-se mais fácil visualizar a evolução, ou seja, em quais momentos a eficiência aumentou ou teve queda.

Gráfico 12 - Mudança na Eficiência Energética

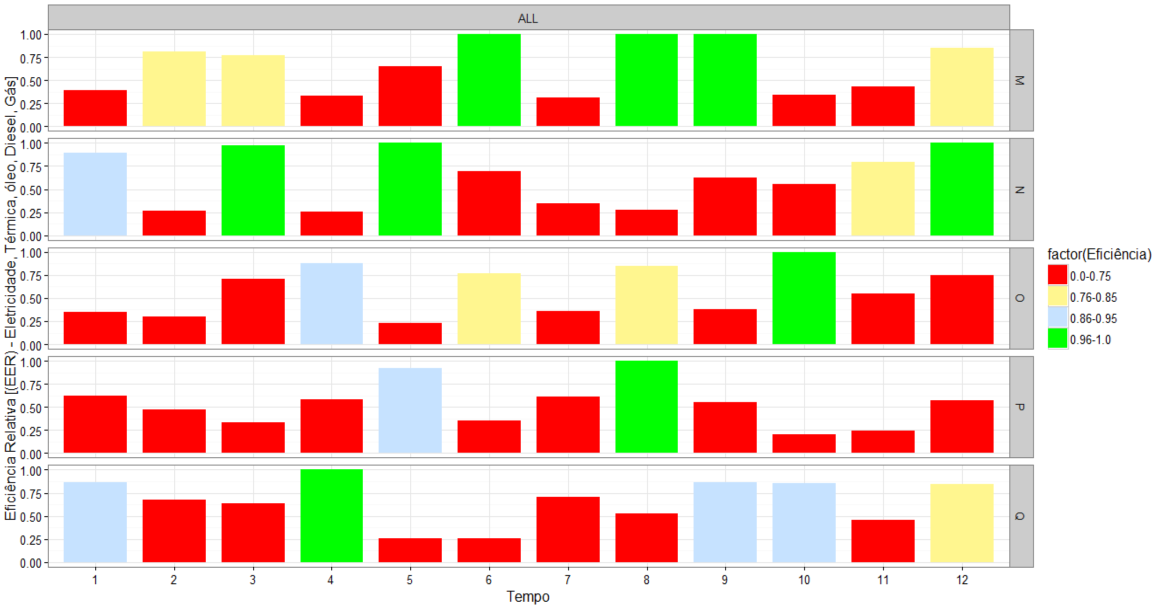


Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: (a) M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; (b) (n=1) na função de simulação da Figura 16; (c) Simulação considerando um período de 12 trimestres; (d) Produzido no pacote *ggplot2* do R, Wickham, 2009.

O Gráfico 13 mostra o cálculo do indicador de eficiência relativa (Equação 3, EER) empregando a técnica da análise envoltória de dados (DEA), assumindo retornos constantes de escala (CHARNES *et al*., 1978; BOGETOFT; OTTO; 2010; ZHU, 2014).

Comparando os Gráficos 11 e 13, a dimensão fontes energéticas (Eletricidade, Energia Térmica, Óleo, Diesel e Gás) desaparece, uma vez que é possível agregar diferentes entradas para o cálculo do indicador (PERRONI *et al*., 2016c). O DEA, representado no Gráfico 13, é considerado como uma análise de fronteira intertemporal, medindo a evolução da eficiência com relação às entradas de energia em períodos de tempo diferentes. Outras entradas (água, matéria prima, capacidade organizacional, subproduto, entre outras) poderiam ser consideradas, bem como outras saídas (resíduos, subprodutos, poluição sonora, entre outras) (ZHU, 2014).

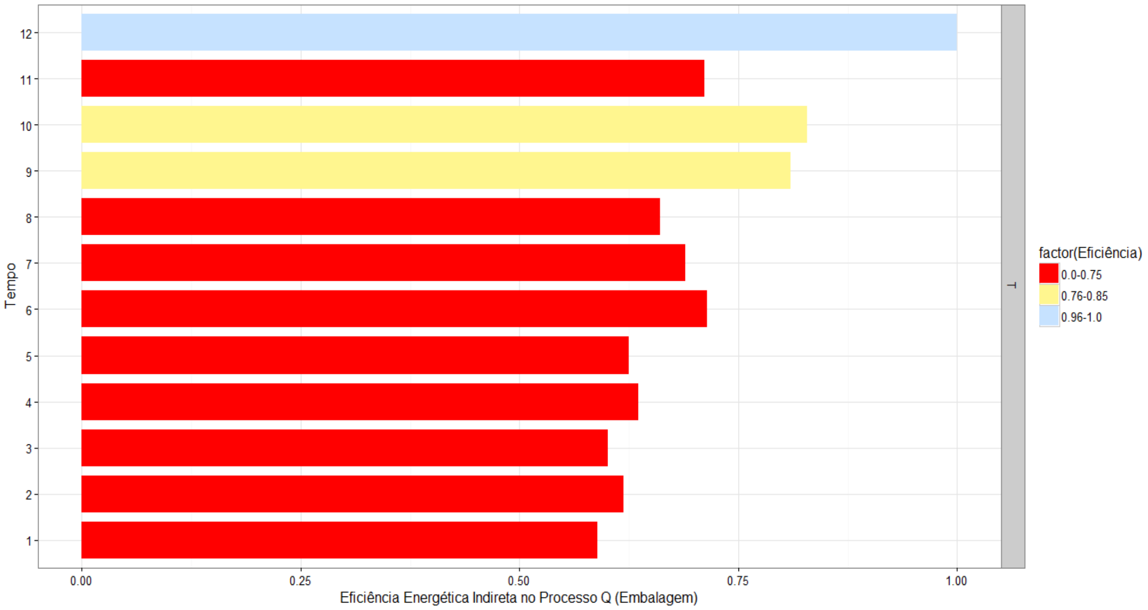
Gráfico 13 - Eficiência Relativa



Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: (a) M – Mistura; N – Secagem; O – Queima; P – Polimento; Q – Embalagem; (b) (n=1) na função de simulação da Figura 16; (c) Simulação considerando um período de 12 trimestres; (d) Produzido no pacote *ggplot2* e *Benchmarking* do R, Wickham, 2009; Bogetoft e Otto, 2014.

O Gráfico 14 foi denominado como Eficiência Global porque considera todas as fontes energéticas e todos os processos, restando a evolução da eficiência no tempo. O cálculo deste gráfico é feito por meio do indicador de eficiência indireta, ou seja, matriz de desempenho indireto (ver Equação 4 e Tabela 6) para o processo de Embalagem (Q).

Gráfico 14 - Eficiência Global

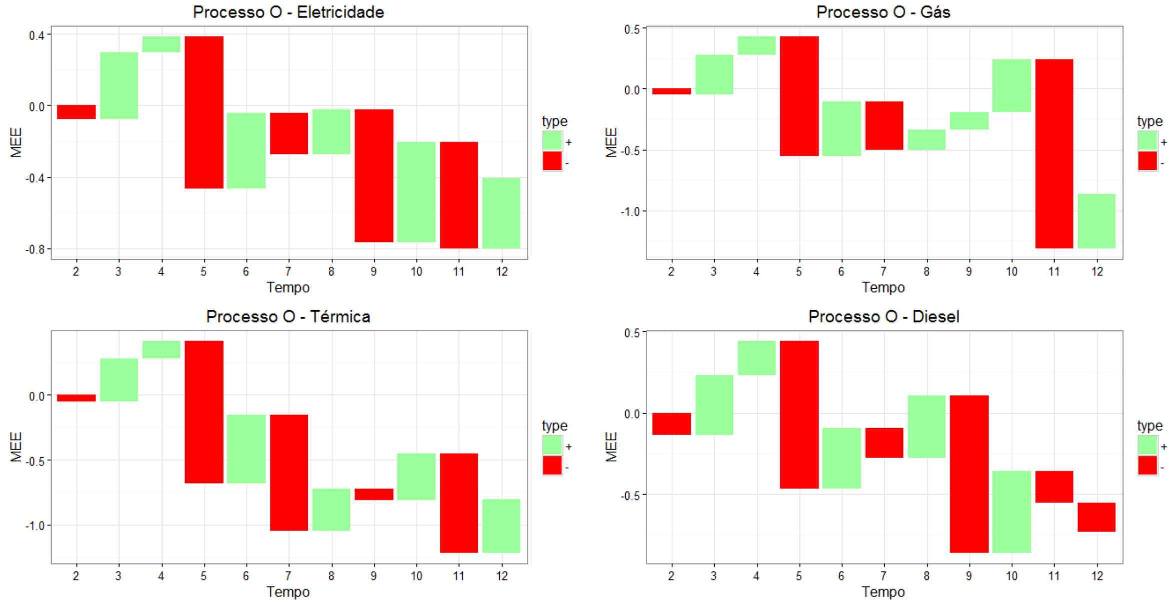


Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: *(*a) (n=1) na função de simulação da Figura 16*;* (b) Simulação considerando um período de 12 trimestres*;* (c) Produzido no pacote *ggplot2* do R, Wickham, 2009.

O Gráfico 15 mostra o indicador de mudança da eficiência energética direta (MEE) para o processo de Queima (O) utilizando a técnica *Waterfall Chart* (WICKHAM, 2011). Por meio deste gráfico é possível visualizar o caminho da aprendizagem, que por sua vez, é uma representação visual (Gráfico 15) que mostra todo um ciclo evolutivo, por meio de um indicador, podendo haver períodos de decréscimo ou acréscimo no indicador. Para que a aprendizagem seja de fato efetuada, espera-se que no final do período, o valor de chegada do indicador seja maior do que o valor de saída.

De acordo com os painéis de gráficos propostos é possível mencionar uma hierarquia de indicadores, baseado nas dimensões do painel de indicadores da Figura 16: fontes energéticas, processo e o tempo (ver Apêndice C). O Gráfico 11 representa os indicadores individuais para as fontes energéticas utilizadas em cada processo. No Gráfico 13 as fontes energéticas foram agregadas representando a evolução da eficiência dos processos. E no Gráfico 14 são consideradas a agregação das fontes energéticas e a energia total (direta mais indireta) consumida ao longo dos processos, incorporada no processo de Embalagem (Q), de modo que apenas a dimensão tempo está presente. Essa possibilidade existe porque os indicadores adimensionais das Equações (4 a 7) estão no intervalo (0,1).

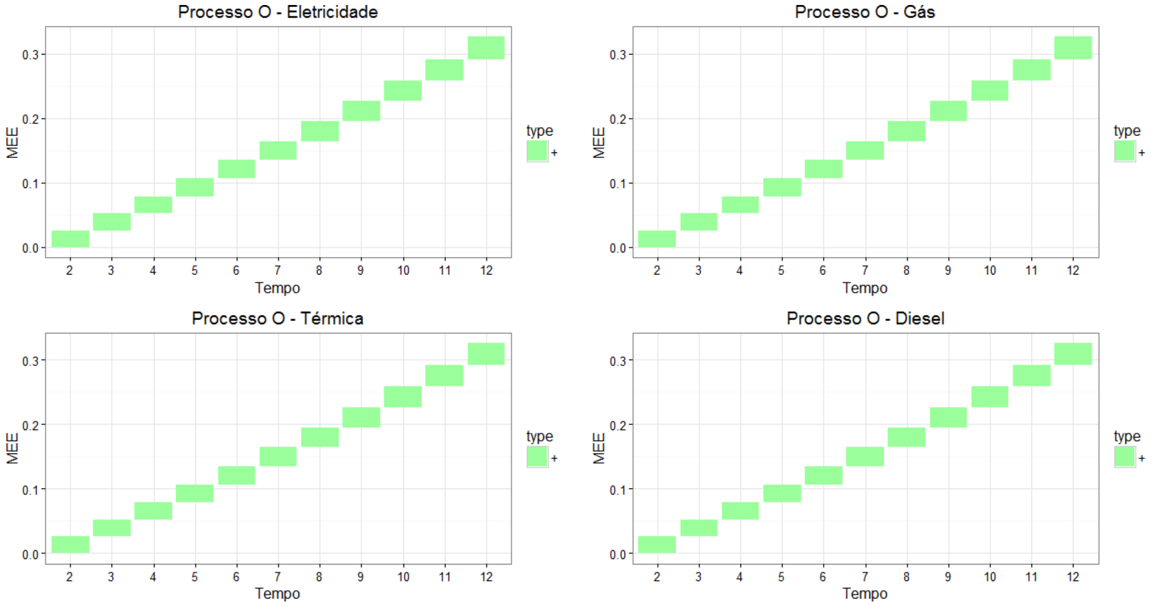
Gráfico 15 - Mudança na Eficiência Energética – Processo O



Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: *(*a) (n=1) na função de simulação da Figura 16*;* (b) Simulação considerando um período de 12 trimestres; (c) Produzido no pacote *ggplot2* do R, Wickham, 2009

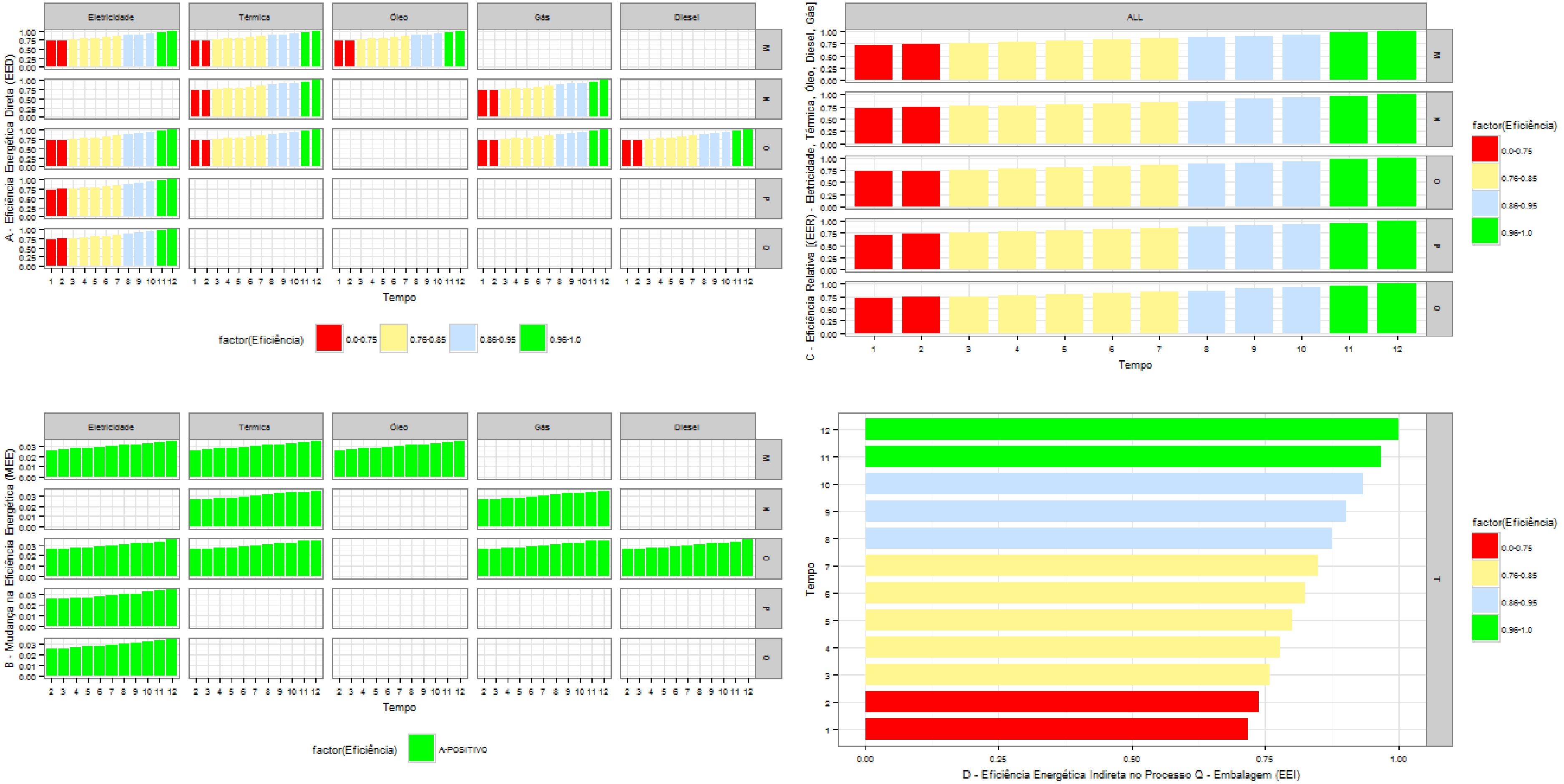
Os Gráficos 11 ao 15 assumem o valor de (*n*=1) na abordagem de simulação da Figura 15. A fim de comparação, os Gráfico 16 e 17 mostram o que acontece com os indicadores, quando o valor de (*n*), no modelo de simulação da Figura 16, assume um valor grande (*n=10.000.000*).

Gráfico 16 - Mudança na Eficiência Energética – Processo O (n=10 milhões)



Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.
Nota: *(*a) (n=10.000.000) na função de simulação da Figura 16*;* (b) Simulação considerando um período de 12 trimestres; (c) Produzido no pacote *ggplot2* do R, Wickham, 2009

Gráfico 17 - Convergência dos indicadores



Fonte: O autor, 2016; Perroni *et al.* 2016d ; Perroni *et al.* 2017- Apêndices L e M.

Nota: (a) (n=10.000.000) na função de simulação da Figura 16; (b) Produzido nos pacotes ggplot2 e *Benchmarking* do R, Wickham, 2009; Bogetoft e Otto, 2014.

Observa-se no Gráfico 16 que, quando o valor de (*n*) na função de simulação assume um valor grande, a mudança na eficiência (MEE) para o processo de Queima (O) é a mesma para todas as fontes energéticas, algo em torno de 30%. Esse fato ocorre devido ao Teorema do Limite Central explicado na seção anterior. Como o Gráfico 16 representa o caminho da aprendizagem, no último trimestre (12) o processo de Queima acumulou uma eficiência de aproximadamente 30% em todas as fontes energéticas.

No Gráfico 17 os valores de eficiência calculados convergem, tendo uma concordância de 100% entre os indicadores, com base na escala de cores, existindo uma concordância entre os indicadores em termos da evolução. Isso significa que todos os indicadores criados na seção 5.1 deste capítulo (EED, MEE, EEI, EER) terão no final do último trimestre (12) uma eficiência de aproximadamente 30%, se comportando de forma semelhante ao Gráfico 16. Dessa forma, pode-se confirmar que todos os indicadores criados capturam a evolução do desempenho energético, pois quando há uma queda nesse desempenho (Gráficos 11 ao 15), o sistema de painel de indicadores criados com a abordagem da gramática dos gráficos consegue capturar a mudança no desempenho (WICKHAM, 2009).

Se o número de processos sob análise aumentar, uma vez que não existe limite matemático para a quantidade, outra possibilidade para visualização seria por meio da análise de rede sociais, útil para representar o fluxo de energia entre os processos como a apresentada na Rede 6 (HANSEN, *et al*., 2011; PRELL, 2012).

6 CONCLUSÃO

Este capítulo tem por finalidade apresentar a conclusão da tese, por meio de quatro seções distintas: objetivos da tese; contribuição para a prática e a teoria; limitações da pesquisa e trabalhos futuros.

6.1 EM RELAÇÃO AOS OBJETIVOS DA TESE

Conforme o Quadro 1 e o mapa da Figura 3, o objetivo deste trabalho foi desenvolver uma abordagem de processos para a medição e controle do desempenho energético integrado. A terminologia - integrado - refere-se ao nível de agregação do desempenho por meio dos processos. Conforme o mesmo quadro e mapa, uma série de objetivos específicos foi estabelecida para a condução da pesquisa.

O primeiro objetivo específico, apresentado no segundo capítulo, analisou a importância do aspecto macro energético para a eficiência energética, contribuindo com a presente tese, de três formas diferentes: (i) melhor entendimento das fontes energéticas como pertencentes a um sistema complexo em evolução porque é influenciado por fatores políticos, tecnológicos, econômicos, culturais, além daqueles relacionados ao meio ambiente; (ii) entendimento da interdependência entre fatores agregados como a política energética e a eficiência energética; (iii) identificação do modelo insumo-produto como uma técnica para o planejamento energético; (iv) percepção do setor industrial, principalmente, a manufatura como relevante para o foco da pesquisa, tanto pelo uso considerável de energia quanto pelo seu impacto nos demais setores.

O segundo objetivo específico, apresentado no terceiro capítulo, identificou as principais contribuições teóricas e práticas para a medição do desempenho energético, no campo da eficiência energética industrial, aplicando uma revisão sistemática da literatura, cuja principal colaboração para a tese, já discutido no terceiro capítulo, foi à identificação de três grupos de autores: (i) gestão e eficiência energética; (ii) desempenho quantitativo; (iii) sustentabilidade envolvendo rede de firmas.

O grupo da gestão e eficiência discute a dinâmica do desempenho energético, identificando condições favoráveis ou não, para o desempenho energético. O grupo do desempenho quantitativo mostra maneiras diferentes de calcular ou estimar a eficiência energética. O grupo da sustentabilidade envolvendo rede de firmas, levanta a hipótese de o desempenho energético melhora se houver o envolvimento de vários participantes, devido à complexidade dos sistemas de energia e seus impactos no meio ambiente.

Os objetivos específicos estabelecidos no nível 3 do mapa da tese da Figura 3, apresentados no quarto capítulo, referem-se aos passos centrais para a resolução do objetivo principal. A construção metodológica da Figura 2, no primeiro capítulo, demonstra como problemas de pesquisa podem ser representados e abordados (SHEHABUDDEN, *et al.*, 1999). A representação do problema do desempenho energético foi feita pelo desenvolvimento de três construções indutivas, representadas nos objetivos específicos: (iii) *framework* que relaciona a dinâmica e a estrutura do desempenho energético de processos; (iv) mapa de indicadores da eficiência energética dos processos; (v) modelo que integra as construções representadas tanto no *framework* quanto no mapa. O modelo escolhido para representar o problema foi o de insumo-produto de processos (LIN; POLENSKE 1998, ALBINO *et al.*, 2003, KUHTZ *et al.* 2010).

O *framework* de processos da Figura 12(A) deixa explícito que a gestão do desempenho energético precisa ser planejada no nível estratégico (BITITCI *et al.*, 2000). É necessário salientar o fato de que, embora a literatura de energia reconheça à importância dessa constatação, na prática a gestão de energia não tem prioridade estratégica, mesmo nas empresas consideradas mais intensivas (ATES; DURKBASA, 2012; RUDBERG *et al.*, 2013).

O processo de melhoria contínua é sugerido pela própria literatura de gestão de energia (KANNAN; BOIE, 2003; GORDIC *et al.*, 2010; NEGAI et., 2013) devido à heterogeneidade dos processos, requerendo soluções em termos de *Energy Efficiency Measures* (EEMs) ou *Energy Efficient Technologies* (EETs) customizadas (ABDELAZIZ *et al.* 2011; VIKHOREV *et al.*, 2013) e também de questões externas particulares, dentre elas a existência ou não de fornecedores da tecnologia ou mesmo políticas de financiamento, entre outras (CAGNO *et al.*, 2013).

O *framework* estrutural do desempenho energético integrado da Figura 12(A)(B) foi suportado pela revisão sistemática de literatura em eficiência energética industrial. Em uma revisão sistemática da literatura recente em gestão de energia na indústria, Shulze *et al.* (2016) apresentam um *framework* de interpretação da literatura com construtos semelhantes, principalmente com relação ao *framework* da dinâmica do desempenho energético da Figura 12(A), no que se refere às dimensões: (i) estratégia; (ii) implementação das medidas (EEMs); (iii) controle (avaliação do desempenho). Como as revisões sistemáticas foram independentes, embora a revisão da literatura feita para a presente tese tenha um escopo mais alargado, a revisão de literatura feita por Shulze *et al*., (2016) pode validar a intepretação da dinâmica do desempenho energético realizada por esta pesquisa na Figura 12(A).

Outra questão relevante, representada no *framework* da Figura12(B), é a estrutura na qual o desempenho energético ocorre. Portanto, como praticamente todos os processos de produção usam energia, ela pode ser analisada como um fluxo na chamada Empresa Estendida, ou rede de processos (O'NEILL; SACKETT, 1994). Dessa forma, a Empresa Estendida terá um desempenho energético comum ou agregado (FOLAN; BROWN, 2005) associada à chamada energia incorporada [*embodied energy of products*] (RAHIMIFARD *et al*., 2010) ou demanda cumulativa [*cumulative energy demamd*] (PATEL, 2003).

A proposição do mapa de indicadores pode ser justificada pela escassez da discussão e proposição de indicadores encontrados na literatura (BUNSE *et al*., 2011), além de existirem muitos termos para representar o desempenho (eficiência energética, produtividade energética, conteúdo energético, intensidade energética, consumo específico de energia e eficiência relativa) e isso gera certa confusão na área (PATTERSON, 1996; PHYLIPSESEN *et al*., 1997; BOYD *et al*., 2008 IEA, 2014a). A proposta do mapa de indicadores é oferecer uma estrutura de indicadores que possa alimentar o modelo insumo-produto. É imprescindível reconhecer a limitação levantada por Patterson (1996) na qual informa que qualquer indicador criado para medir o desempenho ou eficiência energética será uma *proxy* do desempenho, podendo ter vantagens e desvantagens que dependerão do tipo de indicador escolhido. A vantagem de um indicador pode ser a desvantagem de outro, por exemplo, a comparação dos indicadores físico-termodinâmicos em séries longitudinais é muito mais realista do que a comparação longitudinal de indicadores puramente econômicos.

O modelo insumo-produto de processos (LIN; POLENSKE, 1998; ALBINO *et al*., 2003) é uma forma dedutiva simplificada de integrar tanto a estrutura do *framework* da Figura 12(A)(B), quanto os indicadores do mapa da Figura 13. Dada a hipótese de divisibilidade dos processos, poderão ser adicionados tantos processos quantos forem necessários porque a operacionalização do modelo continuará a mesma. No seu formato original o modelo insumo-produto de processo pode representar indicadores físico-termodinâmicos, econômico-termodinâmicos e econômicos. Na Figura 14(A), a variável tempo foi acrescentada ao modelo, tornando-se dessa forma um modelo insumo-produto de processo longitudinal. Essa transformação foi necessária porque um sistema de melhoria contínua exige reavaliações ao longo do tempo. O modelo apresentado como exemplo na Figura 14(A) é mais simples porque representa um ciclo de produção denominado *one-way* (ALBINO *et al*., 2003). O ciclo de produção poderia ser uma forma de delimitar o lapso de tempo para que o sistema/estrutura seja reavaliado.

De acordo com a metodologia da pesquisa em pauta, na Figura 2, a abordagem do problema do desempenho energético foi feita pelo desenvolvimento de três construções dedutivas, apresentadas nos objetivos específicos do nível 4 do mapa da tese: (vi) proposição de indicadores com base na eficiência empresarial; (vii) desenvolvimento de uma abordagem de simulação para alimentar o modelo na sua forma longitudinal; (viii) construção de uma abordagem para visualização multidimensional dos indicadores.

A abordagem para a medição e controle do desempenho energético, utiliza-se dos conceitos apresentados nas construções representativas (*framework*, mapa e modelo) para criar os indicadores e formular um sistema simulado, de forma a representar os indicadores em painéis de visualização. A proposição, principalmente, dos indicadores de eficiência energética direta (EED), mudança na eficiência energética (MEE) e eficiência energética indireta (EEI) vem da constatação de que os indicadores físico-termodinâmicos, econômico-termodinâmicos e econômicos, do mapa da Figura 13, são de desempenho e não de eficiência, definidos conforme a eficiência empresarial. Esse indicador vem da razão de dois indicadores de desempenho (BOGETOFT; OTTO, 2010; PERRONI *et al*., 2016c). Uma vez que os indicadores geram números no intervalo (0-1) facilita a comparação ao longo do tempo.

A abordagem de simulação utiliza-se da estrutura para manufaturar telhas, descrita em 5 processos, conforme Tabela 4. O que a simulação faz na prática é gerar um conjunto de 12 tabelas, similares à Tabela 4, assumindo a ocorrência de ações (EEMs e EETs) que provoque a melhoria contínua no desempenho. Além do cálculo dos indicadores (Equações 4 a 7) também são feitos os cálculos matriciais conforme as tabelas 4 e 5. O painel de indicadores construído alimenta o sistema de visualização desenvolvido no software R. Os Gráficos 11 a 15 mostram os indicadores em situação de aleatoriedade e o Gráfico 17 apresenta a convergência dos indicadores em situação de estabilidade, com base no Teorema do Limite Central (JONES *et al*., 2009; ROBERT; CASELLA, 2010).

A necessidade de um sistema de visualização decorre de que um grande número de indicadores pode ser proposto. A informação visual impõe menor carga cognitiva à memória do indivíduo do que uma informação não visual, facilitando a interpretação (WICKHAM 2011; GROLEMUND; WICKHAM, 2014). Considerando a estrutura de energia da Tabela 4, apenas para o indicador de eficiência energética direta (EED) são gerados 132 indicadores. A criação dos gráficos, em painéis, facilita a identificação de pontos específicos em que há melhoria ou queda do desempenho.

6.2 EM RELAÇÃO À CONTRIBUIÇÃO PARA A TEORIA E A PRÁTICA

O intuito do trabalho em pauta é atender a um *gap* da literatura da área de gestão da energia, no contexto da produção de bens e serviços, no qual faltam a proposição e a discussão de *frameworks*, modelos e indicadores capazes de integrar a gestão da energia na gestão da produção das empresas (BUNSE *et al*., 2011). O objetivo desta tese foi desenvolver uma abordagem de processos para a medição e controle do desempenho energético integrado, cujo principal indicador de desempenho energético é a eficiência energética.

A primeira contribuição teórica da tese refere-se à percepção de que o problema da eficiência energética pertence a um programa de pesquisa de Lakatos (1978), que é o programa de pesquisa da sustentabilidade. Para ser sustentável é condição *sine qua non* ser energeticamente eficiente, desta forma o problema da eficiência energética faz parte da heurística positiva do cinturão protetor desse programa. Ao ser analisado dessa forma, o problema apresenta novas perspectivas em relação ao potencial de aplicação do desenvolvimento desse programa de pesquisa, uma vez que a energia está relacionada com outras variáveis como: crescimento populacional, crescimento da riqueza, mudanças climáticas, entre outras.

A segunda contribuição teórica diz respeito ao posicionamento metodológico da Figura 2, uma vez que problemas complexos, como os relacionados à área de energia, geralmente necessitam de construções múltiplas encadeadas tanto para abordar de maneira prática o problema, quanto para representá-lo.

A terceira contribuição teórica refere-se à identificação de três grupos no campo da eficiência energética industrial. A questão fundamental é que dentre os grupos, muitos autores não reconhecem o desenvolvimento de outros, fato observado durante a leitura dos artigos. Essa característica pode ser observada nas Redes 4 e 5, uma vez que o algoritmo Harel-Koren discriminou autores e temas.

A principal contribuição prática da tese deu-se pela integração de um *framework,* que descreve a dinâmica e a estrutura do desempenho energético, com um mapa que propicia o entendimento do relacionamento da criação de indicadores do desempenho energético, em um modelo insumo-produto, amplamente reconhecido pela literatura, mas adaptado para funcionar de forma longitudinal. O desempenho energético foi operacionalizado utilizando o conceito de processo, sendo possível a integração em um sistema de rede de empresas (Empresa Estendida). O desempenho energético pode ser medido continuamente, tanto por meio de uma fonte energética específica, quanto agregando outras fontes ou outras entradas e saídas, além de ser possível incluí-lo aos processos, considerando o peso do fluxo indireto de energia. A contribuição na abordagem proposta está consolidada em duas frentes: (i) flexibilidade da composição de processos e (ii) possibilidade de escolha de indicadores que melhor representem o contexto.

A contribuição prática secundária está relacionada ao mapa de indicadores da Figura 13, com a percepção de que existem duas formas básicas fundamentais para representar os indicadores de desempenho: produtividade e conteúdo energético. Parte da literatura do grupo do desempenho quantitativo (PATTERSON, 1996; PHYLIPSESEN *et al*., 1997; IEA, 2014a) reconhece de forma equivocada um indicador de desempenho como sendo um indicador de eficiência. Fundamentado na interpretação da literatura de eficiência empresarial (AIGNER *et al*., 1977; CHARNES *et al*., 1978; BOGETOFT; OTTO, 2010) um indicador de eficiência vem da razão de dois indicadores de desempenho (PERRONI *et al*., 2016c), apresentados nas Equações 1, 2 e 3. A matriz de eficiência energética pode vir da razão de duas matrizes de desempenho energético (conteúdo energético), calculada no modelo insumo-produto longitudinal.

A contribuição prática terciária refere-se ao desenvolvimento de indicadores de eficiência das Equações 4 a 7, para acompanhar a medição contínua do desempenho energético. É possível acompanhar o desempenho energético de processos específicos da Empresa Estendida (Eficiência Energética Direta - EED), ou de forma integrada (Eficiência Energética Indireta - EEI) com a incorporação dos processos anteriores e posteriores. Os indicadores (EED) e (EEI) têm origem nas matrizes de coeficientes técnicos do modelo insumo-produto, o qual foi interpretado nesta tese como matrizes de desempenho. A matriz de desempenho indireta, apresentada na Tabela 6, representa indicadores de energia incorporada, tendo a vantagem de não sofrer da mesma limitação colocada por Patterson (1996), em relação à dificuldade de agregação dos indicadores físico-termodinâmicos, uma vez que se trata de processos em rede. O indicador de Eficiência Energética Relativa (EER) (CHARNES *et al*., 1978) foi utilizado para agregar indicadores, embora os indicadores também possam ser integrados pelo indicador (EEI). Outra forma de agregação é pela fronteira estocástica (SFA), destacada no mapa de indicadores da Figura 13.

Uma quarta contribuição destacada faz menção à adaptação da Gramática dos Gráficos em Camadas [*Layered Grammar of Graphics*] (WICKHAM, 2009, 2011) e ao *Framework* de Plotagem Estrutural [*Strucplot Framework*] (FRIENDLY 1994; MEYER *et al*., 2006) para a visualização multidimensional dos indicadores na qual a abordagem proposta facilita o acompanhamento da evolução dos indicadores de desempenho/eficiência.

Como última contribuição prática, destaca-se a integração dos elementos do sistema (*framework*, mapa, modelo, indicadores, simulação e visualização) para representar o desempenho energético da Empresa Estendida. Comparando a contribuição desta tese com a literatura em eficiência energética industrial, pode-se concluir que, na literatura, a maioria dos trabalhos analisados ou discutem o problema da eficiência energética em um nível mais conceitual, lado de cima da Figura 2, ou desenvolvem procedimentos e técnicas, lado de baixo da Figura 2, sem relacionar ambas as partes do problema. O *gap* na literatura estava em como fazer a ligação da parte mais conceitual, naturalmente mais indutiva, com as técnicas dedutivas trabalhadas pela literatura.

6.3 EM RELAÇÃO ÀS LIMITAÇÕES DA PESQUISA

Nesta tese assume-se a hipótese de que é possível identificar tanto medidas (EEMs) quanto tecnologias (EETs) e, por meio de sua implementação, elas possam melhorar o desempenho energético dos processos. Uma vez que não seja possível identificar medidas e tecnologias que possam ser adotadas, o desempenho pode atingir um estágio de saturação. Em períodos de estabilidade, os indicadores podem servir de orientação, para que o desempenho não regrida. Outro ponto relevante é o fato de que quanto mais os indicadores sejam previsíveis, mais o modelo insumo-produto de processos pode ser utilizado para funções de planejamento e previsão, funções originais propostas por Leontief (1966). Neste ponto pode haver uma dualidade entre utilizar o modelo para o controle do desempenho ou como um sistema para planejar as necessidades energéticas da Empresa Estendida. A proposta do presente trabalho está relacionada à medição contínua do desempenho energético, desta forma a preocupação está mais voltada ao controle do desempenho. Enquanto no quarto capítulo o reconhecimento foi para a importância tanto do planejamento, quanto do controle, no quinto capítulo a ênfase foi para os procedimentos e técnicas de controle contínuo do desempenho.

Contudo, algumas limitações podem ser relatadas em relação à aplicação da abordagem. A primeira refere-se às barreiras econômicas, comportamentais e organizacionais, que impedem a identificação e adoção ideal das medidas (EEMs) e tecnologias (EETs) para a eficiência energética levantadas por Cagno *et al*. (2013), que precisam ser pensadas dentro do escopo da gestão de energia de cada processo da Empresa Estendida. O Quadro 3 do terceiro capítulo identifica as principais barreiras investigadas em pesquisas empíricas. Uma limitação importante na conjuntura desta tese é a falta de submedidores, podendo limitar a divisão dos processos. De acordo com a revisão sistemática feita por Shulze *et al*. (2016), e pela revisão de literatura realizada por esta tese, conclui-se que a adoção da gestão de energia precisa evoluir no setor manufatureiro. A tese condicionou o problema da eficiência energética ao programa de pesquisa da sustentabilidade, logo, a evolução da gestão de energia dependerá da evolução desse programa de pesquisa em termos da sustentação de suas hipóteses auxiliares, principalmente, da hipótese da eficiência energética.

A segunda limitação está relacionada à abordagem de aplicação do modelo insumo-produto, uma vez que em contextos específicos não é suficiente avaliar apenas as fontes energéticas, mas construir indicadores da geração/utilização de resíduos e recursos relacionados (água, geração de resíduos, cogeração, utilização de materiais intensivos em energia, entre outros). A boa notícia é que a flexibilidade do modelo insumo-produto longitudinal permite estender a lógica da matriz de energia da Empresa Estendida para outras matrizes (materiais, resíduos e subprodutos) com facilidade, conforme Figura 14(A).

A terceira limitação está ligada a representação do modelo insumo-produto da Figura 14(A), uma vez que são processos com dependências simples (modelo *one-way*), formando um ciclo de produção (sequência de processos). A grande vantagem do modelo insumo-produto está em representar processos com dependência mútua (modelo *mult-way*) (ALBINO *et al*., 2003) criado por uma rede de processos [*network of productions process*], tanto locais quando globais. No caso de uma rede de processos, a visualização também pode ser feita pela análise de redes sociais (BORGATTI; LI, 2009).

A quarta limitação está relacionada ao fato de os indicadores termodinâmicos serem os únicos que a abordagem, em princípio, não consegue tratar adequadamente porque envolve a razão do conteúdo calorífico como a eficiência térmica, ou a razão de eficiências térmicas como o indicador de eficiência ideal, disponível no mapa da Figura 13. No contexto desta tese, que estuda o desempenho, principalmente, da produção manufatureira, torna-se necessário enfatizar o fato reconhecido por Patterson (1996), de que: os indicadores puramente termodinâmicos não são uma boa medida para avaliar o uso do serviço final. Por exemplo, uma máquina com dada eficiência termodinâmica estabelecida pela tecnologia pode ser utilizada de forma inadequada, e assim produzir abaixo da sua capacidade. Embora a máquina do exemplo tenha uma eficiência termodinâmica constante, sua eficiência (desempenho) físico-termodinâmica será variável.

Três outras limitações podem ser discutidas: (i) relação linear entre os insumos e produtos/serviços; (ii) estabilidade da fronteira de produtividade; (iii) identificação e divisibilidade dos processos. A linearidade entre os insumos e a produção é uma suposição do modelo insumo-produto de Leontief (1966). Na análise envoltória (DEA) que também é uma técnica insumo-produto, essa limitação é resolvida com a incorporação dos retornos de escala: crescente e decrescente. Nos indicadores KPIs (insumo/produção) o retorno de escala vai ser sempre constante (BOGETOFT; OTTO, 2010).

A fronteira de produtividade pode ser deslocada por meio da tecnologia (EETs) ou medidas gerais (EEMs). A argumentação que pode ser feita é na hipótese de uma empresa (processo específico) estar atualizada a respeito das (EETs) e das (EEMs), ela entrará em um estágio mais elevado. Este estágio mais elevado pode ser o de "capacidade total de melhoria contínua", com a habilidade em desenvolver novas competências por meio de inovações (incrementais e radicais) (BESSANT *et al*., 2001; ATTADIA; MARTIS, 2003). Na literatura de gestão de energia, esse fato foi destacado nos trabalhos de Gordic *et al*. (2010) e Negai *et al*. (2013). Existe a limitação de que a empresa (processo) não controla o desenvolvimento da tecnologia. Os autores Negai *et al*. (2013) reconhecem cinco níveis de maturidade de evolução da gestão de energia/utilidade (inicial, gerenciado, definido, quantitativamente gerenciado e otimizado). No nível otimizado dá-se a fase de melhoria contínua. Baseado na discussão que a presente pesquisa traz, um novo estágio pode ser acrescentado, o “otimizado em rede”. Trabalhando em rede o desempenho energético poderia dar um salto, porque muitas barreiras descritas em Cagno *et al*. (2013) poderiam ser eliminadas. Em um estágio otimizado em rede, as empresas (processos) em conjunto teriam uma capacidade maior de negociar com os ofertantes de energia, fornecedores de tecnologias ou mesmo montar seu próprio sistema de energia, aproximando-se da rede auto poética proposta por Bititci *et al*., (2012).

O modelo insumo-produto de processo de Lin e Polenske (1998) não entra na questão de como os processos podem ser divididos. De acordo com a presente tese, procurou-se estabelecer uma definição de conceitos hierárquicos: processo, ciclo de produção e rede de processos. Na literatura pesquisada, referente ao modelo insumo-produto de processo, não existe uma forma ou técnica específica de mapear esses processos. Existe a preocupação técnica de como montar as tabelas e matrizes insumo-produto. Em defesa do que já foi mencionado, não existe a necessidade da coincidência entre processos reais e a divisão que está sendo proposta com o intuito da aplicação. Pode-se criar a noção de processo virtual: processo que serviria para fins de monitoramento do desempenho energético. O modelo original de Leontief (1966) pode ser interpretado como uma composição de “processos virtuais” que formam os setores da economia. A palavra virtual aqui tem o sinônio de representativo, por exemplo, na manufatura de telhas o processo de embalagem poderia se juntar com o de estoque ou entrega, formando um processo representativo (virtual) com outro nome.

Para estudar a evolução não importa a divisão dos processos, desde que sejam mantidos os mesmos. A lógica inicial de montar esses “processos virtuais” se daria sempre quando fosse possível identificar insumos que estão relacionados a certos produtos/processos. Para o modelo insumo-produto de processo o grande problema da divisibilidade é que cada processo só pode ter um produto principal, portanto, caso dois ou mais produtos de processos queiram ser analisados, a solução é a divisibilidade por meio da criação de "processos virtuais". Embora o modelo insumo-produto de processo possa se utilizar-se de “processos virtuais”, reconhece-se o fato de que existe a necessidade do desenvolvimento de procedimentos para mapeamento e divisibilidade de processos.

6.4 EM RELAÇÃO AOS TRABALHOS FUTUROS

Uma primeira sugestão para trabalho futuro vem do fato de não existir no Brasil estudos sistemáticos das barreiras econômicas, comportamentais e organizacionais que impedem uma melhor eficiência energética das manufaturas. Tal estudo deveria levar em conta a experiência internacional na identificação das barreiras empíricas.

Uma segunda possibilidade de pesquisas futuras está relacionada ao mapeamento de processos e por consequência das informações necessárias para alimentar a abordagem proposta. Barreiras organizacionais e de interesses econômicos precisam ser superadas, de forma que a abordagem possa funcionar sem ruídos. Uma pergunta fundamental neste estudo seria: o que é necessário para a abordagem funcionar de forma contínua e ainda ter escalabilidade?

Uma terceira proposta seria a implantação da abordagem em uma rede de processos com dependências múltiplas [*mult-way*], levantando informações de energia, insumos primários, resíduos e subprodutos. O estudo de caso da fábrica de telhas, encontrado na literatura, é simples (com poucos processos). A vantagem da utilização do modelo está no fato de que uma maior complexidade, envolvendo dezenas ou centenas de processos, não causa mudanças na forma de aplicação, embora essa maior complexidade torne mais trabalhoso o mapeamento dos processos.

A quarta linha refere-se à viabilidade do desenvolvimento de novos indicadores individuais e integrados utilizando as matrizes de desempenho do modelo insumo-produto e as abordagens de fronteira paramétricas e não paramétricas.

Uma quinta linha de estudo, complementar, pode estar relacionada à construção de um sistema para a abordagem de processos proposta, utilizando a linguagem R aproveitando-se de muitos dos códigos apresentados no Apêndice B. No âmbito do sistema deve existir uma preocupação com a integração dos dados, pensando em um projeto com escalabilidade.

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APÊNDICES A-M

APÊNDICE A

APÊNDICE A: IDENTIFICAÇÃO DE MEDIDAS E TECNOLOGIAS PARA A EFICIÊNCIA ENERGÉTICA NO SETOR CERÂMICO

Esse apêndice utiliza o mesmo procedimento de Perroni *et al*., (2016c), que está descrito na Tabela do artigo 6 no Apêndice K, para demonstrar que pode ser identificado tanto medidas quanto tecnologias para a poupança de energia que contribui para a melhoria do desempenho energético do subsetor do SIC [325 - *Structural Clay Products*]. O subsetor Produtos Estruturais do Barro (setor cerâmico) é composto pelas manufaturas [*3251 Brick And Structural Clay Tile; 3253 Ceramic Wall And Floor Tile; 3255 Clay Refractories; 3259 Structural Clay Products, Nec*][13].

A Tabela A1 apresenta dados de todas as auditoras (70 casos) feitas no subsetor Produtos Estruturais do Barro no período (1981–2016). Pode se notar que o projeto atende pequenas e médias empresas, na qual o número médio de funcionários é 108. Na Tabela A1 também são apresentados o consumo anual de energia (eletricidade em KWH e gás natural em MMBtu), além do custo de implementação do projeto e a poupança de energia em dólares americanos. A Tabela A1 foi classificada pelo número de recomendações feitas (NRec), para os casos, totalizando 507 recomendações. Com média de 7 recomendações por caso. Foi também calculada a correlação entre o número de funcionários como *proxy* do tamanho das empresas e outras variáveis como gastos de energia, custo e poupança. Pelo resultado da correlação pode-se afirmar que o tamanho das empresas está relacionado mais ao gasto de energia do que ao custo ou poupança identificada pelas auditorias nesse subsetor.

Tabela A1 – Auditorias em eficiência energética para o setor cerâmico

Casos	**ID**	**Ano**	**Funcionários**	**Eletricidade (KWH)**	**Gás (MMBtu)**	**NRec**	**Custo - U$**	**Poupança - U$**
1	TT0087	2012	450	30.339.485	448.793	18	671.912	813.142
2	OK0839	2013	42	6.343.132	262.246	16	187.741	192.563
3	BD0350	2008	160	10.107.936	901.559	14	280.778	786.844
4	OK0067	1982	70	5.762.016	349.283	13	87.517	179.228
5	WV0108	1997	125	2.131.594	149.151	11	71.885	129.107
6	AM0579	2010	141	6.054.942	98.282	11	67.887	1.798.535
7	WV0245	2002	110	6.138.639	219.872	11	7.384	23.762
8	MO0202	1997	35	946.073	17.624	11	72.888	84.885
9	WV0110	1997	200	2.091.442	131.467	11	117.339	421.003
10	TN0628	1998	75	5.255.862	191.759	10	138.890	122.360
11	UD0636	2002	91	2.102.480	96.646	10	41.235	116.816
12	BD0377	2010	16	740.773	60.457	10	500.681	218.785
13	SD0365	2005	200	8.623.031	513.901	10	4.351.616	1.966.511
14	BD0108	1998	65	1.980.363	135.687	10	38.420	668.771
15	SF0296	2004	100	789.333	27.234	10	62.280	37.663
16	WV0136	1998	470	19.557.152	350.537	10	37.505	76.202
17	UA0022	2008	79	9.164.168	361.040	9	354.075	231.542
18	MO0237	1998	425	26.232.708	1.027.896	9	37.520	84.857
19	WV0512	2015	40	3.008.662	92.587	9	98.451	56.073
20	OK0099	1983	12	405.920	69.816	9	13.796	30.074
21	AM0365	2000	55	2.530.774	146.532	8	4.928	7.915
22	AM0619	2012	60	11.266.950	-	8	59.472	26.389
23	OK0106	1983	75	3.449.883	91.468	8	14.172	76.922
24	MA0509	2002	53	4.962.960	191.905	8	118.873	51.487
25	NC0127	1997	73	3.239.742	-	8	225.460	210.595
26	TN0427	1991	64	3.361.958	116.214	7	6.002	47.422

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[13] https://iac.university/indexSic/325 - acessado em 24/08/2016.

Casos	ID	Ano	Funcionários	Eletricidade (KWH)	Gás (MMBtu)	NRec	Custo - U$	Poupança - U$
27	OK0468	1995	80	6.848.476	233.907	7	20.200	7.183
28	CO0578	2005	70	3.931.200	122.607	7	147.490	21.000
29	WV0082	1996	100	4.432.884	101.779	7	39.817	60.775
30	CO0427	1998	35	1.438.453	90.908	7	360.122	59.913
31	NC0314	2005	60	3.942.700	180.160	7	7.275	19.631
32	MO0043	1991	104	6.282.532	166.560	7	3.454	21.523
33	SD0351	2004	40	1.594.732	89.289	7	384.627	363.369
34	OK0252	1988	40	2.863.130	191.218	7	27.324	62.272
35	LL0325	2010	40	1.158.633	-	7	5.663	44.456
36	GT0256	1985	30	553.048	15.340	7	12.195	32.133
37	SF0035	1994	210	4.789.273	569.696	7	54.476	171.430
38	OR0526	2007	120	2.729.960	41.200	7	1.221.200	613.100
39	SD0317	2003	80	2.738.146	-	7	30.866	45.322
40	OD0050	1996	65	1.828.253	20.922	7	18.436	34.782
41	NV0151	2000	20	824.736	8.377	7	106.685	26.892
42	MS0097	1997	120	7.051.290	343.161	6	125.224	119.522
43	TN0510	1994	78	5.351.114	259.832	6	8.923	22.104
44	IA0137	1996	160	9.839.977	249.390	6	28.225	28.192
45	AM0226	1995	100	9.207.503	299.560	6	7.745	9.658
46	CO0145	1989	65	7.110.492	377.636	6	26.500	58.905
47	OK0717	2005	50	2.189.358	93.898	6	72.759	45.358
48	MO0169	1996	320	12.303.634	520.359	6	353.076	130.266
49	NC0352	2007	114	11.078.300	461.477	6	14.521	37.470
50	UA0152	2015	210	34.809.355	691.451	5	142.355	125.567
51	MS0012	1994	75	3.623.095	139.828	5	27.950	38.219
52	AM0542	2008	90	3.514.279	154.627	5	19.680	44.325
53	MA0149	1989	52	2.491.208	-	5	59.635	64.118
54	MS0271	2005	68	1.635.091	85.079	5	11.076	50.398
55	NC0030	1994	215	19.891.266	51.555	5	163.972	235.695
56	UL0241	2000	200	11.666.178	399.700	4	104.793	123.006
57	CO0328	1995	60	2.202.227	145.000	4	24.060	11.880
58	OK0017	1982	45	2.772.274	139.350	4	5.754	13.901
59	AT0042	1986	50	2.961.606	14.075	4	659	11.983
60	LE0139	2002	40	3.265.810	108.580	4	247.263	70.483
61	MS0149	1999	38	2.950.762	106.840	4	12.035	18.008
62	AR0168	1999	95	1.811.254	48.710	4	8.458	33.804
63	LT0068	1986	180	3.669.109	106.724	4	45.198	45.570
64	LT0141	1989	65	4.875.147	458.258	4	36.850	75.865
65	AT0043	1986	60	2.916.764	131.400	4	3.346	13.578
66	AT0036	1986	125	8.546.893	11.059	3	26.492	43.640
67	TN0230	1984	100	7.388.628	2.936	3	15.018	13.526
68	GT0158	1982	135	2.567.116	245.398	3	17.651	16.011
69	AT0016	1985	100	2.060.961	106.541	3	1.510	1.229
70	UL0232	1999	150	37.715.124	31.530	3	5.916	67.590
			Média	**Soma**	**Soma**	**Soma**	**Soma**	**Soma**
			108	**450.009.949**	**13.667.872**	**507**	**11.725.181**	**11.613.105**
		Correlação		**0,69**	**0,60**	**0,23**	**0,18**	**0,27**

Fonte: (US DOE-IAC_ARC, 2007; US DOE-IAC, 2011).
Nota: Elaborado a partir da tabela de casos, tabela de recomendações e SIC e standard industrial classification.

A Tabela A2 apresenta a lista de 127 medidas (EEMs) e tecnologias (EETs) em eficiência energética recomendadas 495 vezes para o setor cerâmico (Produtos Estruturais do Barro). Na Tabela A2 apenas as práticas com status implementada e não implementada foram consideradas, dessa forma a diferença de 12 práticas da Tabela A1 para a Tabela A2 (507-495) refere-se ao status (pendente de avaliação) ou pertencente ao setor não classificado 3258.

Na análise da Tabela A2 algumas informações podem ser levantadas: Quando as 20 práticas mais recomendadas do setor cerâmico é comparado com as 20 práticas mais recomendadas considerando todos os 137 subsetores da classificação SIC, há uma coincidência de 11 práticas (27142, 24133, 24236, 24111, 22511, 24221, 27143, 24231, 27134, 27135, 24141) (PERRONI *et al.*, 2016c). Como em Anderson e Newell (2004) aproximadamente a metade das recomendações não foram implementadas. O motivo para esse fato pode estar no custo uma vez que as práticas não implementadas representam 65% do custo para o subsetor cerâmico (ANDERSON; NEWELL, 2004).

Tabela A2– Medidas e tecnologias recomendadas para a eficiência energética no setor cerâmico

Status		**Total**	**Implemented**			**Not Implemented**		
N	**(ARC) Energy efficiency practices recommended**	**Q**	**QI**	**% cost**	**% save**	**NQI**	**% cost**	**% save**
1	27142 utilize higher efficiency lamps and/or ballasts	65	36	5,14%	4,58%	29	1,74%	0,71%
2	24133 use most efficient type of electric motors	33	22	2,45%	0,89%	11	0,34%	0,19%
3	24236 eliminate leaks in inert gas and compressed air lines/	29	21	0,13%	0,36%	8	0,07%	0,24%
4	24111 utilize energy-efficient belts and other improved mech	27	18	0,16%	0,40%	9	0,79%	0,41%
5	22511 insulate bare equipment	21	9	0,23%	0,49%	12	0,41%	1,56%
6	24221 install compressor air intakes in coolest locations	20	9	0,03%	0,13%	11	0,04%	0,14%
7	27143 use more efficient light source	19	12	0,15%	0,17%	7	0,25%	0,10%
8	24231 reduce the pressure of compressed air to the minimum r	14	9	0,04%	0,10%	5	0,00%	0,16%
9	22411 use waste heat from hot flue gases to preheat combusti	9	4	0,96%	1,00%	5	4,93%	4,76%
10	27134 use photocell controls	9	4	0,03%	0,02%	5	0,07%	0,07%
11	36193 install equipment (eg compactor) to reduce disposal co	8	0	0,00%	0,00%	8	1,03%	0,65%
12	22432 recover heat from oven exhaust / kilns	8	0	0,00%	0,00%	8	3,64%	7,22%
13	23212 optimize plant power factor	7	4	0,31%	0,42%	3	0,19%	0,15%
14	22512 increase insulation thickness	7	2	0,15%	0,29%	5	1,00%	1,39%
15	27124 make a practice of turning off lights when not needed	7	6	0,09%	0,38%	1	0,00%	0,04%
16	24314 use synthetic lubricant	7	4	0,03%	0,06%	3	0,00%	0,06%
17	31191 change procedures / equipment / operating conditions	6	2	0,00%	0,07%	4	1,78%	2,12%
18	27135 install occupancy sensors	6	2	0,03%	0,03%	4	0,03%	0,01%
19	24141 use multiple speed motors or afd for variable pump, bl	5	3	0,95%	0,77%	2	0,32%	0,16%
20	26212 turn off equipment during breaks, reduce operating tim	5	2	0,00%	0,01%	3	0,00%	0,14%
21	22434 recover heat from air compressor	5	0	0,00%	0,00%	5	0,09%	0,20%
22	26218 turn off equipment when not in use	4	2	0,01%	0,02%	2	0,00%	0,08%
23	28114 change rate schedules or other changes in utility serv	4	2	0,04%	0,27%	2	0,80%	0,40%
24	27231 use radiant heater for spot heating	4	2	0,12%	0,54%	2	0,12%	0,02%
25	35311 recover and reuse waste material	4	1	0,15%	0,03%	3	0,80%	0,54%
26	21233 analyze flue gas for proper air/fuel ratio	4	3	0,04%	0,73%	1	0,03%	0,17%
27	24144 use adjustable frequency drive to replace mechanical d	4	2	0,26%	0,30%	2	0,17%	0,09%
28	24143 use adjustable frequency drive to replace throttling s	4	2	1,04%	2,63%	2	0,08%	0,06%
29	22443 re-use or recycle hot or cold process exhaust air	4	1	0,17%	0,73%	3	0,83%	0,85%
30	27111 reduce illumination to minimum necessary levels	4	4	0,04%	0,18%	0	0,00%	0,00%
31	34115 recover and reuse cooling water	3	1	0,05%	0,51%	2	0,00%	0,09%
32	24312 improve lubrication practices	3	3	0,00%	0,42%	0	0,00%	0,00%
33	24232 eliminate or reduce compressed air used for cooling, a	3	0	0,00%	0,00%	3	0,79%	0,25%
34	24131 replace over-size motors and pumps with optimum size	3	2	0,25%	0,31%	1	0,04%	0,04%
35	46520 replace existing equipment with more suitable substitu	3	1	2,09%	0,58%	2	0,68%	0,78%
36	24151 develop a repair/replace policy	3	3	0,10%	0,02%	0	0,00%	0,00%
37	46110 begin a practice of predictive / preventative maintena	3	3	0,12%	5,67%	0	0,00%	0,00%
38	24224 upgrade controls on compressors	3	1	0,01%	0,01%	2	0,18%	0,10%
39	27261 install timers and/or thermostats	3	1	0,02%	0,01%	2	0,01%	0,01%
40	35246 segregate metals for sale to a recycler	2	1	0,00%	0,00%	1	0,00%	0,00%
41	44450 install equipment to move product	2	1	0,35%	2,33%	1	0,34%	0,51%

Status		Total	Implemented			Not Implemented		
N	(ARC) Energy efficiency practices recommended	Q	QI	% cost	% save	NQI	% cost	% save
42	38132 use less toxic and volatile solvent substitutes	2	0	0,00%	0,00%	2	0,02%	0,01%
43	26232 install set-back timers	2	0	0,00%	0,00%	2	0,01%	0,02%
44	34114 replace city water with recycled water via cooling tow	2	0	0,00%	0,00%	2	0,11%	0,14%
45	21113 reduce combustion air flow to optimum	2	0	0,00%	0,00%	2	0,04%	0,24%
46	35315 lease / purchase baler; sell cardboard to recycler	2	1	0,00%	0,48%	1	0,00%	0,11%
47	22444 use hot process fluids to preheat incoming process flu	2	0	0,00%	0,00%	2	0,32%	0,79%
48	41260 install sensors to detect defects	2	0	0,00%	0,00%	2	10,01%	3,36%
49	27144 install spectral reflectors / delamp	2	0	0,00%	0,00%	2	0,03%	0,02%
50	46210 use fixtures to reduce machine changeout times	2	0	0,00%	0,00%	2	2,89%	0,36%
51	27224 reduce space conditioning during non-working hours	2	2	0,03%	0,40%	0	0,00%	0,00%
52	24321 upgrade obsolete equipment	2	0	0,00%	0,00%	2	0,00%	0,17%
53	23131 reschedule plant operations or reduce load to avoid pe	2	0	0,00%	0,00%	2	0,07%	0,20%
54	35313 increase amount of waste recovered for resale	2	1	0,03%	0,02%	1	0,00%	0,02%
55	27241 install outside air damper / economizer on hvac unit	2	0	0,00%	0,00%	2	0,05%	0,02%
56	36192 use a less expensive method of waste removal	2	0	0,00%	0,00%	2	0,00%	0,14%
57	22424 use heat in flue gases to preheat products or material	2	1	0,00%	0,01%	1	0,02%	0,12%
58	41220 develop standard procedures to improve internal yields	2	1	0,00%	0,11%	1	0,98%	3,56%
59	27447 install vinyl strip / high speed / air curtain doors	2	1	0,02%	0,01%	1	0,42%	0,44%
60	43220 eliminate old stock and / or modify inventory control	2	2	0,10%	0,07%	0	0,00%	0,00%
61	28123 pay utility bills on time	2	2	0,00%	0,02%	0	0,00%	0,00%
62	25194 redesign process	2	0	0,00%	0,00%	2	0,06%	0,03%
63	23211 use power factor controllers	2	2	0,10%	0,08%	0	0,00%	0,00%
64	26221 use most efficient equipment at it's maximum capacity	2	1	0,00%	0,04%	1	0,00%	0,01%
65	32176 increase use of automation	2	1	0,00%	0,55%	1	0,13%	0,21%
66	23415 use a fossil fuel engine to cogenerate electricity or	2	2	16,25%	7,08%	0	0,00%	0,00%
67	26121 reduce hot water temperature to the minimum required	1	0	0,00%	0,00%	1	0,02%	0,12%
68	44310 train operators for maximum operating efficiency	1	0	0,00%	0,00%	1	0,01%	0,03%
69	41120 replace old machine with new automatic multi-station t	1	1	0,02%	0,08%	0	0,00%	0,00%
70	21135 repair furnaces and oven doors so that they seal effic	1	0	0,00%	0,00%	1	0,00%	0,00%
71	46250 develop standard operating procedures	1	0	0,00%	0,00%	1	0,00%	0,08%
72	21221 replace obsolete burners with more efficient ones	1	0	0,00%	0,00%	1	0,79%	1,11%
73	35316 contract a wood pallet recycling company	1	1	0,00%	0,05%	0	0,00%	0,00%
74	22523 reduce infiltration; isolate hot equipment from refrig	1	1	0,40%	0,17%	0	0,00%	0,00%
75	43210 optimize production lot sizes and inventories	1	0	0,00%	0,00%	1	0,00%	15,11%
76	22531 re-size charging openings or add movable cover or door	1	1	0,01%	0,02%	0	0,00%	0,00%
77	45110 expand operations into unused space	1	0	0,00%	0,00%	1	0,02%	0,01%
78	21311 replace electrically-operated equipment with fossil fu	1	1	0,02%	0,01%	0	0,00%	0,00%
79	27132 install timers on light switches in little used areas	1	1	0,01%	0,05%	0	0,00%	0,00%
80	27145 install skylights	1	0	0,00%	0,00%	1	0,01%	0,01%
81	26211 conserve energy by efficient use of vending machines	1	0	0,00%	0,00%	1	0,01%	0,01%
82	27211 clean and maintain refrigerant condensers and towers	1	1	0,00%	0,00%	0	0,00%	0,00%
83	23412 use waste heat to produce steam to drive a steam turbi	1	0	0,00%	0,00%	1	0,44%	0,17%
84	24227 use compressor air filters	1	0	0,00%	0,00%	1	0,00%	0,00%
85	24157 establish a predictive maintenance program	1	1	0,01%	0,03%	0	0,00%	0,00%
86	27225 close outdoor air dampers during warm-up / cool-down p	1	0	0,00%	0,00%	1	0,01%	0,00%
87	44250 eliminate/reduce redundant inspections	1	0	0,00%	0,00%	1	0,00%	0,19%
88	22212 use minimum safe oven ventilation	1	0	0,00%	0,00%	1	0,01%	0,15%
89	44410 install automatic packing equipment	1	1	0,68%	0,19%	0	0,00%	0,00%
90	47110 initiate a total quality management program	1	1	0,22%	0,31%	0	0,00%	0,00%
91	22422 use waste heat from hot flue gases to generate steam	1	1	0,22%	0,15%	0	0,00%	0,00%
92	22313 use batch firing with kiln "furniture" specifically de	1	0	0,00%	0,00%	1	0,52%	0,24%
93	24222 install adequate dryers on air lines to eliminate blow	1	0	0,00%	0,00%	1	0,03%	0,01%

Status		Total	Implemented			Not Implemented		
N	**(ARC) Energy efficiency practices recommended**	**Q**	**QI**	**% cost**	**% save**	**NQI**	**% cost**	**% save**
94	21131 repair faulty insulation in furnaces, boilers, etc	1	0	0,00%	0,00%	1	0,35%	0,12%
95	35217 reuse / recycle/ sell paper products	1	1	0,00%	0,33%	0	0,00%	0,00%
96	24142 use adjustable frequency drive to replace motor-genera	1	1	0,60%	0,58%	0	0,00%	0,00%
97	21114 limit and control secondary combustion air in furnace	1	0	0,00%	0,00%	1	2,63%	1,81%
98	23132 recharge batteries on during off-peak demand periods	1	1	0,00%	0,01%	0	0,00%	0,00%
99	22442 preheat combustion air with waste heat	1	0	0,00%	0,00%	1	0,02%	0,02%
100	28121 apply for tax-free status for energy purchases	1	1	0,00%	0,18%	0	0,00%	0,00%
101	21134 eliminate leaks in combustible gas lines	1	0	0,00%	0,00%	1	0,04%	0,45%
102	28122 use utility controlled power management	1	1	0,00%	0,06%	0	0,00%	0,00%
103	24112 install soft-start to eliminate nuisance trips	1	0	0,00%	0,00%	1	0,06%	0,03%
104	21133 adjust burners for efficient operation	1	0	0,00%	0,00%	1	0,83%	0,27%
105	26224 schedule baking times of small and large components	1	1	0,00%	0,00%	0	0,00%	0,00%
106	31172 revise raw material specs	1	1	0,04%	0,33%	0	0,00%	0,00%
107	42110 consider use / purchase of bulk materials where possib	1	1	0,28%	0,23%	0	0,00%	0,00%
108	22314 replace heat treating oven with more efficient unit	1	0	0,00%	0,00%	1	21,46%	5,14%
109	26242 minimize operation of equipment maintained in standby	1	1	0,04%	0,03%	0	0,00%	0,00%
110	24322 use or replace with energy efficient substitutes	1	0	0,00%	0,00%	1	0,15%	0,12%
111	44260 modify workload	1	0	0,00%	0,00%	1	0,20%	1,44%
112	34111 use closed cycle process to minimize waste water produ	1	0	0,00%	0,00%	1	0,01%	0,01%
113	44320 cross-train personnel to avoid lost time	1	1	0,18%	0,13%	0	0,00%	0,00%
114	25123 reduce fluid flow rates	1	0	0,00%	0,00%	1	0,04%	0,08%
115	48210 pay bills on time to avoid late fees	1	0	0,00%	0,00%	1	0,00%	0,06%
116	21121 use insulation in furnaces to facilitate heating / coo	1	1	0,01%	0,01%	0	0,00%	0,00%
117	45140 re-arrange equipment layout to reduce handling costs	1	1	0,11%	0,04%	0	0,00%	0,00%
118	34116 meter recycled water (to reduce sewer charges)	1	1	0,05%	0,05%	0	0,00%	0,00%
119	27121 utilize daylight whenever possible in lieu of artifici	1	0	0,00%	0,00%	1	0,00%	0,01%
120	34141 replace the chlorination stage with an oxygen or ozone	1	0	0,00%	0,00%	1	0,07%	1,16%
121	46320 change operating conditions	1	1	0,00%	0,01%	0	0,00%	0,00%
122	34151 minimize water usage	1	0	0,00%	0,00%	1	0,01%	0,01%
123	46530 maintain/enlarge a stock of spare parts	1	1	0,24%	0,16%	0	0,00%	0,00%
124	34154 eliminate leaks in water lines and valves	1	0	0,00%	0,00%	1	0,00%	0,01%
125	35212 regrind, reuse, or sell scrap plastic parts	1	0	0,00%	0,00%	1	0,00%	0,01%
126	27232 replace existing hvac unit with high efficiency model	1	1	0,05%	0,01%	0	0,00%	0,00%
127	27112 reduce exterior illumination to minimum safe level	1	1	0,00%	0,00%	0	0,00%	0,00%
Total		**495**	**250**	**35,47%**	**37,56%**	**245**	**64,53%**	**62,44%**

Fonte: (US DOE-IAC_ARC, 2007; US DOE-IAC, 2011).

Nota: a) (Q= QI+NQI) onde Q é a quantidade de práticas sendo QI as implementadas e NQI as não implementadas. b) %cost (% do custo reportado pelo cliente da auditoria). c) %save (poupança em valores monetários).

APÊNDICE B

APÊNDICE B: CODIFICAÇÃO R PARA A ABORDAGEM DE SIMULAÇÃO

1 - FUNÇÃO DE SIMULAÇÃO [INPUT]

```
SM=function (n=10000000, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))
  return(k)
}
```

2 - FUNÇÃO DE SIMULAÇÃO [OUTPUT]

```
SM2=function (n=10000000, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))
  return(k)
}
```

3 - IMPORTA OS DADOS - KUHTZ*et al.* (2010)

```
data <- read.csv(file="C:/ENG. PRODUÇÃO/LIVROS/ARQUIVOS DE LIVROS/R/Mosaic/DataFrameEIOM.csv",
header=T, sep=";",dec=",")
attach(data)
```

4- CRIA UM OBJETO MATRIZ DE ENERGIA [INPUTS]

```
EI <- (as.matrix(data[Produtos == "Energy inputs",-(1:2)]))
```

5 - CRIA UM OBJETO DE SAÍDA [OUTPUT]

```
OP <- (as.matrix(data[Produtos == "Gross Output",-(1:2)]))
```

6 - MATRIZ DE SIMULAÇÃO DAS ENTRADAS DE ENERGIA

```
ME <- EI-(EI*0.80)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
lin <-c("Electric", "Thermal", "oil", "Diesel","Gas" )
col <- c("M", "N", "O", "P", "Q")
dimnames(SE) = list(Energia_Kcal=c(lin), processo=c(col))
```

7 - MATRIZ DE SIMULAÇÃO DAS SAÍDAS

```
OS <- OP-(OP*0.50)
SEP<-
matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(,OS[1,
5],OP[1,5])), nrow=1, ncol=5,byrow=T)
dimnames(SEP) = list(produto=c("Output")
processo=c("M", "N", "O", "P", "Q"))
```

8 - CALCULO DOS COEFICIENTES DIRETOS

```
ym <- diag(1,5,5)#criação de matriz diagonal
diag(ym) <- 1/OP #Diagonal inversa da saída
coefTecEnergy_inputs <- EI%*%ym #- Coeficientes técnicos original
lin <-c("Electric", "Thermal", "oil", "Diesel","Gas" )
col <- c("M", "N", "O", "P", "Q")
dimnames(coefTecEnergy_inputs) = list(Energia_Kcal=c(lin), processo=c(col))
```

9 - CALCULO DOS COEFICIENTES DE FLUXO

```
Produto <- as.matrix(data[Produtos == "Produto",-(1:2)])
coefTecProduto <- Produto%*%ym
FluxoProduto <- solve(coefTecProduto) #solução da inversa
FluxoEnergia <- coefTecEnergy_inputs%*%FluxoProduto #Coeficietes de fluxo original
lin <-c("Electric", "Thermal", "oil", "Diesel","Gas" )
col <- c("M", "N", "O", "P", "Q")
dimnames(FluxoEnergia) = list(Energia_Kcal=c(lin), processo=c(col))
```

10 - GERAÇÃO DOS CONJUNTOS DE DADOS

```
#-------------------A5---------------------------------------
ME <- EI-(EI*0.05)
```

```
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0,0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
#output smulation
OS <- OP-(OP*0.50) # % = [0.50]
SEP<-
matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(,OS[1,
5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B1 <- SEP
A5 <- coefTecEnergy_inputsSimul
P <- B1
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE5 <- FluxoEnergiaSimul
#--------------------A10----------------------------------------------
ME <- EI-(EI*0.10)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
 0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
#output
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(,
OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
diag(ym2) <- 1/SEP #Gross_Outpt based on Siulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B2 <- SEP
A10 <- coefTecEnergy_inputsSimul
P <- B2
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE10 <- FluxoEnergiaSimul
#--------------------A15----------------------------------------------
ME <- EI-(EI*0.15)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(,
OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
```

```
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B3 <- SEP
A15 <- coefTecEnergy_inputsSimul
P <- B3
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE15 <- FluxoEnergiaSimul
#-------------------A20-------------------------------------------
ME <- EI-(EI*0.20)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(,
OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B4 <- SEP
A20 <- coefTecEnergy_inputsSimul
P <- B4
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE20 <- FluxoEnergiaSimul
#-------------------A25-------------------------------------------
ME <- EI-(EI*0.25)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0,0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(
,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output")
processo=c("M", "N", "O", "P", "Q"))
B5 <- SEP
A25 <- coefTecEnergy_inputsSimul
P <- B5
```

```
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE25 <- FluxoEnergiaSimul
#--------------------A30----------------------------------------------
ME <- EI-(EI*0.30)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(
,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B6 <- SEP
A30 <- coefTecEnergy_inputsSimul
P <- B6
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE30 <- FluxoEnergiaSimul
#--------------------A35----------------------------------------------
ME <- EI-(EI*0.35)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),SM2(
,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B7 <- SEP
A35 <- coefTecEnergy_inputsSimul
P <- B7
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE35 <- FluxoEnergiaSimul
#--------------------A40----------------------------------------------
```

```
ME <- EI-(EI*0.40)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,
OS[1,4],OP[1,4]),SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Siulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B8 <- SEP
A40 <- coefTecEnergy_inputsSimul
P <- B8
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE40 <- FluxoEnergiaSimul
#-------------------A45--------------------------------------------
ME <- EI-(EI*0.45)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
 0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
#output
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,
OS[1,4],OP[1,4]),SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B9 <- SEP
A45 <- coefTecEnergy_inputsSimul
P <- B9
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE45 <- FluxoEnergiaSimul
#-------------------A50--------------------------------------------
ME <- EI-(EI*0.50)
#Energy input matrix
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,
OS[1,4],OP[1,4]),SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
```

```
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Simulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B10 <- SEP
A50 <- coefTecEnergy_inputsSimul
P <- B10
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE50 <- FluxoEnergiaSimul
#------------------A55-----------------------------------------
ME <- EI-(EI*0.55)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
 0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,
OS[1,4],OP[1,4]),SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Siulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B11 <- SEP
A55 <- coefTecEnergy_inputsSimul
P <- B11
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5] ), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE55 <- FluxoEnergiaSimul
#------------------A60-----------------------------------------
ME <- EI-(EI*0.60)
SE<-matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[2,1]
,EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0, 0,0,SM(,ME[4,3],EI[4,3]),0,0,
 0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<-matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,
OS[1,4],OP[1,4]),SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP #Gross_Outpt based on Siulation
coefTecEnergy_inputsSimul <- SE%*%ym2 #- Pode ser original (ym) ou simulado (ym2)
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B12 <- SEP
A60 <- coefTecEnergy_inputsSimul
```

```
P <- B12
produto<- matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-P[4],0,0,0,0,P[5]), nrow=5,ncol=5,
byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto #Coeficietes de fluxo
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE60 <- FluxoEnergiaSimul
```

11 - OBTÉM FLUXO DE ENERGIA PARA O PROCESSO Q

```
FLE <- cbind(FE5[,5],FE10[,5],FE15[,5],FE20[,5],FE25[,5],FE30[,5],FE35[,5],
          FE40[,5],FE45[,5],FE50[,5],FE55[,5],FE60[,5])
```

12 - ÍNDICE GLOBAL GERAL BASEADO NO FLUXO DE ENERGIA

```
onze <- 2:12 # variável tempo 11
doze <- 1:12# variável tempo 12
tFLE <- t(FLE)
apl <- apply(tFLE[,1:5],1, sum)
GENERGY<cbind((min(apl)/apl[1]),(min(apl)/apl[2]),(min(apl)/apl[3]),(min(apl)/apl[4]),(min(apl)/apl[5]),(min(ap
l)/apl[6]),(min(apl)/apl[7]),(min(apl)/apl[8]),(min(apl)/apl[9]),(min(apl)/apl[10]),(min(apl)/apl[11]),(min(apl)/ap
l[12]))GlobalEnergy <- data.frame(
  expand.grid(indSimples=c("Global"),
           processo=c("T"),
           tempo=c(doze),
           energy=c("energy")),
  eff=c(GENERGY))
```

13 - GLOBAL ELETRICIDADE

```
FELEQ <- FLE[1,]
SELEC <- cbind((min(FELEQ)/FELEQ[1]),(min(FELEQ)/FELEQ[2]), (min(FELEQ)/FELEQ[3]),(min(FELEQ)/FELEQ[4]),
 (min(FELEQ)/FELEQ[5]),(min(FELEQ)/FELEQ[6]),(min(FELEQ)/FELEQ[7]),(min(FELEQ)/FELEQ[8]),(min(FELEQ)
/FELEQ[9]),(min(FELEQ)/FELEQ[10]),(min(FELEQ)/FELEQ[11]),(min(FELEQ)/FELEQ[12]))
GlobalElec <- data.frame(
  expand.grid(indSimples=c("Global"),
           processo=c("T"),
           tempo=c(doze),
           energy=c("Elec")),
  eff=c(SELEC))
```

14 - GLOBAL TÉRMICA

```
FTHERM <- FLE[2,]
STHERM<-
cbind((min(FTHERM)/FTHERM[1]),(min(FTHERM)/FTHERM[2]),(min(FTHERM)/FTHERM[3]),(min(FTHERM)/FTHE
RM[4]),(min(FTHERM)/FTHERM[5]),(min(FTHERM)/FTHERM[6]),(min(FTHERM)/FTHERM[7]),(min(FTHERM)/FTH
ERM[8]),(min(FTHERM)/FTHERM[9]),(min(FTHERM)/FTHERM[10]),(min(FTHERM)/FTHERM[11]),(min(FTHERM)/
FTHERM[12]))
GlobalTherm <- data.frame(
  expand.grid(indSimples=c("Global"),
           processo=c("T"),
           tempo=c(doze),
           energy=c("Therm")),
  eff=c(STHERM))
```

15 - GLOBAL ÓLEO

```
FOIL <- FLE[3,]
SOIL<-
cbind((min(FOIL)/FOIL[1]),(min(FOIL)/FOIL[2]),(min(FOIL)/FOIL[3]),(min(FOIL)/FOIL[4]),(min(FOIL)/FOIL[5]),(min
(FOIL)/FOIL[6]),(min(FOIL)/FOIL[7]),(min(FOIL)/FOIL[8]),(min(FOIL)/FOIL[9]),(min(FOIL)/FOIL[10]),(min(FOIL)/FOI
L[11]),(min(FOIL)/FOIL[12]))
GlobalOil <- data.frame(
  expand.grid(indSimples=c("Global"),
           processo=c("T"),
```

```
            tempo=c(doze),
            energy=c("Oil")),
  eff=c(SOIL))
```

16 - GLOBAL DIESEL

```
FDiesel <- FLE[4,]
SDiesel<-
cbind((min(FDiesel)/FDiesel[1]),(min(FDiesel)/FDiesel[2]),(min(FDiesel)/FDiesel[3]),(min(FDiesel)/FDiesel[4])
,(min(FDiesel)/FDiesel[5]),(min(FDiesel)/FDiesel[6]), (min(FDiesel)/FDiesel[7]),(min(FDiesel)/FDiesel[8]),(min
(FDiesel)/FDiesel[9]),(min(FDiesel)/FDiesel[10]), (min(FDiesel)/FDiesel[11]),(min(FDiesel)/FDiesel[12]))
GlobalSDiesel <- data.frame(
  expand.grid(indSimples=c("Global"),
            processo=c("T"),
            tempo=c(doze),
            energy=c("Diesel")),
  eff=c(SDiesel))
```

17 - GLOBAL GÁS

```
FGas <- FLE[5,]
SGas<-cbind((min(FGas)/FGas[1]),(min(FGas)/FGas[2]),(min(FGas)/FGas[3]),(min(FGas)/FGas[4]),(min(FGas)/
FGas[5]),(min(FGas)/FGas[6]),(min(FGas)/FGas[7]),(min(FGas)/FGas[8]),(min(FGas)/FGas[9]),(min(FGas)/FGas[1
0]),(min(FGas)/FGas[11]),(min(FGas)/FGas[12]))
GlobalGas <- data.frame(
  expand.grid(indSimples=c("Global"),
            processo=c("T"),
            tempo=c(doze),
            energy=c("Gas")),
  eff=c(SGas))
```

18 - INDICADOR DE MUDANÇA PROCESSO M

```
EFM <- cbind((A10/A5-1)[1:3,1], (A15/A10-1)[1:3,1], (A20/A15-1)[1:3,1],(A25/A20-1)[1:3,1], (A30/A25-1)[1:3,1],
       (A35/A30-1)[1:3,1], (A40/A35-1)[1:3,1], (A45/A40-1)[1:3,1], (A50/A45-1)[1:3,1], (A55/A50-1)[1:3,1],
(A60/A55-1)[1:3,1])
EFMSinal <- -EFM
dd <- t(EFMSinal)
dd1 <- t(dd[,1])
dd2 <- t(dd[,2])
dd3 <- t(dd[,3])
hh <- rbind(t(dd1), t(dd2), t(dd3))
efficM <- data.frame(
expand.grid(indSimples=c("IndSimp"),
            processo=c("M"),
            tempo=c(onze),
            energy=c("Elec", "Therm", "Oil")),
  eff=c(hh))
```

19 - INDICADOR DE MUDANÇA PROCESSO N

```
EFN <- cbind((A10/A5-1)[c(2,5),2], (A15/A10-1)[c(2,5),2], (A20/A15-1)[c(2,5),2],(A25/A20-1)[c(2,5),2], (A30/A25-
1)[c(2,5),2],(A35/A30-1)[c(2,5),2],(A40/A35-1)[c(2,5),2], (A45/A40-1)[c(2,5),2], (A50/A45-1)[c(2,5),2], (A55/A50-
1)[c(2,5),2], (A60/A55-1)[c(2,5),2])
EFNSinal <- -EFN
dd <- t(EFNSinal)
dd1 <- t(dd[,1])
dd2 <- t(dd[,2])
hh <- rbind(t(dd1), t(dd2))
efficN <- data.frame(
  expand.grid(indSimples=c("IndSimp"),
            processo=c("N"),
            tempo=c(onze),
            energy=c("Therm", "Gas")),
```

```
  eff=c(hh))
```

20 - INDICADOR DE MUDANÇA PROCESSO O

```
EFO<-cbind((A10/A5-1)[c(1,2,4,5),3],(A15/A10-1)[c(1,2,4,5),3],(A20/A15-1)[c(1,2,4,5),3],(A25/A20-1)[c(1,2,4,5)
,3],(A30/A25-1)[c(1,2,4,5),3],(A35/A30-1)[c(1,2,4,5),3],(A40/A35-1)[c(1,2,4,5),3],(A45/A40-1)[c(1,2,4,5),3],(A50/
A45-1)[c(1,2,4,5),3], (A55/A50-1)[c(1,2,4,5),3], (A60/A55-1)[c(1,2,4,5),3])
EFOSinal <- -EFO
dd <- t(EFOSinal)
dd1 <- t(dd[,1])
dd2 <- t(dd[,2])
dd3 <- t(dd[,3])
dd4 <- t(dd[,4])
hh <- rbind(t(dd1), t(dd2), t(dd3),t(dd4))
efficO <- data.frame(
expand.grid(indSimples=c("IndSimp"),
            processo=c("O"),
            tempo=c(onze),
            energy=c("Elec", "Therm", "Diesel","Gas" )),
  eff=c(hh))
```

21 - INDICADOR DE MUDANÇA PROCESSO P

```
EFP <- cbind((A10/A5-1)[1,4], (A15/A10-1)[1,4], (A20/A15-1)[1,4],(A25/A20-1)[1,4], (A30/A25-1)[1,4],(A35/A30
-1)[1,4], (A40/A35-1)[1,4], (A45/A40-1)[1,4], (A50/A45-1)[1,4], (A55/A50-1)[1,4], (A60/A55-1)[1,4])
EFPSinal <- -EFP
dd <- t(EFPSinal)
dd1 <- t(dd[,1])
hh <- rbind(t(dd1))
efficP <- data.frame(
  expand.grid(indSimples=c("IndSimp"),
            processo=c("P"),
            tempo=c(onze),
            energy=c("Elec")),
  eff=c(hh))
```

22 - INDICADOR DE MUDANÇA PROCESSO Q

```
EFQ <- cbind((A10/A5-1)[1,5], (A15/A10-1)[1,5], (A20/A15-1)[1,5],(A25/A20-1)[1,5], (A30/A25-1)[1,5],(A35/A30
-1)[1,5], (A40/A35-1)[1,5], (A45/A40-1)[1,5], (A50/A45-1)[1,5], (A55/A50-1)[1,5], (A60/A55-1)[1,5])
EFQSinal <- -EFQ
dd <- t(EFQSinal)
dd1 <- t(dd[,1])
hh <- rbind(t(dd1))
efficQ <- data.frame(
  expand.grid(indSimples=c("IndSimp"),
            processo=c("Q"),
            tempo=c(onze),
            energy=c("Elec")),
  eff=c(hh))
```

23 - CONSTUÇÃO DA BASE PARA O INDICADOR DE EFICIÊNCIA DIRETA

```
sim2 <- rbind(A5, A10, A15, A20, A25, A30, A35, A40, A45, A50, A55, A60)
fontes <- rownames(sim2)
oo2 <- as.data.frame(sim2, row.names=FALSE)
oo2$Fonte <- fontes
attach(oo2)
```

24 - PROCESSO M INDICADOR DE EFICIÊNCIA DIRETA

```
energyME <- t(as.matrix(oo2[Fonte == "Electric",-(6)]))
ElecM <- energyME[1,]
ELM <- cbind((min(ElecM)/ElecM[1]),(min(ElecM)/ElecM[2]), (min(ElecM)/ElecM[3]),(min(ElecM)/ElecM[4]),
(min(ElecM)/ElecM[5]),(min(ElecM)/ElecM[6]),(min(ElecM)/ElecM[7]),(min(ElecM)/ElecM[8]),(min(ElecM)
/ElecM[9]),(min(ElecM)/ElecM[10]),(min(ElecM)/ElecM[11]),(min(ElecM)/ElecM[12]))
efficELM <- data.frame(
```

```
 expand.grid(indSimples=c("IndGen"),
       processo=c("M"),
       tempo=c(doze),
       energy=c("Elec")),
 eff=c(ELM))
energyMT <- t(as.matrix(oo2[Fonte == "Thermal",-(6)]))
ThermM<-energyMT[1,]THM<-cbind((min(ThermM)/ThermM[1]),(min(ThermM)/ThermM[2]), (min(ThermM)
/ThermM[3]),(min(ThermM)/ThermM[4]),(min(ThermM)/ThermM[5]),(min(ThermM)/ThermM[6]),(min(Therm
M)/ThermM[7]),(min(ThermM)/ThermM[8]),(min(ThermM)/ThermM[9]),(min(ThermM)/ThermM[10]),(min(Th
ermM)/ThermM[11]),(min(ThermM)/ThermM[12]))
efficTHM <- data.frame(
 expand.grid(indSimples=c("IndGen"),
       processo=c("M"),
       tempo=c(doze),
       energy=c("Therm")),
 eff=c(THM))
energyMO <- t(as.matrix(oo2[Fonte == "oil",-(6)]))
OilM <- energyMO[1,]
OIM<- cbind((min(OilM)/OilM[1]),(min(OilM)/OilM[2]), (min(OilM)/OilM[3]),(min(OilM)/OilM[4]),(min(OilM)
/OilM[5]),(min(OilM)/OilM[6]),(min(OilM)/OilM[7]),(min(OilM)/OilM[8]),(min(OilM)/OilM[9]),(min(OilM)
/OilM[10]),(min(OilM)/OilM[11]),(min(OilM)/OilM[12]))
efficOIM <- data.frame(
expand.grid(indSimples=c("IndGen"),
       processo=c("M"),
       tempo=c(doze),
       energy=c("Oil")),
 eff=c(OIM))
```

25 - PROCESSO N INDICADOR DE EFICIÊNCIA DIRETA

```
energyNT <- t(as.matrix(oo2[Fonte == "Thermal",-(6)]))
ThermN<-energyNT[2,]THN<-cbind((min(ThermN)/ThermN[1]),(min(ThermN)/ThermN[2]), (min(ThermN)/
ThermN[3]),(min(ThermN)/ThermN[4]),(min(ThermN)/ThermN[5]),(min(ThermN)/ThermN[6]),(min(ThermN)/T
hermN[7]),(min(ThermN)/ThermN[8]),(min(ThermN)/ThermN[9]),(min(ThermN)/ThermN[10]),(min(ThermN)/T
hermN[11]),(min(ThermN)/ThermN[12]))
efficTHN <- data.frame(
 expand.grid(indSimples=c("IndGen"),
       processo=c("N"),
       tempo=c(doze),
       energy=c("Therm")),
 eff=c(THN))
energyNG <- t(as.matrix(oo2[Fonte == "Gas",-(6)]))
GasN <- energyNG[2,]
GAN<- cbind((min(GasN)/GasN[1]),(min(GasN)/GasN[2]), (min(GasN)/GasN[3]),(min(GasN)/GasN[4]),(min(
GasN)/GasN[5]),(min(GasN)/GasN[6]),(min(GasN)/GasN[7]),(min(GasN)/GasN[8]),(min(GasN)/GasN[9])
,(min(GasN)/GasN[10]),(min(GasN)/GasN[11]),(min(GasN)/GasN[12]))
efficGAN <- data.frame(
 expand.grid(indSimples=c("IndGen"),
       processo=c("N"),
       tempo=c(doze),
       energy=c("Gas")),
 eff=c(GAN))
```

26 - PROCESSO O INDICADOR DE EFICIÊNCIA DIRETA

```
energyOE <- t(as.matrix(oo2[Fonte == "Electric",-(6)]))
ElecO <- energyOE[3,]
ELO <- cbind((min(ElecO)/ElecO[1]),(min(ElecO)/ElecO[2]), (min(ElecO)/ElecO[3]),(min(ElecO)/ElecO[4]),(min
(ElecO)/ElecO[5]),(min(ElecO)/ElecO[6]),(min(ElecO)/ElecO[7]),(min(ElecO)/ElecO[8]),(min(ElecO)/ElecO[9])
,(min(ElecO)/ElecO[10]),(min(ElecO)/ElecO[11]),(min(ElecO)/ElecO[12]))
```

```
efficELO <- data.frame(
  expand.grid(indSimples=c("IndGen"),
            processo=c("O"),
            tempo=c(doze),
            energy=c("Elec")),
  eff=c(ELO))
energyOT <- t(as.matrix(oo2[Fonte == "Thermal",-(6)]))
ThermO<-energyOT[3,]THO<-cbind((min(ThermO)/ThermO[1]),(min(ThermO)/ThermO[2]), (min(ThermO)/
ThermO[3]),(min(ThermO)/ThermO[4]),(min(ThermO)/ThermO[5]),(min(ThermO)/ThermO[6]),(min(ThermO)/T
hermO[7]),(min(ThermO)/ThermO[8]),(min(ThermO)/ThermO[9]),(min(ThermO)/ThermO[10]),(min(ThermO)/T
hermO[11]),(min(ThermO)/ThermO[12]))
efficTHO <- data.frame(
  expand.grid(indSimples=c("IndGen"),
            processo=c("O"),
            tempo=c(doze),
            energy=c("Therm")),
  eff=c(THO))
energyOD <- t(as.matrix(oo2[Fonte == "Diesel",-(6)]))
DieselO<-energyOD[3,]DIO<-cbind((min(DieselO)/DieselO[1]),(min(DieselO)/DieselO[2]), (min(DieselO)/
DieselO[3]),(min(DieselO)/DieselO[4]),(min(DieselO)/DieselO[5]),(min(DieselO)/DieselO[6]),(min(DieselO)/Diese
lO[7]),(min(DieselO)/DieselO[8]),(min(DieselO)/DieselO[9]),(min(DieselO)/DieselO[10]),(min(DieselO)/DieselO[1
1]),(min(DieselO)/DieselO[12]))
efficDIO <- data.frame(
  expand.grid(indSimples=c("IndGen"),
            processo=c("O"),
            tempo=c(doze),
            energy=c("Diesel")),
  eff=c(DIO))
energyOG <- t(as.matrix(oo2[Fonte == "Gas",-(6)]))
GasO <- energyOG[3,]
GAO<-cbind((min(GasO)/GasO[1]),(min(GasO)/GasO[2]),(min(GasO)/GasO[3]),(min(GasO)/GasO[4]),(min(GasO)
/GasO[5]),(min(GasO)/GasO[6]),(min(GasO)/GasO[7]),(min(GasO)/GasO[8]),(min(GasO)/GasO[9]),(min(GasO)/
GasO[10]),(min(GasO)/GasO[11]),(min(GasO)/GasO[12]))
efficGAO <- data.frame(
  expand.grid(indSimples=c("IndGen"),
            processo=c("O"),
            tempo=c(doze),
            energy=c("Gas")),
  eff=c(GAO))
```

27 - PROCESSO P INDICADOR DE EFICIÊNCIA DIRETA

```
energyPE <- t(as.matrix(oo2[Fonte == "Electric",-(6)]))
ElecP <- energyPE[4,]
ELP <- cbind((min(ElecP)/ElecP[1]),(min(ElecP)/ElecP[2]), (min(ElecP)/ElecP[3]),(min(ElecP)/ElecP[4]),(min
(ElecP)/ElecP[5]),(min(ElecP)/ElecP[6]),(min(ElecP)/ElecP[7]),(min(ElecP)/ElecP[8]),(min(ElecP)/ElecP[9])
,(min(ElecP)/ElecP[10]),(min(ElecP)/ElecP[11]),(min(ElecP)/ElecP[12]))
efficELP <- data.frame(
  expand.grid(indSimples=c("IndGen"),
            processo=c("P"),
            tempo=c(doze),
            energy=c("Elec")),
  eff=c(ELP))
```

28 - PROCESSO Q INDICADOR DE EFICIÊNCIA DIRETA

```
energyQE <- t(as.matrix(oo2[Fonte == "Electric",-(6)]))
ElecQ <- energyQE[5,]
ELQ <- cbind((min(ElecQ)/ElecQ[1]),(min(ElecQ)/ElecQ[2]), (min(ElecQ)/ElecQ[3]),(min(ElecQ)/ElecQ[4]),(min
(ElecQ)/ElecQ[5]),(min(ElecQ)/ElecQ[6]),(min(ElecQ)/ElecQ[7]),(min(ElecQ)/ElecQ[8]),(min(ElecQ)/ElecQ[9])
,(min(ElecQ)/ElecQ[10]),(min(ElecQ)/ElecQ[11]),(min(ElecQ)/ElecQ[12]))
```

```
efficELQ <- data.frame(
  expand.grid(indSimples=c("IndGen"),
            processo=c("Q"),
            tempo=c(doze),
            energy=c("Elec")),
  eff=c(ELQ))
```

29 - DADOS PARA O DEA

```
library(Benchmarking)
sim3 <- rbind(B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12)
oo3 <- as.data.frame(sim3,  row.names=FALSE)
```

30 - PROCESSO M - DEA

```
ElectricM <- oo2[(Fonte =="Electric"),][,1]
oilM <- oo2[(Fonte =="oil"),][,1]
ThermalM <- oo2[(Fonte =="Thermal"),][,1]
tedM <- as.data.frame(cbind(ElectricM, oilM, ThermalM))
## IMPUTS
xM <- with(tedM, cbind( ElectricM, OilM, ThermalM))
## OUTPUT
yM <- matrix(with(oo3, M))
teM <- dea(xM,yM,RTS="crs")
DEAM <- teM$eff
```

31 - PROCESSO N - DEA

```
ThermalN <- oo2[(Fonte =="Thermal"),][,2]
GasN <- oo2[(Fonte =="Gas"),][,2]
tedN <- as.data.frame(cbind(ThermalN, GasN))
## IMPUTS
xN <- with(tedN, cbind( ThermalN, GasN))
## OUTPUT
yN <- matrix(with(oo3, N))
teN <- dea(xN,yN,RTS="crs")
DEAN <- teN$eff
```

32 - PROCESSO O - DEA

```
ElectricO <- oo2[(Fonte =="Electric"),][,3]
ThermalO <- oo2[(Fonte =="Thermal"),][,3]
GDieselO <- oo2[(Fonte =="Diesel"),][,3]
GasO <- oo2[(Fonte =="Gas"),][,3]
tedO <- as.data.frame(cbind(ElectricO, ThermalO, GDieselO,GasO ))
#INPUTS
xO <- with(tedO, cbind( ElectricO, ThermalO, GDieselO,GasO))
## OUTPUT
yO <- matrix(with(oo3, O))
teO <- dea(xO,yO,RTS="crs")
DEAO <- teO$eff
```

33 - PROCESSO P - DEA

```
ElectricP <- oo2[(Fonte =="Electric"),][,4]
tedP <- as.data.frame(cbind(ElectricP))
## IMPUTS
xP <- with(tedP, cbind(ElectricP ))
## OUTPUT
yP <- matrix(with(oo3, P))
teP <- dea(xP,yP,RTS="crs")
DEAP <- teP$eff
```

34 - PROCESSO Q DEA

```
ElectricQ <- oo2[(Fonte =="Electric"),][,5]
tedQ <- as.data.frame(cbind(ElectricQ))
## IMPUTS
```

```
xQ <- with(tedP, cbind(ElectricQ ))
## OUTPUT
yQ <- matrix(with(oo3, Q))
teQ <- dea(xQ,yQ,RTS="crs")
DEAQ <- teQ$eff
```

35 - JUNÇÃO DOS MODELOS DEA

```
efficDEAM <- data.frame(
  expand.grid(indSimples=c("DEA"),
             processo=c("M"),
             tempo=c(doze),
             energy=c("ALL")),
  eff=c(DEAM))
efficDEAN <- data.frame(
  expand.grid(indSimples=c("DEA"),
             processo=c("N"),
             tempo=c(doze),
             energy=c("ALL")),
  eff=c(DEAN))
efficDEAO <- data.frame(
  expand.grid(indSimples=c("DEA"),
             processo=c("O"),
             tempo=c(doze),
             energy=c("ALL")),
  eff=c(DEAO))
efficDEAP <- data.frame(
  expand.grid(indSimples=c("DEA"),
             processo=c("P"),
             tempo=c(doze),
             energy=c("ALL")),
  eff=c(DEAP))
efficDEAQ <- data.frame(
  expand.grid(indSimples=c("DEA"),
             processo=c("Q"),
             tempo=c(doze),
             energy=c("ALL")),
  eff=c(DEAQ))
DEAT <- (rbind(efficDEAM,efficDEAN, efficDEAO, efficDEAP, efficDEAQ))
```

36 - AGREGAÇÃO TOTAL E CRIAÇÃO DO DATAFRAME

```
rr3 <- rbind(efficM, efficN, efficO, efficP, efficQ, efficELM, efficTHM,
            efficOIM, efficTHN, efficGAN, efficELO, efficTHO, efficDIO,
            efficGAO, efficELP, efficELQ, DEAT, GlobalEnergy, GlobalElec,
            GlobalTherm, GlobalOil, GlobalSDiesel, GlobalGas)
todos <- as.data.frame(rr3)
#EXPORTA PARA O EXCEL
library(excel.link)
dados <- rr3
xlrc[a1] <- dados
```

37 - FUNÇÃO MULTPLOT -http://www.cookbook-.com/Graphs/Multiple_graphs_on_one_page_(ggplot2)/

```
multiplot <- function(..., plotlist=NULL, file, cols=1, layout=NULL) {
  library(grid)
  # Make a list from the ... arguments and plotlist
  plots <- c(list(...), plotlist)
  numPlots = length(plots)
  # If layout is NULL, then use 'cols' to determine layout
  if (is.null(layout)) {
    # Make the panel
    # ncol: Number of columns of plots
```

```
  # nrow: Number of rows needed, calculated from # of cols
  layout <- matrix(seq(1, cols * ceiling(numPlots/cols)),
          ncol = cols, nrow = ceiling(numPlots/cols))
 }
  if (numPlots==1) {
  print(plots[[1]])
 } else {
  # Set up the page
  grid.newpage()
  pushViewport(viewport(layout = grid.layout(nrow(layout), ncol(layout))))
  # Make each plot, in the correct location
  for (i in 1:numPlots) {
   # Get the i,j matrix positions of the regions that contain this subplot
   matchidx <- as.data.frame(which(layout == i, arr.ind = TRUE))
   print(plots[[i]], vp = viewport(layout.pos.row = matchidx$row,
                  layout.pos.col = matchidx$col))
  }
 }
}
```

38 - CARREGAR PACOTES

```
library(ggplot2)
library(vcd)
library(vcdExtra)
library(MASS)
```

39 - CONSTRUÇÃO DE GRÁFICOS GGPLOT E MOSAICO

```
EIM <- EI
lin <-c("Electric", "Thermal", "oil", "Diesel","Gas" )
col <- c("M", "N", "O", "P", "Q")
dimnames(EIM) = list(Energy_Kcal=c(lin), processes=c(col))
dimnames(coefTecEnergy_inputs) = list(Energy_Kcal=c(lin), processes=c(col))
mosaic(EIM/10000, gp = shading_max)
FluxoEn <- FluxoEnergia
dimnames(FluxoEn) = list(Energy_Kcal=c(lin), processes=c(col))
tile(FluxoEn/10000, tile_type = "area", halign = "center", valign = "center", shade=TRUE)
```

40 - MOSAICO DO FLUXO

```
EFM <- as.table(FluxoEnergia)
dimnames(EFM) = list(Energia_Kcal=c(lin), processo=c(col))
expected <- independence_table(EFM)
(x <- (EFM - expected)/sqrt(expected))
shading2_fun <- function(x) gpar(fill = ifelse(x > 0, "azure", "darkgoldenrod1"))
mosaic(EFM, gp = shading2_fun)
```

41 - PAINEL DE INDICADORES - EFICIÊNCIA ENERGÉTICA DIRETA

```
ind2<-todos[(todos$indSimples =="IndGen") ,]
x <- ind2$eff
ind2$x <-
Efficiency <- cut(x, breaks = c(0,0.75,0.85,0.95, 1), labels = c("0.0-0.75","0.76-0.85","0.86-0.95", "0.96-1.0"))
ind2$Efficiency <- Efficiency
k <- ggplot(ind2, aes(factor(tempo), eff)) + facet_grid(processo ~ energy)
k + geom_bar(stat = "identity", aes(fill=factor(Efficiency),width=0.8)) + scale_fill_manual(values =
(c("red","khaki1","slategray1", "green")))+ theme_bw()+
labs(title = "EXTENDED ENTERPRISE - ENERGY MATRIX") + xlab("TIME") + ylab("INDICATOR - DIRECT ENERGY
EFFICIENCY")+
theme(legend.position = "bottom", legend.box = "horizontal")
```

42 - PAINEL DE INDICADORES - MUDANÇA EFICIÊNCIA ENERGÉTICA DIRETA

```
ind2<-todos[(todos$indSimples =="IndSimp") ,]
Efficiency <- ind2$eff
```

```
shading1_obj <- ifelse(Efficiency > 0, "A-POSITIVE", "B-NEGATIVE")
ind2$Efficiency <- shading1_obj
k <- ggplot(ind2, aes(factor(tempo), eff)) + facet_grid(processo ~ energy)
k + geom_bar(stat = "identity", aes(fill=factor(Efficiency))) + scale_fill_manual(values = (c("green", "red")))+
theme_bw()+
labs(title = "EXTENDED ENTERPRISE - ENERGY MATRIX") + xlab("TIME") + ylab("INDICATOR - CHANGE IN
DIRECT ENERGY EFFICIENCY")+
theme(legend.position = "bottom", legend.box = "horizontal")
```

43 - STARIRCASE GRAPHIC - ELETRICIDADE PROCESSO O

```
balance <- data.frame(
  desc = c(2:12),
  amount = c(EFOSinal[1,]))
balance$desc <- factor(balance$desc, levels = balance$desc)
balance$id <- seq_along(balance$amount)
balance$type <- ifelse(balance$amount > 0, "+", "-")
balance$type <- factor(balance$type, levels = c("+","-"))
balance$end <- cumsum(balance$amount)
balance$start <- c(0, head(balance$end, -1))
balance$type <- as.factor(balance$type)
p1 <- ggplot(balance, aes(desc, fill=type)) + geom_rect(aes(x=desc,xmin = id - 0.45,
                                                  xmax=id + 0.45, ymin=end, ymax=start))
pp1 <- p1 + scale_fill_manual(values = (c("palegreen1", "red")))+ theme_bw()+
  theme(legend.position = "right", legend.box = "horizontal")+
  labs(title = "Process O - Electric")  + xlab("Time") + ylab("Change in Efficiency")
```

44 - STARIRCASE GRAPHIC - TÉRMICA PROCESSO O

```
balance <- data.frame(
  desc = c(2:12),
  amount = c(EFOSinal[2,]))
balance$desc <- factor(balance$desc, levels = balance$desc)
balance$id <- seq_along(balance$amount)
balance$type <- ifelse(balance$amount > 0, "+", "-")
balance$type <- factor(balance$type, levels = c("+","-"))#mudança da cor
balance$end <- cumsum(balance$amount)
balance$start <- c(0, head(balance$end, -1))
#balance <- balance[, c(3, 1, 4, 6, 5,2)]
balance$type <- as.factor(balance$type)
p1 <- ggplot(balance, aes(desc, fill=type)) + geom_rect(aes(x=desc,xmin = id - 0.45,
                                                  xmax=id + 0.45, ymin=end, ymax=start))
pp2 <- p1 + scale_fill_manual(values = (c("palegreen1", "red")))+ theme_bw()+ theme(legend.position = "right",
legend.box = "horizontal")+
  labs(title = "Process O - Thermal")  + xlab("Time") + ylab("Change in Efficiency")
```

45 - STARIRCASE GRAPHIC - DIESEL PROCESSO O

```
balance <- data.frame(
  desc = c(2:12),
  amount = c(EFOSinal[3,]))
balance$desc <- factor(balance$desc, levels = balance$desc)
balance$id <- seq_along(balance$amount)
balance$type <- ifelse(balance$amount > 0, "+", "-")
balance$type <- factor(balance$type, levels = c("+","-"))#mudança da cor
balance$end <- cumsum(balance$amount)
balance$start <- c(0, head(balance$end, -1))
#balance <- balance[, c(3, 1, 4, 6, 5,2)]
balance$type <- as.factor(balance$type)
p1 <- ggplot(balance, aes(desc, fill=type)) + geom_rect(aes(x=desc,xmin = id - 0.45,
                                                  xmax=id + 0.45, ymin=end, ymax=start))
pp3 <- p1 + scale_fill_manual(values = (c("palegreen1", "red")))+ theme_bw()+ theme(legend.position = "right",
legend.box = "horizontal")+
```

```
  labs(title = "Process O - Diesel")  + xlab("Time") + ylab("Change in Efficiency")
```

46 - STARIRCASE GRAPHIC - GÁS PROCESSO O

```
balance <- data.frame(
  desc = c(2:12),
  amount = c(EFOSinal[4,]))
balance$desc <- factor(balance$desc, levels = balance$desc)
balance$id <- seq_along(balance$amount)
balance$type <- ifelse(balance$amount > 0, "+", "-")
balance$type <- factor(balance$type, levels = c("+","-"))#mudança da cor
balance$end <- cumsum(balance$amount)
balance$start <- c(0, head(balance$end, -1))
#balance <- balance[, c(3, 1, 4, 6, 5,2)]
balance$type <- as.factor(balance$type)
p1 <- ggplot(balance, aes(desc, fill=type)) + geom_rect(aes(x=desc,xmin = id - 0.45,
                                                          xmax=id + 0.45, ymin=end, ymax=start))
pp4 <- p1 + scale_fill_manual(values = (c("palegreen1", "red")))+ theme_bw()+ theme(legend.position = "right",
legend.box = "horizontal")+
  labs(title = "Process O - Gas")  + xlab("Time") + ylab("Change in Efficiency")
```

47 - PLOTA COM A FUNÇÃO MULTPLOT

```
multiplot(pp1, pp2, pp4, pp3, cols=2)
```

48- PAINEL EFICIÊNCIA RELATIVA

```
ind2<-todos[(todos$indSimples =="DEA") ,]
x <- ind2$eff
ind2$x <-
  Efficiency <- cut(x, breaks = c(0,0.75,0.85,0.95, 1), labels = c("0.0-0.75","0.76-0.85","0.86-0.95", "0.96-1.0"))
ind2$Efficiency <- Efficiency
k <- ggplot(ind2, aes(factor(tempo), eff)) + geom_bar(stat = "identity", aes(fill=factor(Efficiency),width=0.8)) +
scale_fill_manual(values = (c("red","khaki1","slategray1", "green")))
deaeff <- k + facet_grid(processo ~energy)+ theme_minimal()+ theme(legend.position = "right", legend.box =
"horizontal")+
  labs(title = "Extended Enterprise - Energy Matrix")  + xlab("Time") + ylab("Relative Efficiency (Electric - Thermal
- Oil - Diesel - gas)")
```

49 - PAINEL EFICIÊNCIA GLOBAL

```
ind10<-todos[(todos$indSimples == "Global") & (todos$energy == "energy"),]
x <- ind10$eff
ind10$x <-
  Efficiency <- cut(x, breaks = c(0,0.75,0.85,0.95, 1), labels = c("0.0-0.75","0.76-0.85","0.86-0.95", "0.96-1.0"))
ind10$Efficiency <- Efficiency
k <- ggplot(ind10, aes(factor(tempo), eff)) + geom_bar(stat = "identity", aes(fill=factor(Efficiency),width=0.8)) +
scale_fill_manual(values = (c("red","khaki1","slategray1", "green")))
global <- k + facet_grid(processo ~ .)+ theme_minimal()+ theme(legend.position = "right", legend.box =
"horizontal")+
  labs(title = "Extended Enterprise - Energy Matrix") + xlab("Time") + ylab("Indirect Energy Efficiency in Process
Q (Packaged tiles) - Global Efficiency")+
  coord_flip()
```

50 - PAINEL EFICIÊNCIA RELATIVA E GLOBAL

```
multiplot(deaeff, global, cols=2)
```

APÊNDICE C

APÊNDICE C: EXEMPLO DO PAINEL DE INDICADORES

Tabela C1 - Exemplo do painel de indicadores – Figura 16

N	Indicador	Processo	Tempo	Energia	Eficiência	N	Indicador	Processo	Tempo	Energia	Eficiência
1	MUDANÇA	M	2	Elec	0,104301	193	DIRETA	O	12	Elec	0,548684
2	MUDANÇA	M	3	Elec	-0,052785	194	DIRETA	O	1	Therm	0,503816
3	MUDANÇA	M	4	Elec	0,135043	195	DIRETA	O	2	Therm	0,676493
4	MUDANÇA	M	5	Elec	-0,283721	196	DIRETA	O	3	Therm	0,399047
5	MUDANÇA	M	6	Elec	0,331024	197	DIRETA	O	4	Therm	0,826711
6	MUDANÇA	M	7	Elec	-0,025618	198	DIRETA	O	5	Therm	0,724714
7	MUDANÇA	M	8	Elec	-0,544621	199	DIRETA	O	6	Therm	0,594168
8	MUDANÇA	M	9	Elec	-0,089737	200	DIRETA	O	7	Therm	0,582003
9	MUDANÇA	M	10	Elec	0,298408	201	DIRETA	O	8	Therm	0,772663
10	MUDANÇA	M	11	Elec	-0,227423	202	DIRETA	O	9	Therm	0,510708
11	MUDANÇA	M	12	Elec	0,043519	203	DIRETA	O	10	Therm	0,568766
12	MUDANÇA	M	2	Therm	0,191814	204	DIRETA	O	11	Therm	1,000000
13	MUDANÇA	M	3	Therm	-0,196098	205	DIRETA	O	12	Therm	0,784327
14	MUDANÇA	M	4	Therm	0,146820	206	DIRETA	O	1	Diesel	0,426859
15	MUDANÇA	M	5	Therm	0,020741	207	DIRETA	O	2	Diesel	0,548913
16	MUDANÇA	M	6	Therm	0,097010	208	DIRETA	O	3	Diesel	0,359155
17	MUDANÇA	M	7	Therm	0,080105	209	DIRETA	O	4	Diesel	0,679747
18	MUDANÇA	M	8	Therm	-0,500107	210	DIRETA	O	5	Diesel	0,750193
19	MUDANÇA	M	9	Therm	-0,114017	211	DIRETA	O	6	Diesel	0,490315
20	MUDANÇA	M	10	Therm	0,114467	212	DIRETA	O	7	Diesel	0,416647
21	MUDANÇA	M	11	Therm	-0,056539	213	DIRETA	O	8	Diesel	1,000000
22	MUDANÇA	M	12	Therm	0,022054	214	DIRETA	O	9	Diesel	0,647288
23	MUDANÇA	M	2	Oil	0,207801	215	DIRETA	O	10	Diesel	0,691944
24	MUDANÇA	M	3	Oil	-0,111038	216	DIRETA	O	11	Diesel	0,677210
25	MUDANÇA	M	4	Oil	0,136519	217	DIRETA	O	12	Diesel	0,577194
26	MUDANÇA	M	5	Oil	-0,331384	218	DIRETA	O	1	Gas	0,416108
27	MUDANÇA	M	6	Oil	0,330539	219	DIRETA	O	2	Gas	0,567580
28	MUDANÇA	M	7	Oil	-0,037094	220	DIRETA	O	3	Gas	0,347678
29	MUDANÇA	M	8	Oil	-0,028896	221	DIRETA	O	4	Gas	0,671118
30	MUDANÇA	M	9	Oil	-0,097026	222	DIRETA	O	5	Gas	0,610231
31	MUDANÇA	M	10	Oil	-0,237893	223	DIRETA	O	6	Gas	0,571898
32	MUDANÇA	M	11	Oil	0,350963	224	DIRETA	O	7	Gas	0,535929
33	MUDANÇA	M	12	Oil	-1,137364	225	DIRETA	O	8	Gas	1,000000
34	MUDANÇA	N	2	Therm	-0,345713	226	DIRETA	O	9	Gas	0,431320
35	MUDANÇA	N	3	Therm	0,395068	227	DIRETA	O	10	Gas	0,708775
36	MUDANÇA	N	4	Therm	0,145000	228	DIRETA	O	11	Gas	0,451453
37	MUDANÇA	N	5	Therm	-0,159816	229	DIRETA	O	12	Gas	0,754635
38	MUDANÇA	N	6	Therm	-0,117389	230	DIRETA	P	1	Elec	0,510513
39	MUDANÇA	N	7	Therm	-0,734563	231	DIRETA	P	2	Elec	0,712931
40	MUDANÇA	N	8	Therm	0,214630	232	DIRETA	P	3	Elec	0,773321
41	MUDANÇA	N	9	Therm	0,565982	233	DIRETA	P	4	Elec	0,683073
42	MUDANÇA	N	10	Therm	-1,022594	234	DIRETA	P	5	Elec	1,000000
43	MUDANÇA	N	11	Therm	0,347883	235	DIRETA	P	6	Elec	0,608543
44	MUDANÇA	N	12	Therm	-0,002166	236	DIRETA	P	7	Elec	0,894584
45	MUDANÇA	N	2	Gas	-0,321691	237	DIRETA	P	8	Elec	0,783179
46	MUDANÇA	N	3	Gas	0,403424	238	DIRETA	P	9	Elec	0,785594
47	MUDANÇA	N	4	Gas	0,048843	239	DIRETA	P	10	Elec	0,932567
48	MUDANÇA	N	5	Gas	-0,015731	240	DIRETA	P	11	Elec	0,615633
49	MUDANÇA	N	6	Gas	-0,140695	241	DIRETA	P	12	Elec	0,806195
50	MUDANÇA	N	7	Gas	-0,609556	242	DIRETA	Q	1	Elec	0,600314
51	MUDANÇA	N	8	Gas	0,017799	243	DIRETA	Q	2	Elec	0,406064
52	MUDANÇA	N	9	Gas	0,580711	244	DIRETA	Q	3	Elec	0,531701
53	MUDANÇA	N	10	Gas	-1,418055	245	DIRETA	Q	4	Elec	0,403428

N	Indicador	Processo	Tempo	Energia	Eficiência	N	Indicador	Processo	Tempo	Energia	Eficiência
54	MUDANÇA	N	11	Gas	0,615228	246	DIRETA	Q	5	Elec	0,548978
55	MUDANÇA	N	12	Gas	-0,326586	247	DIRETA	Q	6	Elec	0,471721
56	MUDANÇA	O	2	Elec	0,222008	248	DIRETA	Q	7	Elec	0,551059
57	MUDANÇA	O	3	Elec	-0,584865	249	DIRETA	Q	8	Elec	1,000000
58	MUDANÇA	O	4	Elec	0,548344	250	DIRETA	Q	9	Elec	0,548237
59	MUDANÇA	O	5	Elec	-0,042211	251	DIRETA	Q	10	Elec	0,915613
60	MUDANÇA	O	6	Elec	-0,518921	252	DIRETA	Q	11	Elec	0,697790
61	MUDANÇA	O	7	Elec	0,138179	253	DIRETA	Q	12	Elec	0,631755
62	MUDANÇA	O	8	Elec	0,198358	254	DEA	M	1	ALL	0,584946
63	MUDANÇA	O	9	Elec	-0,324914	255	DEA	M	2	ALL	0,831895
64	MUDANÇA	O	10	Elec	-0,082014	256	DEA	M	3	ALL	0,649909
65	MUDANÇA	O	11	Elec	0,278342	257	DEA	M	4	ALL	0,924372
66	MUDANÇA	O	12	Elec	-0,610786	258	DEA	M	5	ALL	0,676355
67	MUDANÇA	O	2	Therm	0,255254	259	DEA	M	6	ALL	0,972877
68	MUDANÇA	O	3	Therm	-0,695271	260	DEA	M	7	ALL	1,000000
69	MUDANÇA	O	4	Therm	0,517307	261	DEA	M	8	ALL	0,671013
70	MUDANÇA	O	5	Therm	-0,140741	262	DEA	M	9	ALL	0,611665
71	MUDANÇA	O	6	Therm	-0,219714	263	DEA	M	10	ALL	0,532188
72	MUDANÇA	O	7	Therm	-0,020901	264	DEA	M	11	ALL	0,693031
73	MUDANÇA	O	8	Therm	0,246756	265	DEA	M	12	ALL	0,363987
74	MUDANÇA	O	9	Therm	-0,512924	266	DEA	N	1	ALL	0,507398
75	MUDANÇA	O	10	Therm	0,102077	267	DEA	N	2	ALL	0,283211
76	MUDANÇA	O	11	Therm	0,431234	268	DEA	N	3	ALL	0,791706
77	MUDANÇA	O	12	Therm	-0,274979	269	DEA	N	4	ALL	0,886823
78	MUDANÇA	O	2	Diesel	0,222356	270	DEA	N	5	ALL	0,806526
79	MUDANÇA	O	3	Diesel	-0,528349	271	DEA	N	6	ALL	0,619265
80	MUDANÇA	O	4	Diesel	0,471635	272	DEA	N	7	ALL	0,223868
81	MUDANÇA	O	5	Diesel	0,093903	273	DEA	N	8	ALL	0,264480
82	MUDANÇA	O	6	Diesel	-0,530021	274	DEA	N	9	ALL	1,000000
83	MUDANÇA	O	7	Diesel	-0,176812	275	DEA	N	10	ALL	0,301284
84	MUDANÇA	O	8	Diesel	0,583353	276	DEA	N	11	ALL	1,000000
85	MUDANÇA	O	9	Diesel	-0,544908	277	DEA	N	12	ALL	0,717326
86	MUDANÇA	O	10	Diesel	0,064538	278	DEA	O	1	ALL	0,402344
87	MUDANÇA	O	11	Diesel	-0,021757	279	DEA	O	2	ALL	0,709969
88	MUDANÇA	O	12	Diesel	-0,173280	280	DEA	O	3	ALL	0,254655
89	MUDANÇA	O	2	Gas	0,266873	281	DEA	O	4	ALL	1,000000
90	MUDANÇA	O	3	Gas	-0,632487	282	DEA	O	5	ALL	0,920838
91	MUDANÇA	O	4	Gas	0,481942	283	DEA	O	6	ALL	0,485316
92	MUDANÇA	O	5	Gas	-0,099776	284	DEA	O	7	ALL	0,490282
93	MUDANÇA	O	6	Gas	-0,067028	285	DEA	O	8	ALL	1,000000
94	MUDANÇA	O	7	Gas	-0,067115	286	DEA	O	9	ALL	0,432788
95	MUDANÇA	O	8	Gas	0,464071	287	DEA	O	10	ALL	0,430917
96	MUDANÇA	O	9	Gas	-1,318466	288	DEA	O	11	ALL	0,794366
97	MUDANÇA	O	10	Gas	0,391458	289	DEA	O	12	ALL	0,640600
98	MUDANÇA	O	11	Gas	-0,569987	290	DEA	P	1	ALL	0,319596
99	MUDANÇA	O	12	Gas	0,401760	291	DEA	P	2	ALL	0,606285
100	MUDANÇA	P	2	Elec	0,283923	292	DEA	P	3	ALL	0,715481
101	MUDANÇA	P	3	Elec	0,078092	293	DEA	P	4	ALL	0,529803
102	MUDANÇA	P	4	Elec	-0,132121	294	DEA	P	5	ALL	1,000000
103	MUDANÇA	P	5	Elec	0,316927	295	DEA	P	6	ALL	0,380965
104	MUDANÇA	P	6	Elec	-0,643270	296	DEA	P	7	ALL	0,693855
105	MUDANÇA	P	7	Elec	0,319748	297	DEA	P	8	ALL	0,666024
106	MUDANÇA	P	8	Elec	-0,142248	298	DEA	P	9	ALL	0,668078
107	MUDANÇA	P	9	Elec	0,003074	299	DEA	P	10	ALL	0,862816
108	MUDANÇA	P	10	Elec	0,157601	300	DEA	P	11	ALL	0,385404
109	MUDANÇA	P	11	Elec	-0,514809	301	DEA	P	12	ALL	0,444402
110	MUDANÇA	P	12	Elec	0,236372	302	DEA	Q	1	ALL	0,475075
111	MUDANÇA	Q	2	Elec	-0,478372	303	DEA	Q	2	ALL	0,208397
112	MUDANÇA	Q	3	Elec	0,236293	304	DEA	Q	3	ALL	0,383801
113	MUDANÇA	Q	4	Elec	-0,317958	305	DEA	Q	4	ALL	0,207045

N	Indicador	Processo	Tempo	Energia	Eficiência	N	Indicador	Processo	Tempo	Energia	Eficiência
114	MUDANÇA	Q	5	Elec	0,265128	306	DEA	Q	5	ALL	0,396272
115	MUDANÇA	Q	6	Elec	-0,163778	307	DEA	Q	6	ALL	0,274897
116	MUDANÇA	Q	7	Elec	0,143975	308	DEA	Q	7	ALL	0,397774
117	MUDANÇA	Q	8	Elec	0,448941	309	DEA	Q	8	ALL	1,000000
118	MUDANÇA	Q	9	Elec	-0,824030	310	DEA	Q	9	ALL	0,395737
119	MUDANÇA	Q	10	Elec	0,401235	311	DEA	Q	10	ALL	0,724595
120	MUDANÇA	Q	11	Elec	-0,312161	312	DEA	Q	11	ALL	0,600740
121	MUDANÇA	Q	12	Elec	-0,104526	313	DEA	Q	12	ALL	0,499957
122	DIRETA	M	1	Elec	0,700450	314	Global	T	1	energy	0,662914
123	DIRETA	M	2	Elec	0,782016	315	Global	T	2	energy	0,686051
124	DIRETA	M	3	Elec	0,742807	316	Global	T	3	energy	0,689809
125	DIRETA	M	4	Elec	0,858778	317	Global	T	4	energy	0,702641
126	DIRETA	M	5	Elec	0,668976	318	Global	T	5	energy	0,702431
127	DIRETA	M	6	Elec	1,000000	319	Global	T	6	energy	0,809963
128	DIRETA	M	7	Elec	0,975022	320	Global	T	7	energy	0,782073
129	DIRETA	M	8	Elec	0,631237	321	Global	T	8	energy	0,822527
130	DIRETA	M	9	Elec	0,579256	322	Global	T	9	energy	0,804155
131	DIRETA	M	10	Elec	0,825632	323	Global	T	10	energy	0,937766
132	DIRETA	M	11	Elec	0,672655	324	Global	T	11	energy	0,960311
133	DIRETA	M	12	Elec	0,703259	325	Global	T	12	energy	1,000000
134	DIRETA	M	1	Therm	0,670869	326	Global	T	1	Elec	0,713415
135	DIRETA	M	2	Therm	0,830092	327	Global	T	2	Elec	0,709006
136	DIRETA	M	3	Therm	0,694000	328	Global	T	3	Elec	0,739000
137	DIRETA	M	4	Therm	0,813428	329	Global	T	4	Elec	0,768208
138	DIRETA	M	5	Therm	0,830656	330	Global	T	5	Elec	0,796681
139	DIRETA	M	6	Therm	0,919895	331	Global	T	6	Elec	0,847478
140	DIRETA	M	7	Therm	1,000000	332	Global	T	7	Elec	0,911468
141	DIRETA	M	8	Therm	0,666619	333	Global	T	8	Elec	0,780177
142	DIRETA	M	9	Therm	0,598392	334	Global	T	9	Elec	0,806647
143	DIRETA	M	10	Therm	0,675742	335	Global	T	10	Elec	0,952435
144	DIRETA	M	11	Therm	0,639581	336	Global	T	11	Elec	0,933198
145	DIRETA	M	12	Therm	0,654004	337	Global	T	12	Elec	1,000000
146	DIRETA	M	1	Oil	0,637094	338	Global	T	1	Therm	0,619764
147	DIRETA	M	2	Oil	0,804209	339	Global	T	2	Therm	0,640989
148	DIRETA	M	3	Oil	0,723836	340	Global	T	3	Therm	0,625237
149	DIRETA	M	4	Oil	0,838277	341	Global	T	4	Therm	0,653883
150	DIRETA	M	5	Oil	0,629628	342	Global	T	5	Therm	0,661146
151	DIRETA	M	6	Oil	0,940500	343	Global	T	6	Therm	0,724173
152	DIRETA	M	7	Oil	0,906861	344	Global	T	7	Therm	0,714971
153	DIRETA	M	8	Oil	0,881392	345	Global	T	8	Therm	0,659767
154	DIRETA	M	9	Oil	0,803438	346	Global	T	9	Therm	0,705162
155	DIRETA	M	10	Oil	0,649037	347	Global	T	10	Therm	0,795204
156	DIRETA	M	11	Oil	1,000000	348	Global	T	11	Therm	1,000000
157	DIRETA	M	12	Oil	0,467866	349	Global	T	12	Therm	0,960403
158	DIRETA	N	1	Therm	0,533324	350	Global	T	1	Oil	0,491749
159	DIRETA	N	2	Therm	0,396313	351	Global	T	2	Oil	0,538794
160	DIRETA	N	3	Therm	0,655137	352	Global	T	3	Oil	0,558702
161	DIRETA	N	4	Therm	0,766242	353	Global	T	4	Oil	0,526843
162	DIRETA	N	5	Therm	0,660658	354	Global	T	5	Oil	0,485987
163	DIRETA	N	6	Therm	0,591252	355	Global	T	6	Oil	0,630104
164	DIRETA	N	7	Therm	0,340865	356	Global	T	7	Oil	0,569947
165	DIRETA	N	8	Therm	0,434018	357	Global	T	8	Oil	0,802344
166	DIRETA	N	9	Therm	1,000000	358	Global	T	9	Oil	0,731381
167	DIRETA	N	10	Therm	0,494415	359	Global	T	10	Oil	0,649037
168	DIRETA	N	11	Therm	0,758168	360	Global	T	11	Oil	1,000000
169	DIRETA	N	12	Therm	0,756530	361	Global	T	12	Oil	0,582680
170	DIRETA	N	1	Gas	0,535902	362	Global	T	1	Diesel	0,552403
171	DIRETA	N	2	Gas	0,405467	363	Global	T	2	Diesel	0,540751
172	DIRETA	N	3	Gas	0,679657	364	Global	T	3	Diesel	0,587664
173	DIRETA	N	4	Gas	0,714559	365	Global	T	4	Diesel	0,577688
174	DIRETA	N	5	Gas	0,703492	366	Global	T	5	Diesel	0,684557

N	Indicador	Processo	Tempo	Energia	Eficiência	N	Indicador	Processo	Tempo	Energia	Eficiência
175	DIRETA	N	6	Gas	0,616722	367	Global	T	6	Diesel	0,634522
176	DIRETA	N	7	Gas	0,383163	368	Global	T	7	Diesel	0,539187
177	DIRETA	N	8	Gas	0,390106	369	Global	T	8	Diesel	0,849857
178	DIRETA	N	9	Gas	0,930401	370	Global	T	9	Diesel	0,935462
179	DIRETA	N	10	Gas	0,384772	371	Global	T	10	Diesel	1,000000
180	DIRETA	N	11	Gas	1,000000	372	Global	T	11	Diesel	0,876385
181	DIRETA	N	12	Gas	0,753814	373	Global	T	12	Diesel	0,746953
182	DIRETA	O	1	Elec	0,556897	374	Global	T	1	Gas	0,572634
183	DIRETA	O	2	Elec	0,715813	375	Global	T	2	Gas	0,592743
184	DIRETA	O	3	Elec	0,451656	376	Global	T	3	Gas	0,601373
185	DIRETA	O	4	Elec	1,000000	377	Global	T	4	Gas	0,606817
186	DIRETA	O	5	Elec	0,959498	378	Global	T	5	Gas	0,593095
187	DIRETA	O	6	Elec	0,631697	379	Global	T	6	Gas	0,757245
188	DIRETA	O	7	Elec	0,732980	380	Global	T	7	Gas	0,719268
189	DIRETA	O	8	Elec	0,914349	381	Global	T	8	Gas	0,854486
190	DIRETA	O	9	Elec	0,690119	382	Global	T	9	Gas	0,688218
191	DIRETA	O	10	Elec	0,637810	383	Global	T	10	Gas	0,990258
192	DIRETA	O	11	Elec	0,883813	384	Global	T	11	Gas	0,644500
						385	Global	T	12	Gas	1,000000

Fonte: o autor, 2016

APÊNDICE D

APÊNDICE D: RELATÓRIO DE ESTUDO INDEPENDENTE - ENTENDIMENTO DO RELACIONAMENTO INSUMO-PRODUTO

1. OBJETIVO

Este relatório apresenta o resultado de um estudo independente que foi realizado no período entre Fevereiro/2014 a Dezembro/2015. O principal objetivo do estudo independente refere-se ao entendimento do funcionamento do modelo insumo-produto desenvolvido por Leontief (1966) bem como do modelo insumo-produto de processo desenvolvido por Lin e Polenske (1998).

2. MODELO INSUMO PRODUTO - ANÁLISE INSUMO PRODUTO

2.1 Variáveis

$$\begin{bmatrix} x_{11}+x_{12}+x_{13}\dots x_{1n} \\ x_{21}+x_{22}+x_{23}\dots x_{2n} \\ \vdots \\ x_{n1}+x_{n2}+x_{n3}\dots x_{nn} \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}$$

x_{ij} = vendas do setor i para o setor j (compras do setor j no setor i).

y_i = demanda final pelos produtos do setor i.

X_i = produção total do setor i

2.2 Sistemas de equações insumo-produto

Baseado em $a_{ij} = \frac{x_{ij}}{X_j}$ onde $a_{ij} * X_j = x_{ij}$, pode se obter o sistema de equações lineares abaixo, sendo que a_{ij} é a quantidade de insumos do setor i para produzir uma unidade de produção (em valores monetários) do setor j.

$$\begin{bmatrix} a_{11}X_1+a_{12}X_2+a_{13}X_3\dots a_{1n}X_n \\ a_{21}X_1+a_{22}X_2+a_{23}X_3\dots a_{2n}X_n \\ \vdots \\ a_{n1}X_1+a_{n2}X_2+a_{n3}X_3\dots a_{nn}X_n \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}$$

Na forma reduzida:

$AX + Y = X$ onde $X = (I - A)^{-1}$
X = vetor de produção; Y= vetor da demanda final; A = matriz de coeficientes técnicos; I = matriz identidade.

2.3 Exemplo numérico

Matriz input-output	Agri.	Manu.	Transp.	Elec.	Petro.	Demanda	Produção
Agricultura	10	20	0	0	5	55	90
Manufatura	20	30	20	10	10	40	130
Transporte	10	10	0	10	10	20	60
Eletricidade	10	40	20	5	5	30	110
Petróleo	20	20	30	5	5	10	90

Matriz A	Agri.	Manu.	Transp.	Elec.	Petro.
Agricultura	0,1111	0,1538	0,0000	0,0000	0,0556
Manufatura	0,2222	0,2308	0,3333	0,0909	0,1111
Transporte	0,1111	0,0769	0,0000	0,0909	0,1111
Eletricidade	0,1111	0,3077	0,3333	0,0455	0,0556
Petróleo	0,2222	0,1538	0,5000	0,0455	0,0556

Matriz I	Agri.	Manu.	Transp.	Elec.	Petro.
Agricultura	1	0	0	0	0
Manufatura	0	1	0	0	0
Transporte	0	0	1	0	0
Eletricidade	0	0	0	1	0
Petróleo	0	0	0	0	1

Matriz $(I-A)^{-1}$	Agri.	Manu.	Transp.	Elec.	Petro.
Agricultura	1,2727	0,3246	0,1967	0,0563	0,1395
Manufatura	0,6412	1,6813	0,8187	0,2546	0,3468
Transporte	0,3009	0,2899	1,2532	0,1569	0,2085
Eletricidade	0,4941	0,7123	0,7757	1,2024	0,2748
Petróleo	0,5870	0,5380	0,8804	0,1957	1,2717

Supondo que a produção agrícola aumente em 10 (65-55). Qual aumento da produção necessário dos outros setores para atender essa nova demanda do setor agrícola? Quanta energia adicional (Eletricidade e Petróleo) será necessária para atender essa demanda?

$(I-A)^{-1}Y = X$	Agri.	Manu.	Transp.	Elec.	Petro.	Nova Demanda	Produção necessária	Variação na produção
Agricultura	1,2727	0,3246	0,1967	0,0563	0,1395	**65**	102,73	12,73
Manufatura	0,6412	1,6813	0,8187	0,2546	0,3468	40	136,41	6,41
Transporte	0,3009	0,2899	1,2532	0,1569	0,2085	20	63,01	3,01
Eletricidade	0,4941	0,7123	0,7757	1,2024	0,2748	30	114,94	4,94
Petróleo	0,5870	0,5380	0,8804	0,1957	1,2717	10	95,87	5,87

2.4 Matrix de energia

$$E_i = \sum_{K=1}^{n} E_{ik} + E_{iy}$$

E_i = Produção total de energia do setor i.
E_{ik} = Venda de energia do tipo i para o setor k (Uso indireto de energia).
E_{iy}= Venda de energia do tipo i para a demanda final (Uso direto de Energia).

$$E_{ik} = \left(\frac{E_{ik}}{X_k}\right) X_k \text{ onde } R_{ik} = \frac{E_{ik}}{X_k}$$

$$E_{ik} = R_{ik} \sum_{L=1}^{n} [I - A]^{-1}_{KL} Y_L$$

$$\sum_{K=1}^{n} E_{ik} = \sum_{K=1}^{n} R_{ik} \sum_{L=1}^{n} [I - A]^{-1}_{KL} Y_L$$

$$U = [R(I - A)^{-1}]Y$$

$E_{\text{uso direto}} = SY$,S_{ik} =1 se i=k = setor de energia, S_{ik} =0, caso contrário.

$$E = [R(I - A)^{-1} + S]Y$$

2.5 *Exemplo da matriz de energia*

Matriz R	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0,111	0,308	0,3333	0,045	0,056
Petróleo	0,222	0,154	0,5	0,045	0,056

Matriz S	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0	0	0	1	0
Petróleo	0	0	0	0	1

$R(I\text{-}A)^{-1}$	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0,494	0,712	0,7757	0,202	0,275
Petróleo	0,587	0,538	0,8804	0,196	0,272

E=R+S	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0,494	0,712	0,7757	1,202	0,275
Petróleo	0,587	0,538	0,8804	0,196	1,272

2.6 *Segunda opção de calculo*

$$E = G\hat{X}^{-1}(I - A)^{-1}$$

G	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0	0	0	110	0
Petróleo	0	0	0	0	90

Produção na inversa iagonal

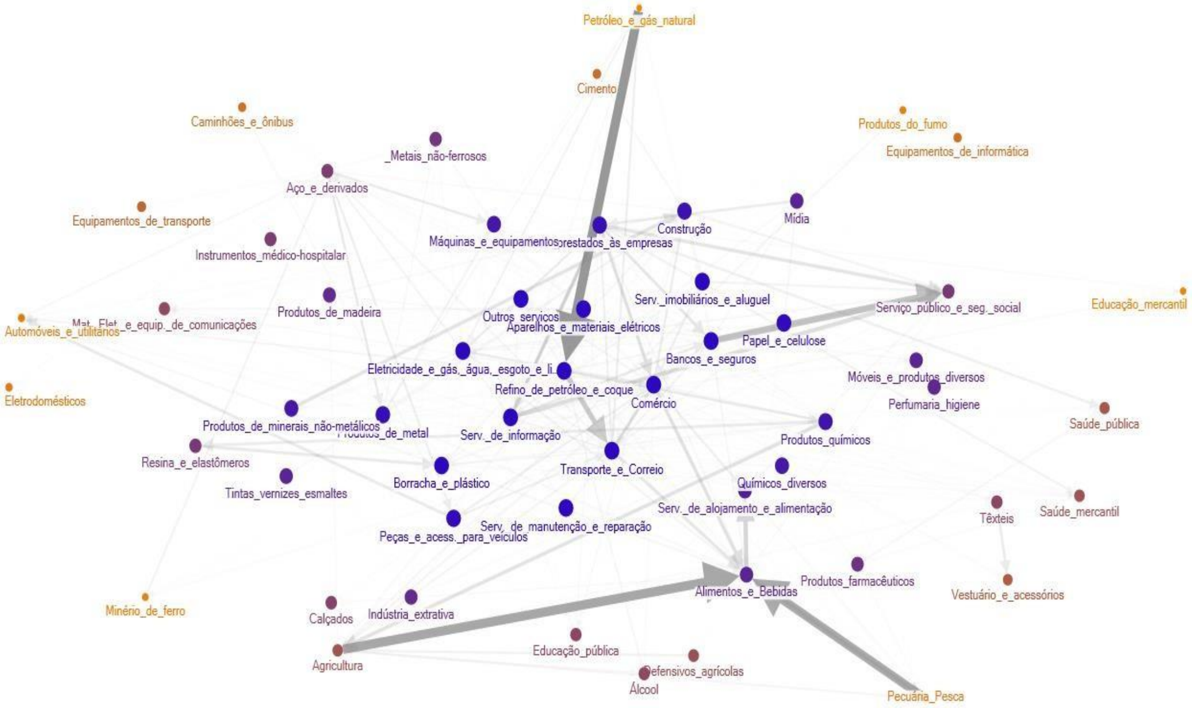
$\hat{X}^{1}$	Agri.	Manu.	Transp.	Elec.	Petro.
Agricultura	0,011111111	0	0	0	0
Manufatura	0	0,007692308	0	0	0
Transporte	0	0	0,007692308	0	0
Eletricidade	0	0	0	0,009090909	0
Petróleo	0	0	0	0	0,011111111

$\hat{G}X^{1}$	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0	0	0	1	0
Petróleo	0	0	0	0	1

E	Agri.	Manu.	Transp.	Elec.	Petro.
Eletricidade	0,494052502	0,712315422	0,775669948	1,202420016	0,274849604
Petróleo	0,586956522	0,538043478	0,880434783	0,195652174	1,27173913

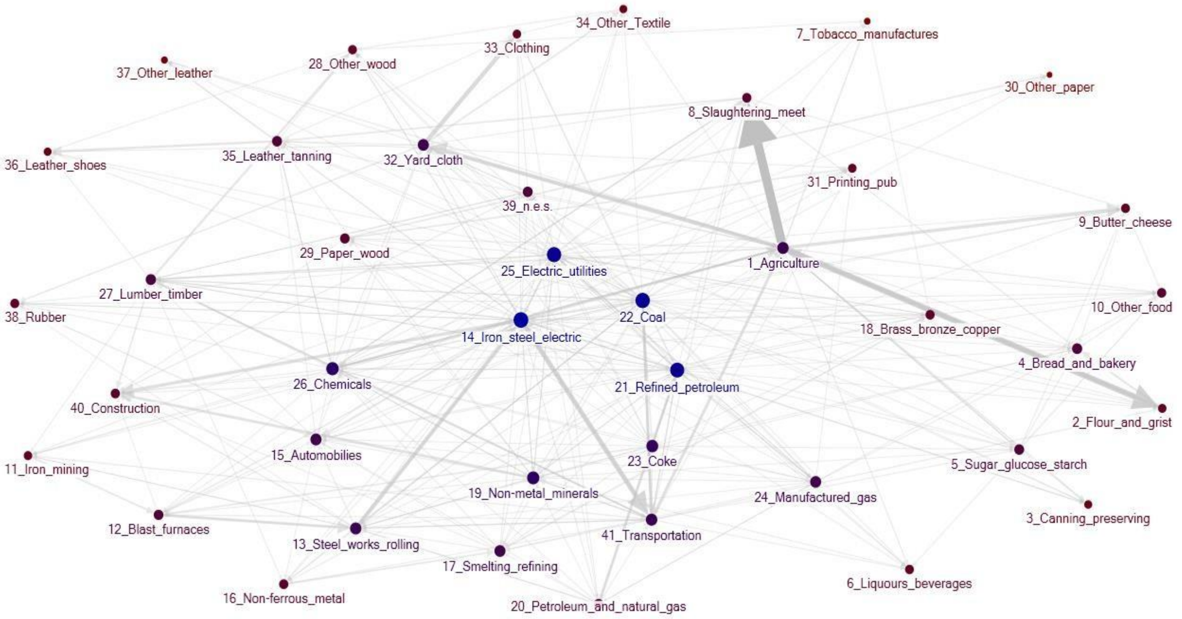
3 MODELO INSUMO PRODUTO COMO UMA REDE DE PROCESSOS AGREGADOS

Rede D1 - Matriz Insumo-Produto do Brasil



Fonte: Nota: (a) Elaborado a partir da matriz insumo produto do Brasil para o ano de 2005, disponível em ibge.gov.br/home/estatistica/economia/matrizinsumo_produto (Oferta e demanda da produção, Tabela 3)

Rede D2 - Matriz Insumo-Produto dos Estados Unidos



Fonte: Nota: (a) Elaborado a partir dos dados do artigo "*Quantitative input and output relations in the economic system of the United states*" (Leontief, 1936)

4 MODELO INSUMO-PRODUTO DE PROCESSO

4.1 Estrutura básica do modelo insumo-produto de processo

$Item$	$Processos$					
		$\mathbf{1}$	$\mathbf{2}$	$\mathbf{3}$	$\boldsymbol{n}$	
$Produto\ Principal$	$\mathbf{1}$	Z_{11}	Z_{12}	Z_{13}	Z_{1n}	Y_1
	$\mathbf{2}$	Z_{21}	Z_{22}	Z_{23}	Z_{2n}	Y_2
	$\mathbf{3}$	Z_{31}	Z_{32}	Z_{33}	Z_{3n}	Y_3
	$\boldsymbol{n}$	Z_{n1}	Z_{n2}	Z_{n3}	Z_{nn}	Y_n
$Insumos\ comprados$	$\mathbf{1}$	M_{11}	M_{12}	M_{13}	M_{1n}	X_1^m
	$\mathbf{2}$	M_{21}	M_{22}	M_{23}	M_{2n}	X_2^m
	$\mathbf{3}$	M_{31}	M_{32}	M_{33}	M_{3n}	X_3^m
$Subprodutos\ e\ Resíduos$	$\mathbf{1}$	W_{11}	W_{12}	W_{13}	W_{1n}	X_1^m
	$\mathbf{2}$	W_{21}	W_{22}	W_{23}	W_{2n}	X_2^m
	$\mathbf{3}$	W_{31}	W_{32}	W_{33}	W_{3n}	X_3^m
$Insumos\ primários$	$\mathbf{1}$	V_{11}	V_{12}	V_{13}	V_{1n}	X_1^v
	$\mathbf{2}$	V_{21}	V_{22}	V_{23}	V_{2n}	X_2^v
	$\mathbf{3}$	V_{31}	V_{32}	V_{33}	V_{3n}	X_3^v
$Prod. processo\ principal$		X_1^z	X_2^z	X_3^z	X_n^z	

Z – Matriz de produção e consumo intermediário do produto principal;

Y – Matriz da produção final dos produtos principais;

M – Matriz do consumo dos insumos comprados;

X^m – Matriz da demanda total dos insumos comprados;

W – Matriz de geração e eliminação de subprodutos e resíduos;

X^w - Matriz de descarga de subprodutos e resíduos;

V - Matriz de insumos primários consumidos;

X^v –Matriz da demanda total de insumos primários;

X^z- Matriz da produção bruta do produto principal.

4.2 Sistemas de equações do modelo de processos

$$Z_{i1} + Z_{i2} + Z_{i3} + \cdots + Z_{ij} + \cdots + Z_{in} = Y_i$$
$$M_{i1} + M_{i2} + M_{i3} + \cdots + M_{ij} + \cdots + M_{in} = X_i^m$$
$$W_{i1} + W_{i2} + W_{i3} + \cdots + W_{ij} + \cdots + W_{in} = X_i^w$$
$$V_{i1} + V_{i2} + V_{i3} + \cdots + V_{ij} + \cdots + V_{in} = X_i^v$$
$$X_{i=j}^z$$

4.3 *Coeficientes diretos e indiretos*

$$
\begin{array}{llll}
\text{Coeficientes diretos} & \text{Matrizes} & \text{Total} & \text{Coeficiente indiretos} \\
a_{ij} = \dfrac{Z_{ij}}{X_j} = [ZX^{z-dinv}]_{ij} & Z = AX^{z-d} & A(X^{z})^{T} = Y & X^{z} = A^{-1}Y \\
b_{ij} = \dfrac{M_{ij}}{X_j} = [MX^{z-dinv}]_{ij} & M = BX^{z-d} & B(X^{z})^{T} = X^{m} & X^{m} = BA^{-1}Y \\
c_{ij} = \dfrac{W_{ij}}{X_j} = [WX^{z-dinv}]_{ij} & W = CX^{z-d} & C(X^{z})^{T} = X^{w} & X^{w} = CA^{-1}Y \\
d_{ij} = \dfrac{V_{ij}}{X_j} = [VX^{z-dinv}]_{ij} & V = DX^{z-d} & D(X^{z})^{T} = X^{v} & X^{v} = DA^{-1}Y
\end{array}
$$

A^{-1}= Equivalente à inversa de Leontief

BA^{-1}= Total de insumos comprados por unidade de produção

CA^{-1} = Geração ou uso total de resíduos por unidade de produção

DA^{-1} = Insumos primários totais por unidade de produção

4.4 *Demonstração do modelo insumo-produto de processo*

Elaborado com base nos dados fornecidos por Kuhtz *et al*. (2010) para os insumos energéticos em uma fábrica de telhas na China.

A - Produto Principal, Matriz $\boldsymbol{Z_0}$

	Units per year 10^4	**M**	**N**	**O**	**P**	**Q**	**Final demand f_i**
M - Clay misture	**t**	16,3	-16,3	0	0	0	**0**
N - Dried tiles	**t**	0	15,6	-15,6	0	0	**0**
O - Cooked tiles	**t**	0	0	15,13	-15,13	0	**0**
P - Polished tiles	**t**	0	0	0	14,74	-14,74	**0**
Q - Packaged tiles	**t**	0	0	0	0	14,76	**14,76**

B – Entradas de Energia $\boldsymbol{E_{aj}}$

Types of Energy inputs	**Units 10^4**	**M**	**N**	**O**	**P**	**Q**	**Total**
Electric Power KWh	**KWh**	1260	0	1110	1400	40	3810
Thermal Power Kcal	**Kcal**	4.387.224	1.203.847	9.780.426	0	0	15.371.497
Heavy oil	**Kcal**	4.387.224	0	0	0	0	4.387.224
Diesel oil	**Kcal**	0	0	1.848.000	0	0	1.848.000
Natural gas	**Kcal**	0	1.203.847	7.932.426	0	0	9.136.273

C – Saídas $\boldsymbol{X_o}$ e diagonal inversa $\hat{\boldsymbol{X}}^{1}_{\boldsymbol{o}}$

Gross Output	**M**	**N**	**O**	**P**	**Q**
	16,3	15,6	15,13	14,74	14,76
Inverse Gross Output Diagonal	**M**	**N**	**O**	**P**	**Q**
	0,061349693	0	0	0	0
	0	0,064102564	0	0	0
	0	0	0,066094	0	0
	0	0	0	0,067842605	0
	0	0	0	0	0,06775068

D – Coeficientes Técnicos $\boldsymbol{A^o} = \boldsymbol{Z_0}\hat{\boldsymbol{X}}_{\boldsymbol{o}}^{\boldsymbol{1}}$

	M	N	O	P	Q
M	1	-1,04487179	0	0	0
N	0	1	-1,03106411	0	0
O	0	0	1	-1,026458616	0
P	0	0	0	1	-0,998645
Q	0	0	0	0	1

E – Indicador de Conteúdo Energético $\boldsymbol{SEC} = \boldsymbol{E_{aj}}\hat{\boldsymbol{X}}_{\boldsymbol{o}}^{\boldsymbol{1}}$

	M	N	O	P	Q
Electric Power KWh	77,30061	0	73,36417713	94,97964722	2,7100271
Thermal Power Kcal	269154,8	77169,67949	646426,041	0	0
Heavy oil	269154,8	0	0	0	0
Diesel oil	0	0	122141,4408	0	0
Natural gas	0	77169,67949	524284,6001	0	0

F – Inversa de Leontief $\boldsymbol{L^i} = (\boldsymbol{1} - \boldsymbol{A})^{-\boldsymbol{1}}$

	M	N	O	P	Q
M	**1**	**1,044872**	**1,07733**	**1,105834**	**1,104336**
N	**0**	**1**	**1,031064**	**1,058345**	**1,056911**
O	**0**	**0**	**1**	**1,026459**	**1,025068**
P	**0**	**0**	**0**	**1**	**0,998645**
Q	**0**	**0**	**0**	**0**	**1**

G – Indicador de Fluxo de Energia $\boldsymbol{EF^{aj}} = \boldsymbol{L^i} * \boldsymbol{SEC}$

	M	N	O	P	Q
Electric Power KWh	77,30061	80,76923	156,6424	255,7666	258,1301
Thermal Power Kcal	269154,8	358402	1015961	1042842	1041429
Heavy oil	269154,8	281232,3	289968,5	297640,7	297237,4
Diesel oil	0	0	122141,4	125373,1	125203,3
Natural gas	0	77169,68	603851,5	619828,6	618988,7

5 CONCLUSÃO

O modelo insumo-produto foi desenvolvido nas pesquisas do Prêmio Nobel de Economia[14] Leontief (1936, 1966). Baseado em Leontief (1966) a análise de insumo-produto é uma extensão prática da teoria clássica de interdependência geral que vê toda a economia (região, país, mundo) como um sistema interdependente de transações entre as empresas/setores (ver rede 1). A ideia central da análise insumo-produto é que existe uma relação fundamental entre o volume de produção de uma indústria/empresa e o vulto de insumos que ela absorve. A relação descrita é uma relação linear entre a quantidade de insumos e a quantidade a ser produzida de produtos e serviços. O modelo insumo-produto tem procedimentos e técnicas específicas como a elaboração das tabelas insumo-produto e o cálculo dos coeficientes diretos/indiretos. As tabelas insumo-produto descrevem o fluxo de bens e serviços entre todos os setores em um período específico de tempo. Os coeficientes diretos são coeficientes técnicos de produção que mostra a relação entre os insumos e os produtos/serviços. Os coeficientes indiretos também são conhecidos como matriz de Leontief mostrando a relação direta e indireta entre insumos e produtos/serviços. A relação direta é a necessidade direta de insumos para o produto/serviço, onde é necessário energia para a produção do aço (energia direta) e a relação indireta é a necessidade indireta de insumos como e energia para a produção do pneu do caminhão que transportou o aço (energia indireta). Uma vez que a coleta dos dados para as tabelas insumo-insumo produto de todas as transações entre empresas seria praticamente impossível (nos tempos de Leontief) a solução encontrada foi a agregação das empresas em setores demonstrando o relacionamento entre os setores (LEONTIEFF, 1936; LEONTIEF, 1966).

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[14] Prêmio Nobel de 1973.

O trabalho desenvolvido pela orientanda de doutorado de Leontief [Karen Rosel Polenske] reorganizou as tabelas insumo-produto para funcionar com processos empresariais, sendo uma abordagem de processos do modelo insumo-produto de Leontief. A abordagem de processos proposta por Lin e Polenske (1998) é conhecida como modelo insumo-produto de processo ou modelo insumo-produto empresarial (LIN; POLENSKE, 1998 ALBINO et al., 2003). A justificativa dos autores está na inadequação dos sistemas contábeis de lidar como fatores como suporte a estratégia operacional, flexibilidade, qualidade, divisibilidade do desempenho, impactos diretos e indiretos além do desempenho de longo prazo.

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APÊNDICE E

APÊNDICE E: PROJETOS DE INICIAÇÃO CIENTÍFICA (PIBIC)

Período	Alunos	Projeto	Objetivo Principal	PIBICS
2013/2014	Caroline Bauer Ohpis	Implicações das mudanças na fronteira do paradigma tecnológico em energia para a engenharia de produção	Entender e avaliar quais são as implicações que as mudanças dos paradigmas tecnológicos podem trazer para a engenharia de produção.	PIBIC-1
2013/2014	Bruno Paparella	Impacto das estruturas de mercado das empresas de Energia para a estratégia de produção das firmas Manufatureiras.	Desenvolver um breve estudo do impacto das estruturas de mercado das firmas em energia para a estratégia de produção das firmas manufatureiras	PIBIC-2
214/2015	Letícia Portilho Amorim	Implicações da sustentabilidade para a gestão energética da manufatura	Desenvolver uma análise das implicações dos três níveis da sustentabilidade para a gestão energética de uma manufatura.	PIBIC-3
214/2015	Bruno Paparella	Barreiras para a eficiência energética industrial	Identificar as principais barreiras para a eficiência/gestão energética	PIBIC-4
2015/2016	Ana Carolina Claudino	Analise da adoção de medidas para a gestão e eficiência energética industrial: o caso das auditorias do departamento de energia americano	Desenvolver uma análise descritiva das práticas implementadas pelas empresas auditadas pelo programa dos EUA para eficiência energética industrial	PIBIC-5
2015/2016	Kassio Hoinski Filipak	Evolução do grau de adoção de medidas em gestão energética e tecnologias para poupança de energia no setor manufatureiro: uma análise do manufacturing energy consumption survey (mecs) dos eua.	Analisar a evolução do grau de adoção de medidas em gestão energética e da adoção de tecnologias para poupança de energia no setor manufatureiro utilizando a pesquisa Manufacturing Energy Consumption Survey (MECS) dos EUA	PIBIC-6

Nota: Projetos já aprovados pela comissão julgadora do Seminário de Iniciação Científica (SEMIC) da PUCPR.

APÊNDICE F

APÊNDICE F: ARTIGO 1 - ANALYSIS OF INCOME ELASTICITIES OF BRAZIL'S ENERGY MATRIX

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Abstract: This study aims to estimate and analyze the income elasticities of Brazil's energy matrix, represented by the supply and consumption of energy. We sought to compare the income elasticities of both energy products and consumption through secondary sources and consumer sectors. This is an explanatory or relational research of an *ex-post-facto* nature, analyzing the period from 1970 to 2011, using the ANCOVA-EC estimation method. The results obtained from the estimates show that both for energy products, as in relation to industrial sectors, the elasticities are statistically different. The naphta, natural gas and ethyl alcohol had the highest elasticities in the energy matrix, and the industries ferro-alloy, non-ferrous metals and non-energy are the most sensitive to income growth. When elasticities are compared with the sectoral energy intensity index, there is evidence that less efficient sectors have higher income elasticities. In summary the results show that there is sectors or products that are more sensitive to economic growth where the energy-intensive and demand presented as the main factors to explain the sensitivity, there is also evidence to demonstrate that the level of efficiency is different compared the different sectors.

Keywords: *Income Elasticity, Price Elasticity, Energy Matrix, Sector Demand for Energy*

JEL Classifications: E3, G38, K23, M48, Q4

1 INTRODUCTION

The subject of energy is often only associated with the production/generation and supply of electricity (Taffarel et al., 2015). It should be noted that the concept of energy studied herein is in accordance with the descriptions of the National Energy Balance (Balanço Energético Nacional – BEN)[15], and also presented in publications of the International Energy Agency (IEA), where energy takes shape and flow. By "shape," we mean, being a primary energy source within an energy matrix (oil, natural gas, coal, uranium, hydraulic, firewood, and sugarcane, among others) and secondary sources (diesel oil, fuel oil, gasoline, gas, naphtha, kerosene, coal coke, electricity, charcoal, and alcohol, among others). Energy can be represented as a flow, in the sense that energy users cannot

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[15] Published by the Ministry of Mines and Energy (MME); available on www.mme.gov.br

directly consume the primary sources, requiring energy to be processed into sources that meet the demand, which can be in the form of lighting, climatization, transportation, motive power, electrochemical reduction of materials, and so on (Perroni et al., 2015).

What should be produced from primary sources and what they should be processed into is part of the national energy policy, given that energy itself cannot be replaced (Tanaka, 2011; Moralejo et al., 2016). It is possible to replace the hydraulic force of plants with coal or gas to generate electricity, but not (at least not yet) replace electricity itself (an industrial electric motor runs on electricity, it does not work without it; in this case, there is no approximate viable replacement).

This process moves a considerable part of national economies, forming a concept described by Pinto Jr. et al. (2007) as energy chains. For example, the oil chain begins from the discovery of the product in the well, and moves on to taking care of a transportation need or the need to make polyvinyl chloride (PVC) linings for a home – a process that includes production, processing, transportation, and trade.

What justifies energy chains is precisely the non-perfect substitution between energy sources, at least in the short term. Some chains have taken new directions since the ‘90s, reflecting a change in the technological trajectory as explained by Dosi (1982). With both processing and consuming devices that use more than one energy source, it may provide more flexibility to the system.

Until the ‘70s, energy was just another factor of production, but the oil crises changed the scenario:

> The impact of the Arab oil embargo and the subsequent emergence of OPEC as the most powerful cartel in history focused as never before on the issue of energy supply. OPEC has contributed wonderfully to concentrate efforts – in this case, on the adequacy of energy supplies to the maintenance of a continuous economic growth (Rosenberg, 1982:132).

In their classic book on innovation, Freeman and Soete (1997) present a schematic summary of the main characteristics of *Kondratieff*[16] long waves, where on the fifth wave (information and communication Kondratieff), which starts in 1980, energy appears as a limitation of the techno-economic paradigm, i.e., the limitation of energy intensity may be a delay factor in the development of societies.

A wide range of studies, especially after the turn of the millennium, have discussed energy efficiency measures and the adoption of more efficient technologies, noting the existence of what was addressed in the literature as Energy Efficiency Gap. The existence of this gap is confirmed by the non-implementation of measures for the efficiency or conservation of energy, even though they were evaluated as cost-effective by techniques such as payback, IRR (Internal Rate of Return), or NPV (Net Present Value) (Jaffe and Stavins, 1994; Decanio, 1998; Anderson and Newell, 2004; Vieira and Veiga, 2009; Backlund, S. et al., 2012; Cagno et al., 2013; Ciscato et al., 2016; Hazer et al., 2016).

Based on the importance of energy problem discussed, this paper aims to estimate the income elasticities of each BEN energy series for Brazil, i.e., domestic energy supply, consumption by source, and consumption by sectors of the economy. The main objective is to compare these elasticities in order to answer the following questions: What energy sectors or products are more sensitive to economic growth? If there are differences, what could explain such differences? Is it possible to conclude that there are sectors that are more efficient than others? The goal, then, is to shed light on these issues. We also intend to present the sectoral energy intensity index in order to compare it with the results obtained. According to the international energy agency (IEA, 2014a p.17) the energy intensity index is an economic indicator, being the amount of energy consumed per activity.

The remaining part of this article is divided into three sections. The second section presents the literature review. The third presents the methodological process, tying the previous parts of the work. Finally, we show a graphical presentation of the results, from the application of the methodology, along with a conclusion.

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[16] Kondratieff, Nicolai Dmitrievitch (1892-1930) – Russian economist and statistician who had his name associated with the study of the long economic cycles

2 LITERATURE REVIEW

As discussed anteriorly, this work offers a broader analysis of energy, keeping in mind that technological changes cannot stay out of the evaluation process; in fact, they need to be incorporated as an explanatory factor. A survey of papers related to energy demand and economic growth showed that the vast majority of studies on energy in Brazil are concerned with electricity.

As per Garcez and Ghirardi (2002), the quantitative methods most used to understand power consumption are: linear transfer function (LTF), autoregressive models with distributed lags (ADL), partial adjustment models (PAM), vector autoregressive models (VAR-VEC), and cointegration models (Kudlawicz et al., 2016; Moreira et al., 2016; Veiga et al., 2015).

One of the classic works in Brazil is by Modiano (1984), who uses a partial adjustment model based on the Koyck transformation (Gujarati and Porter, 2011). In this work, the author estimated the income elasticity of electricity consumption for the residential, industrial, and commercial sectors, to reach long-term elasticities of 1.17%, 1.67% and 1.15%, respectively, with corresponding price elasticities of -0.46%%, -0.001%, and -0.23%.

Andrade and Lobão (1997), as identified by the authors of this article in order to update the work by Modiano (1984), used more efficient econometric methods to estimate the residential demand for electricity: (1) ordinary least squares (OLS); (2) two-stage least squares with instrumental variables (2SLS); and (3) vector autoregressive modeling with error correction (VAR-VEC). As per the authors' analysis, the results obtained by the three different methods converge to a long-term income elasticity of around 0.21% for residential electricity consumption, diverging from Modiano's work (1984) for being inelastic, even in the long term. Price elasticity was at the same level, i.e., -0.17%.

In another study that covered the 1994-2002 period for the state of Bahia, Garcez and Ghirardi (2002) found income elasticities ranging from 0.13% to 0.40%, confirming the inelastic demand of residential electricity consumption. Using VAR-VEC modeling, Schmidt and Lima (2003) found a 1.72% income elasticity of industrial electricity consumption for the period 1969–1999.

Irffi et al. (2009), covering the period 1970 to 2003, drew on a model of dynamic ordinary least squares (DOLS), finding inelastic results in the short term and elastic results in the long term. Later, Amaral and Monteiro (2010), using the OLS model but with correction of the dummy variable, found an income elasticity of 0.61% after a blackout and of 0.74% before the blackout.

Regarding gasoline, Roppa (2005) used a model of cointegration and found lower income elasticities for the long term compared to the short term – 0.47% and 0.16%, respectively. Chart 1 is a summary of the estimated elasticities for the studies evaluated:

Authors	Method	Period	Price elasticity	Income elasticity
Modiano (1984)	Partial adjustment	1963 - 1981	$-0,001_{industrial}$	$1,67_{industrial}$
Andrade e Lobão (1997)	OLS –2SLS– VAR	1963 - 1995	$-0,17_{residential}$	$0,21_{residential}$
Ghirardi e Garcez (2002)	Cointegration	1994 - 2002	$-0,07_{residential}$	$0,39_{residential}$
Schmidt e Lima (2003)	VAR-VEC	1969 - 1999	$-0,13_{industrial}$	$1,72_{industrial}$
Roppa(2005)	Cointegration	1979 - 2000	$-0,32_{gasoline}$	$0,16_{gasoline}$
Irffi et al. (2009)	DOLS	1970 - 2003	$-3,71_{industrial}$	$1,21_{industrial}$
Amaral e Monteiro (2010)	OLS – *dummy*	1974 - 2008	$-0,43_{residential}$	$0,61_{residential}$

Chart 1 – Estimates of income and price elasticities by author

Note, in Chart 1, the income elasticity of residential electricity consumption tends to be inelastic, and that of industrial consumption to be elastic, since price elasticity tends to be inelastic. The only disagreement is the work of Irffi et al. (2009), which talks about a very high price elasticity.

As a reference, this article also highlights the work of those who are considered evolutionists[17]: Nelson and Winter (1974), Dosi (1982), Rosenberg (1982), Mowery and Rosenberg (1998) and Freeman and Soete (1997).

In Rosenberg (1982), for example, one characteristic of industrialization is the use of increasing amounts of energy, which is governed by the operation of a dynamic technological system. The author argues for the non-perfect substitution of alternative technologies in energy, which implies not using a cheaper source in the short term. For the author, technological innovation happening through product or process determines the supply of energy, which in turn determines the long-term real GDP. Long-term here does not refer to the partial equilibrium adjustment from one period to another, but can mean decades. Rosenberg (1982) makes a case study of metallurgy, where iron and steel, albeit less abundant in the Earth's crust than aluminum, were more widely used due to the immense amount of energy required to produce the latter. According to Rosenberg, the search for improved fuel efficiency was so intense in metallurgy that: (1) the input-output coefficients are not stable from one decade to another; and (2) an understanding of what was shaping the sector's structure and performance could not be focused only on the aggregate demand for energy and the final bulk product.

Against the background of what has been discussed above, Pinto Jr. et al. (2007) reported several studies that sought to measure the relationship between energy and economic growth. Some of these studies reported an elasticity close to the unit. Janosi and Grayson (1972) confirmed the strong relationship between economic growth and energy consumption, but it ranged from 2.07% (Philippines) to 0.48% (UK). In general, the conclusion of the later studies is that energy consumption is not fully explained by economic activity, when different countries are compared. Energy consumption in countries with the same level of income may be different.

The contemporary model to explain total energy consumption takes into account the activity effect (economic growth), the structure effect (sector relative share), and the content effect (technological process in each energy-consuming product), which is known as the index decomposition analysis (IDA) approach (Ang and Xu, 2013). An IDA method, widely used in the literature, is the Logarithmic Mean Divisia Index (LMDI[18]) (Ang, 2013). Based on the decomposition equation shown in Ang:

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_i Q S_i I_i \qquad (1)$$

Where E= total energy consumption; Q= global activity; E_i= energy consumption of sector i; Q_i= activity of sector i; S_i= participation of sector i in activity; I_i= energy intensity of sector i.

Equation (1) can still be broken down as defined in (2), where 2a (content effect), 2b (structure effect) and 2c (activity effect) plus an error variable. The ΔEC is the variation in energy consumption and GDP is the gross domestic product.

$$\Delta EC = \left(\sum_i \Delta\left(\frac{EC_i}{GDP_i}\right) \times \frac{GDP_i}{GDP} \times GDP\right) \qquad (2a)$$

$$+ \left(\sum_i \frac{EC_i}{GDP_i} \times \Delta\left(\frac{GDP_i}{GDP}\right) \times GDP\right) \qquad (2b)$$

$$+ \left(\sum_i \frac{EC_i}{GDP_i} \times \frac{GDP_i}{GDP} \times \Delta(GDP)\right) + \varepsilon \qquad (2c)$$

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[17] Current thought influenced by the works of Joseph Alois Schumpeter (1883-1950)

[18] The additive LMDI formula would be $\Delta E_{act} = \sum_i w_i \ln\left[\frac{Q^t}{Q^o}\right]$; $\Delta E_{str} = \sum_i w_i \ln\left[\frac{S_i^t}{S_i^o}\right]$; $\Delta E_{int} = \sum_i w_i \ln\left[\frac{I_i^t}{I_i^o}\right]$ where $w_i = E_i^t - E_i^o / \ln E_i^t - \ln E_i^o$

The equation (2) shows that the energy consumption from one period to another depends on: (a) the sector energy content, which is somewhat connected to the technological developments over time; (b) the structure or participation effect of each sector in the total output over time, which is linked to the strategic options of a country; and (c) the activity effect, i.e., country's level of growth and an error value that can be represented by other factors without major impact on the long-term model.

3 METHODOLOGICAL PROCEDURES

This work asserts that any chosen analysis method has to explicitly or implicitly consider the factors considered in the previous step of the work.

3.1 Characterization of Research and Data Collection

From what has been discussed, the objective of this work is to estimate the income elasticities of the national energy matrix of energy consumption by sector and energy consumption by source, taking into account that the activity effect is not the only force that influences total energy consumption due to the wide nature of the work.

This is an applied research of explanation or relational nature, as it seeks to better understand the behavior of several variables and elements that influence a particular phenomenon. In addition, it is an *ex-post-facto* study, since the observations made in this study are done after the research in order to prevent any interference from the researcher.

Energy source	**Consumption by source**	**Consumption by sector**
Non-renewable	Coal	Non-energy final consuption
	Firewood	Energy final consuption
Oil and its products	Sugarcane bagasse	Energy sector
	Other renewable primary sources	Residential
Natural gas	Coke oven gas	Commercial
	Coal Coke	Public
Coal and its products	Electrity	Agriculture
	Charcoal	**Consumption in transportation**
Uranium (u3o8) and its products	Ethyl alcohol	Road
	Other secondary and tar	Rail
Renewable	**Petroleum products**	Air
	Diesel oil	Water
Hydraulic and electricity	Fuel oil	**Industrial consumption**
	Gasoline	Cement
Firewood and charcoal	Liquefied petroleum gas	Pig iron and still
	Naphta	Iron-alloy
Sugarcane products	Kerosene	Mining and pelletizing
	Piped gas	Non-ferrous and other metals
Other renewables	Other secondary petroleum	Chemicals
	Non-energy petroleum products	Food and beverage
		Textile
		Pulp and paper
		Ceramics
		Other industries

Chart 2 –National Energy Balance items
Source: Séries Históricas Balanço Energético Nacional, 1970-2011

To estimate these elasticities, we intend to use the data obtained from the National Energy Balance Historical Series (Séries Históricas Balanço Energético Nacional)[19] for the period 1970 to 2011, published on Ministry of Mines and Energy's website, which is developed in association with the Energy Research Company (Empresa de Pesquisas Energéticas). For information on the GDP, we will use data from IPEADATA's[20] website on the real GDP for the same period. Chart 2 shows the items in the National Energy Balance.

Chart 2 shows the items to be considered in the estimation of income elasticities. The first column in Chart 2 contains both renewable and non-renewable energy sources. The second and third columns show the energy demand by energy sources and sectors, respectively.

3.2 Econometric Modeling

As specified in the theoretical basis, there are different methods of estimating the elasticities of the items in Chart 2. Considering that the central objective is to compare the elasticities, we started to estimate constant elasticities using a basic method as described by Varian (2010), Wooldridge (2010), and Gujarati and Porter (2011), according to the specifications of model (3).

Model (3) is based on a simple linear equation where EC_t is the amount of energy consumed in time t, and depends on GDP_t, which is the income in period t.

$$EC_t = \beta_1 + \beta_2 GDP_t \tag{3}$$

The income elasticity is expressed in equation (4).

$$\frac{dEC_t}{dGDP_t} \cdot \frac{GDP_t}{EC_t} = \beta_2 \cdot \frac{GDP_t}{EC_t} = \beta_2 \cdot \frac{GDP_t}{\beta_1 + \beta_2 GDP_t} \tag{4}$$

The problem is that elasticity changes with change in variables within period $t + n$, therefore taking the form of an exponential equation, as can be seen in (5).

$$EC_t = \beta_1 GDP_t^{\beta_2} e^{u_t} \text{ In linear, it becomes } \ln EC_t = \ln \beta_1 + \beta_2 \ln GDP_t + u_t \tag{5}$$

Taking the constant income elasticity over the period $t + n$, we get an algebraic expression (6):

$$\frac{d \ln EC_t}{d \ln GDP_t} = \beta_2 \tag{6}$$

Based on the model defined in (3), the income elasticities of the items in Chart 2 were estimated, obtaining a confidence level that was above 95% of the β_2 estimated, with R^2 being close to the unit. The problem is that, as described in the classic work by Granger and Newbold (1973), a Durbin-Watson statistic that was near-zero was obtained for the majority of cases, featuring an evidence for spurious regression and a non-stationarity of the time series.

The solution to this as perceived by Gujarati and Porter (2011) and raised by Maddala (2003) involves obtaining the first difference in the equation whenever statistic d (Durbin-Watson) is less than R square (R^2). Granger and Newbold (1973) recommend: (a) including lagged dependent variables; (b) obtaining the first differences of the variables involved; and (c) setting an autoregressive model of the first order for the waste. With these alternatives, the series become stationary and the traditional student's t-test can be applied normally without bias.

Based on the above, it is important to know whether the series are stationary or non-stationary. (Veiga et al., 2016). For this work, there is evidence, according to the Durbin-Watson statistics, that at least the majority of the series are non-stationary. If the series are stationary, it is said that they are integrals of order $I(0)$.If the series are integrals of order $I(d)$, it means that the series must be differentiated d times to make them stationary, as exposed in Bueno (2011).

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[19] The unit of measure of the BEN items is the tonne of oil equivalent (TOE), which represents an energy content of 10.000 kcal; of this series of items, piped gas presents the lowest periodicity for the period from 1970 to 2002, and Uranium from 1984 to 2011.

[20] Data on the GDP can be found on www.ipeadata.gov.br

To test whether the series are stationary, the Dickey & Fuller test (1979) is used, considering a white noise of the residuals. However, due to the problem of autocorrelation of the residuals, the augmented Dickey-Fuller test is applied[21]. Another important concept that arises is the non-stationary, but cointegrated, stochastic process. It is said that a stochastic process is cointegrated, according to Engle and Granger (1987), if the series are integrated of the $I(d)$order, but there is a vector which is a linear combination of the series that establishes a long-term relationship. In practice, a regression of these variables produces stationary residuals. The cointegration test of Engle-Granger[22] was developed to determine whether the series are cointegrated.

Given what had been discussed in the study, we went for a new approach, which is cointegration. The basic plan is that a model that considers income as the only variable may be poorly specified. In view of this, we started from the elementary theory of demand, where the demand for energy is explained by both income and price. We adopted the ANCOVA-EC model, or an ANOVA model, with covariates plus structural correction, as specified by Gujarati and Porter (2011), Field (2009), and as found in (7).

$$\ln EC_t = \ln \beta_1 + \beta_2 \ln GDP_t + \beta_3 \ln P_t + a_1 D_t + a_2 TCH_t + a_3 (TCH_t . GDP_t) + u_t \tag{7}$$

where $\ln\ EC_t$is the logarithm of energy consumption; $\ln\ GPD_t$ is the logarithm of the GDP; $\ln\ P_t$is the logarithm of price of an oil barrel[23] as proxy of the energy price; D_t is a dummy variable that assumed the value of 0 when the price series was increasing (1970–1980/1999–2011) and 1 when the series was decreasing (1981-1998); $TCH_t$is a dummy variable assuming the value of 0 for the first half of the period (1970–1990) and 1 for the second half (1991–2011); while $TCH_t.\ GDP_t$ is an interaction dummy variable related to income.

In fact, $a_2 TCH_t + a_3 (TCH_t.\ GDP_t)$ is the method of binary variables for the Chow test[24], which will reveal whether there was a structural break in relation to income from one period to another, or otherwise an intuitive approach of the effect of the content change and structure on energy consumption represented by equation (2a and 2b). In practice, since it is difficult to measure the content and structure effects over time, the method should be indicative of the action of the structure and content effect over time.

The base model then estimates equation (7) as a cointegration equation and applies the augmented Dickey-Fuller test on the residuals in order to verify the evidence of a unit root, as can be seen in (8).

$$\mathrm{u_t} = \ln EC_t - \ln \beta_1 - \beta_2 \ln GDP_t - \beta_3 \ln P_t - a_1 D_t - a_2 TCH_t - a_3 (TCH_t . GDP_t) \tag{8}$$

As per Gujarati and Porter (2011), by verifying that $u_t$is I(0), it can be affirmed that the traditional regression method can be applied.
The partial derivatives become long-term partial elasticities of the series, as in (9).

$$\beta_2 = \frac{\partial lnEC_t}{\partial lnGDP_t} ; \beta_3 \frac{\partial lnEC_t}{\partial lnP_t} = ; a_1 = \frac{\partial lnEC_t}{\partial lnD_t} ; a_2 = \frac{\partial lnEC_t}{\partial lnTCH_t} ; a_3 = \frac{\partial lnEC_t}{\partial lnTCH_t . GDP_t} \tag{9}$$

Therefore, $\beta_2$is income elasticity; $\beta_3$is price elasticity; $a_1$gives the indicative of the change in the growth rate when the energy price (Oil) was decreasing (1981–1998); $a_2$is the change in the growth rate during the periods 1970–1990 and 1991–2011; and $a_3$shows whether there was a change in income elasticity between the previous periods.

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[21] In practice, according to Gujarati and Porter (2011), the Dickey-Fuller test uses statistics (tau) r to verify whether the series is a random walk (with and without detachment or time trend) considering a white noise of the error values. Given a simple random walk $Y_t = \rho Y_{t-1} + u_i$ transforming $Y_t - Y_{t-1} = (\rho - 1)Y_{t-1} + u_i\cdot$, whereas $\delta = (\rho - 1)$, testing the null hypothesis $H_o\colon \delta = 0$ is the same thing as testing $H_o\colon \rho = 1$. For the case in which the regression errors exhibit autocorrelation, the lagged values of the dependent variable are added, and so the test is called augmented Dickey-Fuller, and the equation representing a complete detachment and time trend is correlacionados adiciona-se os valores $\Delta Y_t = \beta_1 + \beta_2 t + \delta Y_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \varepsilon_t \cdot\cdot$.

[22] Basically, it is the application of the Dickey-Fuller or augmented Dickey-Fuller test on the residual of the regression of the variable in level using the Engle-Granger statistics. If the residuals are white noise, it is said that the series are cointegrated, although non-stationary.

[23] Real price of the oil barrel published by BP Statistics.

[24] Study presented to the magazine *Econometrica* in 1960 “Test of Equality Between Sets of Coefficients in Two Linear Regressions”

4 DATA PRESENTATION AND ANALYSIS

When presenting the results, a greater emphasis will be given on income elasticities, considering that this is part of the main objective of this work.

4.1 The National Energy Matrix

Based on the last report by IEA, Key World Energy Statistics (2014), 81% of the energy used in the world comes from fossil fuels (coal 29%; oil 31.4% natural gas 21.3%), but the energy is not equally consumed around the world. According to the same report, the per capita consumption in the industrialized countries of the OECD, with the year 2012 as a basis, was 4.19 tonne of oil equivalent (TOE), while in Brazil, the per capita consumption was 1.42 TOE, which indicates, as per similar analysis in Goldemberg (2000), that there is still a long way to go. Figure 1 shows the change in the energy matrix between the 1970s (1970–1980) and the 2000s (2000–2011) for Brazil and Figure 2 shows the change in the energy matrix between 1973 and 2012 for World.

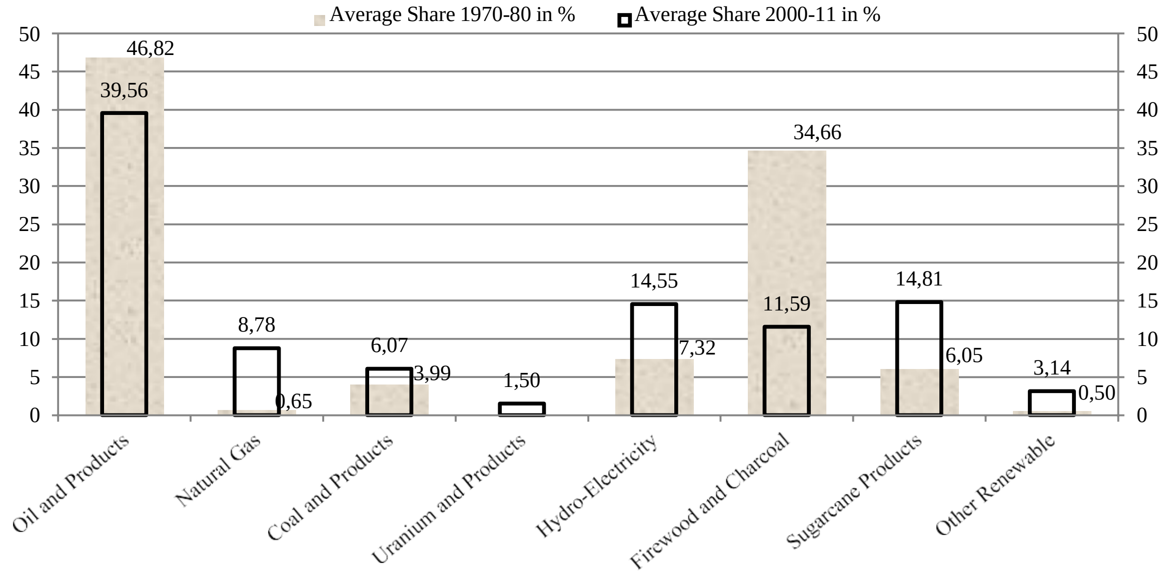

Figure 1 – Change in Brazil's Energy Matrix
Source: Séries Históricas Balanço Energético Nacional 1970-2011

It is important to note that Brazil's Energy Matrix has certain peculiarities, due to both the choices made and allocation of natural resources. As per Pinto Jr. et al. (2007), unlike the World Energy Matrix, Brazil has a cleaner Energy Matrix, using approximately 55% of fossil fuels, with the year 2005 as a reference. Figure 1 was constructed based on the average share of the primary energy source in the total domestic energy supply, measured in the TOE for each decade. For example, in the 1970s, the average share of oil and its products in the domestic energy supply was approximately 46.8% in Brazil.

From Figure 1, some characteristics can be noted. In the 1970s, compared to the 2000s, there was a reduction in oil products from 46.8% to 39.6%; a reduction in the use of firewood and charcoal from 34.7% to 11.6%; an increase in the share of electricity from 7.3% to 14.6%; and an increase in the share of sugarcane products from 6.1% to 14.8%. Furthermore, the use of natural gas intensified, although it was hardly ever used earlier. In general, it can be said that, except for firewood and charcoal, the share of all renewable energy sources such as hydraulic and sugarcane products grew, particularly replacing firewood.

Based on Goldemberg (2000), and Lucon and Goldemberg (2009), we can highlight a shy change in other renewables, such as biomass, eolic, solar, and geothermal, from 0.5% in the 1970s to 3.1% in the 2000s, if the Brazilian potential in this area is considered.

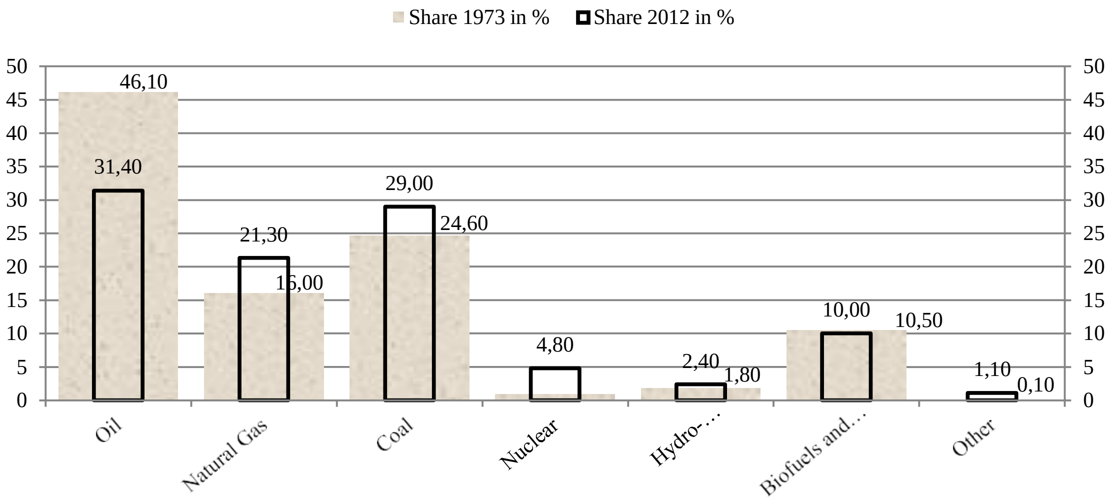

Figure 2 – Change in World's Energy Matrix
Source: World Energy Statistics-2014

As per the report from the Ministry of Mines and Energy, "*Matriz Energética Nacional 2030*" (2007, p.168), changes in the Energy Matrix shown in Figure 1 should continue until 2030. Based on predictions made in the report and on the data in Figure 1, we can see that the change expected for Brazil's Energy Matrix for the period 2000–2011 to 2030 should be: oil and products (39.6% to 28%); natural gas (8.8% to 15.5%); coal and products (6% to 6.9%); uranium and products (1.5% to 3%); hydraulics and electricity (14.6% to 13.5%); firewood and charcoal (11.6% to 5.5%); sugarcane products (14.8% to 18.5%); and other renewables (3.1% to 9.1%).

According to the report's forecasts, the highest growth in shares will occur in sugarcane products and other renewables, which together should add up to 27.6% of Brazil's Energy Matrix in 2030.

4.2 Model Estimates' Results

Table 1 presents the estimates of the ANCOVA-EC model for energy supply during the 1970–2011 period, considering the income, price, and auxiliary variables of Brazil's energy supply.

Table 1 – Estimates of Elasticities in Income, Price, and Auxiliary Variables of the Energy Supply

Energy supply	GDP	P	D	TCH	TCH.GDP	R^2	F	DW	ADF-C	ADF-CT
Non-renewable	1.09^{***}	-0.02	-0.12^{***}	0.28^{***}	-0.00^{***}	0.99	937	1.10	0.006	0.029
Oil and products	0.89^{***}	0.01	-0.13^{***}	0.45^{***}	-0.00^{***}	0.97	224	0.57	0.113	0.317
Natural gas	3.63^{***}	-0.27^{***}	-0.04	-0.23	0.00	0.98	316	0.61	0.098	0.285
Coal and products	1.78^{***}	-0.14^{***}	0.12^{**}	0.55^{***}	-0.00^{***}	0.97	212	0.92	0.001	0.002
Uranium/products	-2.56	0.19	-1.48^{**}	-2.52	-0.00	0.66	8	1.75	0.001	0.007
Renewable	0.65^{***}	-0.07^{***}	0.09^{***}	-0.61^{***}	0.00	0.97	271	0.82	0.020	0.076
Hydro-electricity	1.79^{***}	-0.07^{***}	0.10^{***}	0.47^{***}	-0.00^{***}	0.99	1054	1.15	0.000	0.001
Firewood/charcoal	-0.06	0.03	0.00	-0.44^{***}	0.00	0.77	24	0.73	0.022	0.102
Sugarcane products	1.73^{***}	-0.15^{***}	0.34^{***}	-0.63^{***}	0.00^{***}	0.97	270	1.04	0.004	0.021
Other renewables	2.42^{***}	-0.12^{*}	0.17^{**}	-0.32	0.00^{**}	0.98	394	0.62	0.010	0.037

Source: Estimates are based on data from BEN, IPEADATA and BP-STATISTICS using the GRETL package
NOTE: *** Significant at 1%; ** Significant at 5%; * Significant at 10%

In general, it can be seen that income elasticities (GDP) are characterized as elastic and were statistically significant, except uranium and firewood, which are not significant. Most of the items for supply have a negative sign to its elasticity, this can be explained because the long-run supply might be being determined by demand, since the oil price influences the price of the composition of other supply intens.

As for the variable (D), which can be interpreted as a change in the growth rate in the downturn in oil prices during 1981–1998, the signs are negative for non-renewable energy sources and positive for renewable, which is contrary to what was expected, given that the oil price decreased and the growth rate of the supply was lower during this period[25].

As for the estimators of the Chow test for TCH and TCH.GDP income, the change did not occur in the slope of TCH.GDP curves. Although significant, the values are close to zero, but occurred in the TCH constant, as the data are in logarithms, and represent a change in the growth rate during the period 1970–1990 to 1991–2011. Looking at these two periods, the growth rate of non-renewable sources other than electricity increased during the 1991–2011 period.

Given the small probability value (p-value) of the augmented Dickey-Fuller test cases with constant ADF-C and augmented Dickey-Fuller with constant and trend ADF-CT, there is evidence for the vast majority of cases that the model is cointegrated.

Table 2 presents estimates of the ANCOVA-EC model for the elasticities in income, price, and auxiliary variables for consumption by energy source.

Table 2 - Estimates of Elasticities in Income, Price, and Auxiliary Variables of Energy Consumption by Source

Source	GDP	P	D	TCH	TCH.GDP	R^2	F	DW	ADF-C	ADF-CT
Natural gas	4.02^{***}	-0.14^{*}	-0.02	0.42	-0.00	0.98	440	0.73	0.052	0.175
Coal	3.31^{***}	-0.16	0.43^{*}	-0.22	-0.00	0.89	61	0.41	0.014	0.133
Firewood	-0.55^{***}	0.07^{***}	-0.05^{**}	-0.73^{***}	0.00^{***}	0.96	178	1.38	0.001	0.004
Sugarcane bagasse	1.34^{***}	-0.09^{**}	0.22^{***}	-0.63^{***}	0.00^{***}	0.97	269	1.08	0.007	0.034
Other prim. renew.	2.59^{***}	-0.12^{**}	0.12^{*}	0.13	0.00	0.99	520	0.75	0.024	0.079
Coke gas	1.88***	-0.16^{***}	0.18^{***}	0.66^{***}	-0.00^{***}	0.96	186	1.07	0.000	0.000
Coal coke	1.83^{***}	-0.14^{***}	0.15^{**}	0.81^{***}	-0.00^{***}	0.96	187	1.17	0.000	0.000
Electricity	1.77^{***}	-0.08^{***}	0.08^{**}	0.26^{**}	-0.00	0.99	948	0.83	0.001	0.004
Charcoal	1.34^{***}	0.01	0.09	0.49^{**}	-0.00^{***}	0.87	50	0.84	0.025	0.099
Ethyl alcohol	3.36^{***}	-0.37^{***}	0.69^{***}	-0.19	-0.00	0.95	127	0.86	0.000	0.003
Other sec. tar	1.35^{***}	-0.02	0.32^{***}	0.77^{***}	-0.00^{***}	0.94	114	1.29	0.001	0.006
Diesel oil	1.40^{***}	-0.00	-0.02	0.38^{***}	-0.00^{***}	0.99	2082	0.94	0.003	0.021
Fuel oil	0.21	0.18^{**}	-0.19^{**}	1.95^{***}	-0.00^{***}	0.70	17	0.42	0.027	0.105
Gasoline	-0.18	0.07	-0.23^{***}	-0.09	0.00^{*}	0.80	29	0.63	0.014	0.064
Liq. petroleum gas	1.50^{***}	-0.13^{***}	0.07^{**}	0.62^{***}	-0.00^{***}	0.98	462	1.03	0.004	0.017
Naphta	5.06^{***}	0.25	-0.23	4.12^{***}	-0.00^{***}	0.86	45	0.96	0.000	0.000
Kerosene	0.72^{***}	0.03	-0.04	0.33	-0.00^{*}	0.82	33	0.65	0.104	0.312
Piped gas	0.75^{***}	-0.01	0.20^{*}	5.78^{***}	-0.00^{***}	0.93	70	1.08	0.000	0.006
Other sec. oil	2.68^{***}	0.00	-0.26^{***}	0.70^{**}	-0.00^{***}	0.98	334	1.10	0.059	0.240
Non-energ. oil	1.01^{***}	0.14^{***}	-0.06	-0.03	-0.00	0.95	133	1.35	0.000	0.003

Source: Estimates are based on data from BEN, IPEADATA, and BP-STATISTICS using the GRETL package
Note: *** Significant at 1%; ** Significant at 5%; * Significant at 10%

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[25] The original intention of variable D was to isolate the periods of growth and non-growth of the oil price series. However, the curious fact is that just as the price series was decreasing during 1981–1998, Brazil had very low GDP growth rates, according to IPEADATA. The average growth rates of the GDP during the respective periods were: (1970–1980: 8.83%), (1981–1998: 2.07%) and (1999–2011: 3.36%). Thus, there is also the income effect on variable D. The price effect may cause variable D to present a positive sign, but the income effect may cause variable D to present an opposite sign.

Again, from the results in Table 2, we see that in most cases, the income (GDP) and price (P) elasticities have the expected signs – most cointegrated models, taking into account the probability values (p-values), are considered small.

The D estimates show mostly positive signs, while respecting the fact that when the signs are negative, there may be an income effect. For TCH, most estimates have positive signs, i.e., a significant change in the growth rate from one period to another, and TCH.GDP, although significant, has values close to zero.

Table 3 shows estimates of the ANCOVA-EC model for energy consumption per sector in the period considered.

Table 3 - Estimates of Elasticities in Income, Price, and Auxiliary Variables Energy Consumption by Sector

Sectors	GDP	P	D	TCH	TCH.GDP	R^2	F	DW	ADF-C	ADF-CT
Non-energy	2.01^{***}	-0.02	0.04	0.76^{***}	-0.00^{***}	0.98	434	1.38	0.000	0.000
Energy	1.95^{***}	-0.05	0.26^{***}	-0.01	-0.00	0.98	389	1.06	0.000	0.001
Residential	-0.16^{***}	0.02^{**}	-0.07^{***}	-0.32^{***}	0.00^{***}	0.94	108	1.47	0.000	0.000
Commercial	1.33^{***}	-0.08^{***}	-0.02	-0.01	0.00	0.99	575	0.86	0.001	0.004
Public	1.57^{***}	-0.10^{***}	-0.04	0.49^{***}	-0.00^{**}	0.99	532	0.99	0.013	0.058
Agriculture	0.26^{***}	-0.05^{***}	-0.00	-0.48^{***}	0.00^{***}	0.98	431	1.62	0.001	0.006
Total transportation	0.90^{***}	-0.02	-0.04	-0.03	0.00^{*}	0.99	702	0.84	0.016	0.080
Road	0.95^{***}	-0.05^{***}	-0.05^{**}	-0.04	0.00^{**}	0.99	773	0.87	0.022	0.089
Rail	0.04	0.13^{***}	0.11^{**}	-0.87^{***}	0.00^{***}	0.70	17	0.77	0.047	0.177
Air	1.03^{***}	0.02	-0.01	0.43^{**}	-0.00^{**}	0.92	78	0.58	0.128	0.356
Hydro	0.15	0.42^{***}	0.16^{*}	0.09	-0.00	0.76	23	1.06	0.000	0.000
Total industrial	1.12^{***}	-0.03^{**}	-0.05^{***}	0.03	-0.00	0.99	1439	0.80	0.001	0.004
Cement	0.63^{***}	0.09	-0.15^{**}	0.03	-0.00	0.80	28	0.61	0.004	0.026
Pig iron and still	1.62^{***}	-0.09^{**}	-0.02	0.63^{***}	-0.00^{***}	0.97	241	1.32	0.000	0.000
Iron-alloy	2.27^{***}	-0.01	0.21^{***}	0.64^{**}	-0.00^{***}	0.97	252	0.95	0.010	0.041
Mining and pelletizing	1.77^{***}	0.12^{***}	-0.17^{***}	0.63^{***}	-0.00^{***}	0.99	504	1.30	0.001	0.005
Non-ferrous and other metals	2.09^{***}	-0.08^{**}	0.04	0.57^{***}	-0.00^{***}	0.99	606	1.01	0.001	0.006
Chemicals	1.43^{***}	0.01	-0.05	0.50^{***}	-0.00^{***}	0.98	328	0.44	0.035	0.035
Food and beverage	0.54^{***}	-0.02	-0.05	-0.68^{***}	0.00^{***}	0.97	238	1.02	0.014	0.066
Textile	0.37^{***}	0.03	-0.03	0.18^{*}	-0.00^{***}	0.78	25	0.79	0.034	0.127
Pulp and paper	1.47^{***}	-0.03	0.00	0.05	0.00	0.99	1077	1.00	0.005	0.021
Ceramics	0.66^{***}	-0.02	-0.05^{**}	-0.45^{***}	0.00^{***}	0.97	240	1.46	0.001	0.003
Other sectors	0.97^{***}	0.04^{*}	-0.19^{***}	0.08	-0.00^{*}	0.97	269	1.19	0.003	0.014

Source: estimates based on data from BEN, IPEADATA, and BP-STATISTICS using the GRETL package
Note: *** Significant at 1%; ** Significant at 5%; * Significant at 10%

Most income (GDP) and price (P) elasticities have the expected signs. As for D, it can be seen that most industrial sectors had the lowest growth rate during the period in which the per-barrel price of oil was decreasing, or GDP slowing. Through the TCH estimates, it was also confirmed that there was a structural break in the growth of the series. The ADF-C and ADF-CT tests failed to accept the null hypothesis for the unit root of the residues for most cases.

4.3 Graph Presentation of Elasticities

In this stage of the study, we show a graphic representation of income elasticities (GDP), as this factor has the most weight in terms of elasticity in the model, along with the graphing of the share of each item in total. Figure 3 shows the behavior of the income elasticity of the supply and share of energy sources in total.

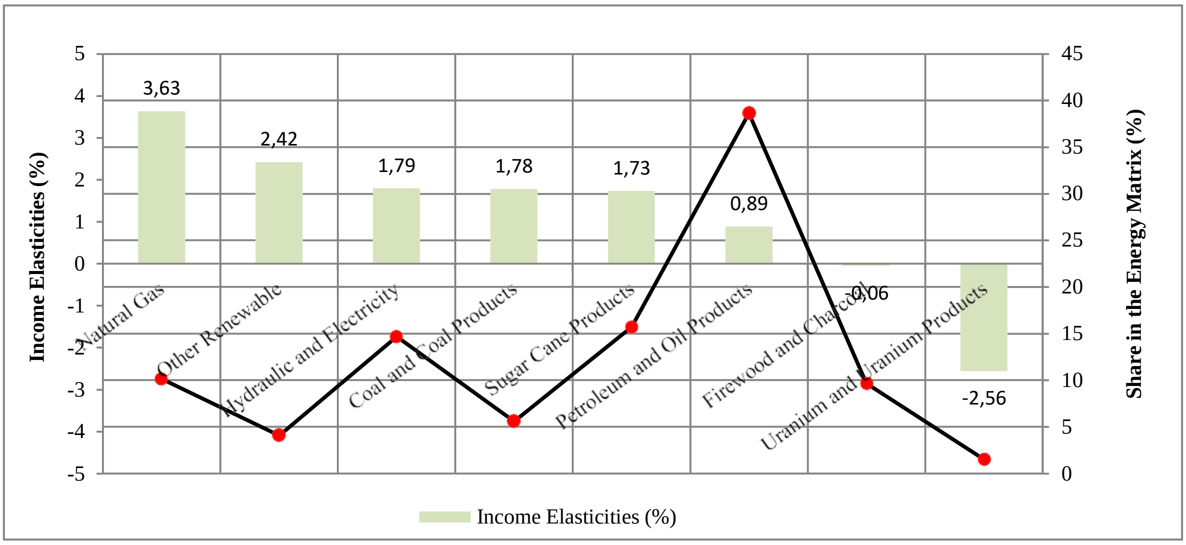

Figure 3 - Elasticity of Supply and Participation Sources in Relation to Total

Figure 3 shows that the largest proportional share of oil and derivatives in the supply, and in general, renewable sources with higher elasticities. Uranium, although not significant in the model, also had a lower frequency during 1984 to 2011.

Figure 4 shows the behavior of income elasticities (GDP) in relation to the share of energy consumption by source in relation to total consumption.

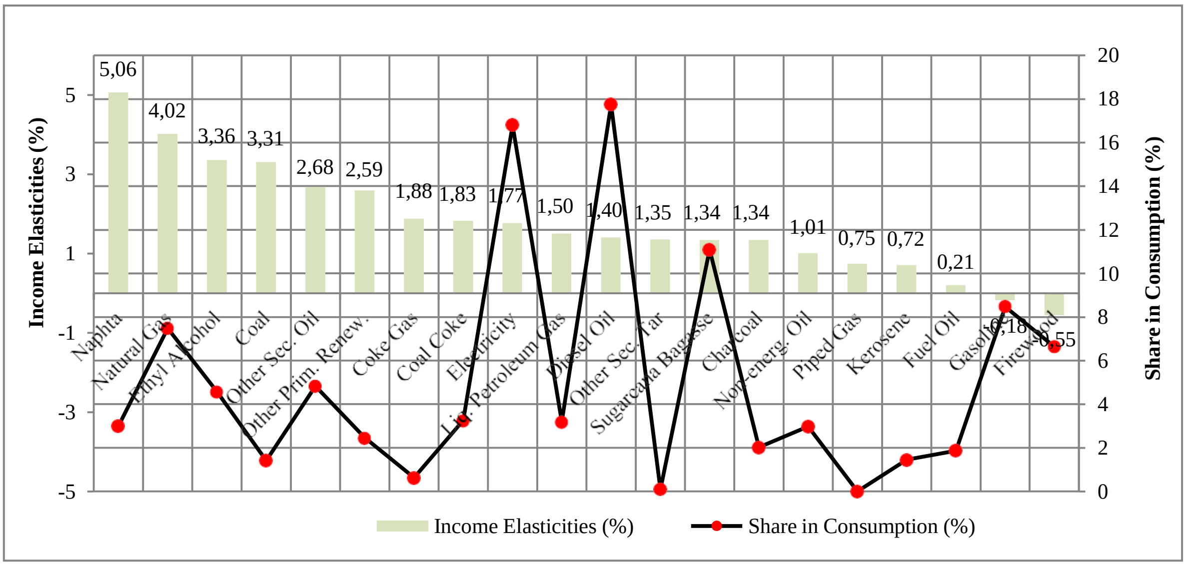

Figure 4 - Energy Consumption Elasticities by Source and Participation in Total Consumption

Notably, according to Figure 4, diesel fuel and electricity have a share of 17.8% and 16.8%, respectively, in consumption per source, representing approximately 35% of the total. It is clear that diesel fuel and electricity are the most consumed energy products, despite having intermediate elasticities when compared with other energy products.

Naphtha had the highest elasticity, as can also be seen in Figure 4. A possible explanation could be related to the change in the growth rate of naphtha during the period from 1991 to 2011, as measured by the TCH estimate, which was 4.12, as shown in Table 3.

Figure 5 shows the behavior of income elasticities (GDP) by sector of economic activity and their shares in total consumption.

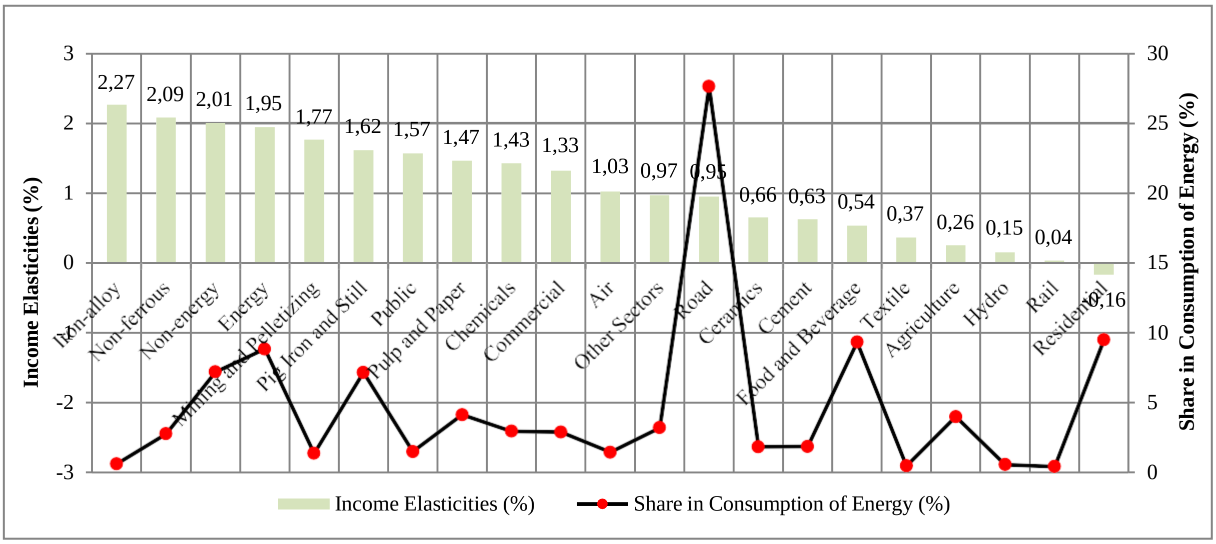

Figure 5 - Energy Consumption Elasticities by Sector and Share in Total Consumption

In the analysis of consumption by sector, the largest share of consumption appears to be that of the road transportation sector, which confirms the higher share of diesel, as shown in Figure 4, and indicates that the largest elasticities are in the industrial sector, in industries considered energy-intensive. It may be also noted that all sectors that had positive change in growth from the last two decades, as measured by TCH in Table 3, have higher elasticities.

4.4 Evaluation Based on Energy Intensity Index

According to Philipsen et al. (1997), energy efficiency can be defined as the amount of services (lighting, heating, transportation, etc.) provided per unit of energy used. Thus, the energy is related to the quality of a system or equipment. Usually, an energy efficiency indicator is used as an approximate factor for measuring this efficiency. This indicator, in turn, is represented by a numerator and a denominator (measurement of activity *versus* measurement of energy consumption). Philipsen et al. (1997) present two general energy efficiency indicators: economic (energy intensity) and physical (specific energy consumption). The economic indicators are more applicable in an aggregate level, and the physical indicators in a disaggregated level. Figure 6 shows the graph of the energy intensity index measured in terms of TOEs per USD1,000.

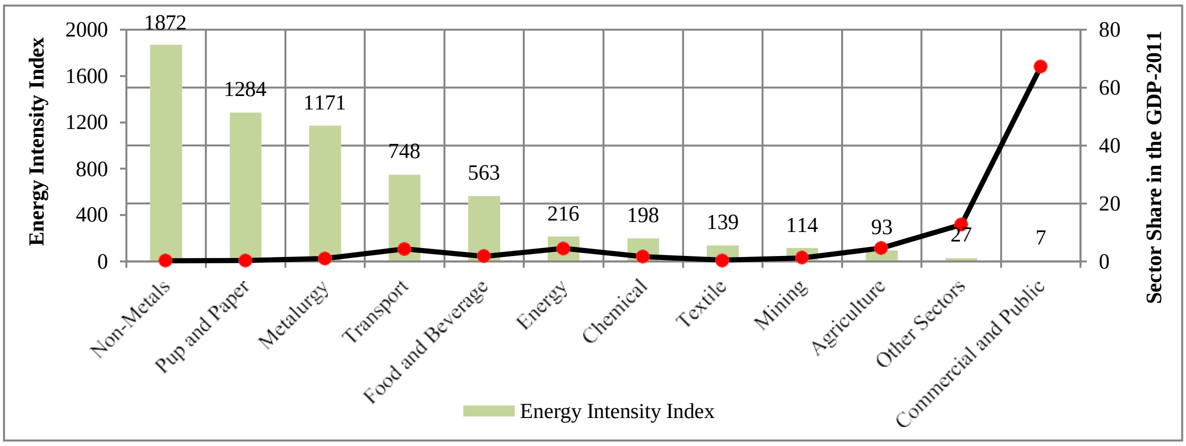

Figure 6 - Sector Energy Intensity Index and Sector Share in the GDP
Source: Compiled from BEN's historical data

Note that the bars in Figure 6[26] can be interpreted as showing how much energy each sector spends to generate USD1,000 of GDP.

Through Figure 6, it becomes clear that there is a considerable difference between the industrial and non-industrial sectors. Through Figure 6 and Table 3, it can also be observed that the sectors with the highest energy intensity have higher income elasticity. Figure 7 shows the evolution of the energy intensity index during the period 2002 to 2011.

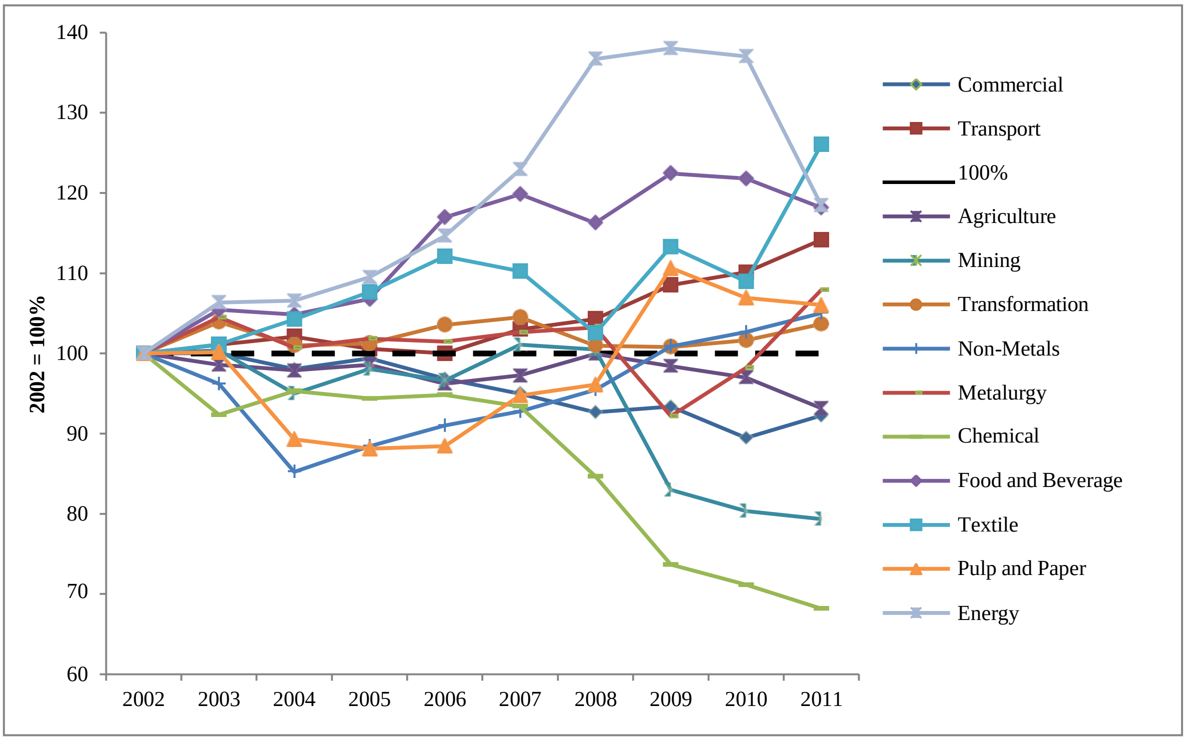

Figure 7 - Energy Intensity Comparison Based on the Year 2002
Source: Compiled from BEN's historical data

In Figure 7, the numbers show that this indicator has increased year after year in Brazil, i.e., with each year, more energy is spent to produce the same monetary value in various sectors. The signatures of Figures 6 and 7 are in accordance with Lucon and Goldemberg (2009), who reported that, in terms of energy intensity, Brazil was the only country to regress (stay above the 100% line) during the period 1990–2005. In a study of the energy content of the exports of 30 countries, J. Amador (2012) notes that the energy content of exports from Taiwan, China, India, and Brazil grew to be above the world average. In a energy analysis of pulp and paper industry through an energy decomposition Fracaro et al. (2012) estimated there is still a potential reductionof 146.2 PJ and 7.8 PJ in fuels and electricity consumption, respectively.

It can be argued that if there is an increase in efficiency, the elasticities tend to be smaller, given that a growth in income does not cause an explosive growth in consumption. One factor to consider in developing countries such as Brazil is the "pent-up demand" factor, meaning many people's needs remain unmet. This can be seen clearly when comparing the energy consumed per capita in developed countries – USA (6.81 TOE), Finland (6.15 TOE), Sweden (5.27 TOE), the Netherlands (4.69 TOE), Germany (3.82 TOE), and Denmark (3.10 TOE)—with the energy per capita of developing countries—South Africa (2.68 TOE), China (2.14 TOE), Brazil (1.42 TOE), and India (0.64 TOE) (IEA, 2014b). The pent-up demand factor can cause elasticity consumption to increase, even in the hypothesis of greater efficiency.

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[26] Non-Metals corresponds to the cement and ceramics industries, Metallurgy corresponds to the iron, steel, iron-alloys and non-ferrous metallurgical and other metallurgical products.

5. CONCLUSION

The aim of this paper was to estimate and analyze the income elasticities of Brazil's energy matrix, represented by the supply and consumption of energy. The following questions were dropped: What energy sectors or products are more sensitive to economic growth? If there are differences, what could explain such differences? Is it possible to conclude that there are sectors that are more efficient than others?

In a general context, the ANCOVA-EC model was satisfactory to compare elasticities, mainly income and price. The signatures of the elasticities can be compared in Chart 1, where different methods were used, but also in general, to estimate the elasticities of electricity.

The estimate D can be considered a viable alternative, given the limitation that it can only be interpreted through the income effect and the price effect, although the income effect tends to beat the price effect due to its greater elasticity. Regarding the Chow test, significant change from one period to another can be confirmed with respect to the growth rate, although there was no evidence of changes in the slope, i.e., in the very elasticities when compared to income (GDP). A cointegration was found in most estimates, one that had not been found before, with a simple regression that considered only the variables' income (GDP) and energy consumption.

We can conclude that we have reached the main objective of the study, which was to compare elasticities while supporting our specific objectives. What energy sectors or products are more sensitive to economic growth? If visually analyzed through the charts (3 to 5), elasticities were different among all groups calculated, i.e., supply and demand by source or sector. We found that there are energy sectors and products more sensitive to economic growth, such as the naphtha, natural gas and ethyl alcohol for energy products or iron alloy, non-ferrous and non-energy for sectors, throwing light on the first specific purpose.

Considering the second question: What could explain such differences? The task of explaining the differences was accomplished by identifying that the elasticities were higher in the energy-intensive sectors, and that energy products had the greatest growth in Brazil's Energy Matrix. Is it possible to conclude that there are sectors that are more efficient than others? Still, visually speaking, in Figures 5 and 6, the shape of distribution of elasticities is similar to the shape of distribution of the energy intensity index. It could be the beginning of evidence that the least efficient sectors, energy-wise, have higher elasticities. The chart in Figure 7 identifies that industries like Chemical and Mining increased their efficiency, but on the other hand, several sectors are above the line of 100%, as: Energy, Food and Beverage, Transport, Pulp and Paper, No-Metals, Metallurgy and Transformation, generating generating evidence to conclude that some sectors are more efficient than others.

This study was not intended to exhaust all possibilities of analysis on the implementation of the ANCOVA-EC model, given the sectorial specificities. We recognize that the modeling of many stochastic processes, although limited to some homogeneous point, has been a surprise in the significance items, R^2adjustment, and the residuals stationarity test.

We suggest future studies with other comparative methods, or even targeting some sectors such as industry and transportation, using a production efficiency and elasticity approach by applying methods such as data envelopment analysis (DEA) or stochastic frontier analysis (SFA). Possible studies could compare, for example: Why do paper and pulp have an energy intensity index greater than metallurgy, which includes pig iron, steel, iron-alloys, and non-ferrous, which historically demand more energy?

The comparison of the sectorial energy efficiency is recognized as a major project involving the development of specific methodologies for this aim, given the difficulty of establishing a threshold parameter between energy efficiency and inefficiency when working with sectors.

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APÊNDICE G

APÊNDICE G: ARTIGO 2 - EVOLUTION OF RISKS FOR ENERGY COMPANIES FROM THE ENERGY EFFICIENCY PERSPECTIVE: THE BRAZILIAN CASE

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Abstract

This study aims to evaluate whether energy savings from energy efficiency programs in Brazil affected the risks taken by energy companies during the period 2000–2013, based on the following research question: Can we assume that energy conservation programs affect return risks to electrical energy companies? The results obtained through risk assessment models, exponentially weighted moving averages, and the capital asset pricing model indicated that during periods of crisis, both volatility and required returns were higher, but during less difficult periods, risks taken were significantly reduced. Further, as research contribution, this research suggests the elimination the affirmative hypothesis that a possible increase in energy efficiency affects the risks taken by electrical energy companies.

Keywords: Capital Asset Pricing Model; PROCEL, Energy Conservation Programs.

JEL Classifications: E30; G38; K23; M48; Q4

1 Introduction

After the oil crisis in the 1970s, and given the excessive reliance on this non-renewable energy source (Dixon et al., 2010; Geller et al., 2006; Lee and Zhong, 2015**)**, which in 2005 still accounted for around 40% of both the Brazilian and world energy needs, its risk of depletion has been constant. Investments have been made in alternative energy sources and energy conservation, as well as efficiency, which is one of the main concerns involving electrical energy (Pinto Jr. et al., 2007; Guerra et al., 2014; Taffarel et al., 2015).

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According to Pinto Jr. et al. (2007) and Taylor et al., (2008), hydroelectricity accounted for 6% of the world energy matrix and around 13% in Brazil in 2005. According to a report published by the Ministry of Mines and Energy (MME) in collaboration with the Brazilian Energy Research Company (EPE) titled "*2030 National Energy Matrix*" (2007), hydroelectricity accounts for 19% of the world's electrical energy, 75% of the installed power in Brazil, and supplies 93% of the total electrical energy required by the National Interconnected Energy System (SIN). The same report shows that only 30% of the national hydropower potential is explored, indicating a growth potential for this sector (Guerra et al., 2014)

The demand for energy, according to Castro et al. (2013), is closely related to trends in the level of economic activity, technological paradigms (Emodi et al., 2015), and economic structure. This relationship is not constant, and is essentially characterized by scarce energy resources and the efficient use of energy, as described in Phylipsen et al's., 1997 study.

According to the National Energy Efficiency Plan (PNEE) published in 2011, one of Brazil's main initiatives towards energy conservation was the creation of a National Electrical Energy Conservation Program - PROCEL (Geller et al., 2000; Can et al., 2014) in 1985. This program's main objective was to publish and distribute materials on the efficient use of electrical energy, conduct specialized training, impose technical regulations, create laboratories and labeling programs, among others. From 2000 onwards, Law 9.991 determined the mandatory investments of electrical energy distributors in energy efficiency programs, who generated investments of around R$2 billion (MME, 2011).

Therefore, electrical energy companies are affected in two ways: they are required to allocate resources from their own profits towards energy efficiency programs (Hobbs et al., 1994; Scott et al., 2008; Kama and Kaplan, 2013) and face reduced demand due to greater efficiency. It seems contradictory that energy companies encourage a reduction in demand for electricity. Therefore, can we assume that energy conservation programs affect return risks to electrical energy companies? The main contribution of this study is to analyze whether energy efficiency programs affect the risks of energy companies and attempt to define a possible fragility of the system. The PROCEL program is addressed here as the legislation used in such program implementation.

2 Theoretical-Empirical Framework

This study is based on two apparently distinct research areas: (1) research and application in energy efficiency and (2) financial risk calculation methods.

2.1 Energy efficiency

Figure 1 represents the energy efficiency indicators (Vikhorev et al., 2013), and demonstrates that efficiency may occur from the bottom of the pyramid (equipment efficiency) to the top (efficiency of the economy as a whole).

Tanaka (2011) stresses on the relationship between energy efficiency policies and industry, trade associations, the government, and the economy as a whole. In his 2011 model, he classifies energy efficiency measures as prescriptive measures, economic measures, supportive measures, and direct investments (Arroyo et al., 2014). This energy efficiency model corresponds with the energy efficiency pyramid, as its policies or measures may be applied to equipment or the economy as a whole.

According to Lucon and Goldemberg (2009), in the developed Organization for Economic Co-operation and Development (OECD) countries, energy efficiency accounted for 58% of the total profits in 2005. This is largely due to the legislation forcing manufacturers to produce more efficient equipment. In Brazil, the most popular energy efficiency program is PROCEL. According to institutional information, the program was created in 1985 by the Ministries of Mines and Energy and Industry & Commerce. In the following 25 years after its creation, the following subdivisions responsible for energy efficiency were incorporated: Procel Info (information); Procel Edifica (Buildings); Procel Selo (equipment); Procel Indústria (industry); Procel Sanear (environmental sanitation); Procel EPP (public buildings); Procel GEM (municipalities); Procel Educação (education); and Procel Reluz (public lighting). According to PROCEL results (2013) published by Eletrobrás, using 2012 as the base year, these subdivisions saved 9,097 GWh by implementing energy efficiency measures, which accounts for 2.03% of the total consumption of electrical energy in Brazil (Eletrobrás, 2013).

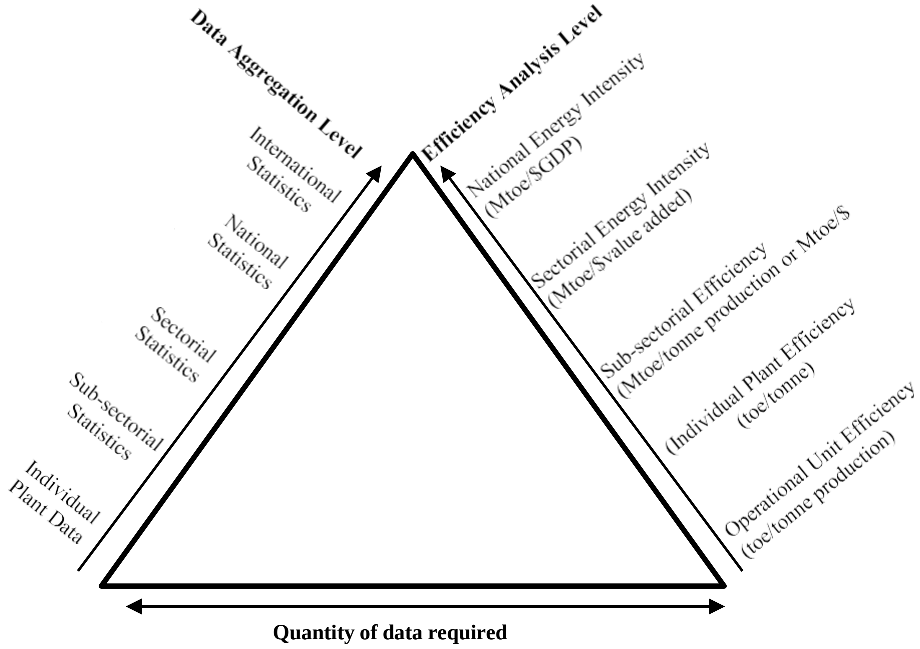

Figure 1. Energy Efficiency Indicators Pyramid.
Source: Phylipsen et al., 1997 and Vikhorev et al. 2013.

This study does not focus on discussing all the activities of PROCEL, but focuses on its main objective, i.e., reducing energy consumption via efficiency measures. The efficiency program here is identified by the regulations (Leme et al., 2014) created to support it. Table 1 classifies the regulations by date.

Table 1- National Regulations Related to Energy Efficiency

Date	**Regulations and Associated Projects**	**EE**
Dec 30, 1985	Directive 1.877 – National Electrical Energy Conservation Program (PROCEL)	EE
Jan 9, 1987	Decree 93.901 – Electrical energy rationing criteria	RZ
Oct 26, 1990	Decree 99.656 – Internal Commission for Energy Conservation (CICE)	EE
Nov 23, 1993	Decree 34.979 – State Program for Energy Conservation in Buildings	EE
Dec 8, 1993	Decree 0-002 – Creates the National Award of Energy Conservation and Rational Use	CS
Dec 8, 1993	Decree 0-006 – Creates the Green Seal of Energy Efficiency	EE
Jan 11, 1994	Decree 1.040 – Conservation project funding by financial agents	CS
Nov 12, 1997	Directive 466 – Provides general conditions of electrical energy supply	O
Aug 13, 1998	Directive 001 – Creates a workgroup to study energy efficiency	EE
Dec 2, 1999	ANEEL Resolution 334 – Projects aiming to improve load factor	EE
Jan 6, 2000	Decree 3.330 – Goal of energy consumption reduction in public bodies	RC
July 24, 2000	Law 9.991 – Establishes mandatory resource allocation to R&D and energy efficiency	EE
Nov 14, 2000	Decree 19.147 – Electrical energy consumption reduction in public buildings	RC
Nov 29, 2000	ANEEL Resolution 456 – Establishes electrical energy supply conditions	O
Jan 1, 2001	Law 3.486 – Installation of solar energy and gas heating equipment in Varginha	EQ
Jan 26, 2001	Decree 45.643 – Procedures for high-performance lamp acquisition	EQ
Mar 7, 2001	Directive 46 – Creates the Energy Conservation Goal Supervision Committee	CS

Apr 18, 2001	Decree 3.789 – Offer and Consumption Rationalization Management Commission	RZ
Apr 26, 2001	Decree 3.806 – Addresses emergency measures for energy rationalization	RZ
May 4, 2001	Decree 45.765 – State Program for Energy Use Reduction and Rationalization	RZ
May 15, 2001	Provisional Measure 2.147 – Electrical Energy Crisis Management Chamber (GCE)	CM
May 22, 2001	CGCE Resolution 004 – Special regimes of billing, usage limits, and supply	TR
May 25, 2001	Directive 174 – Creates the internal commission for energy consumption reduction	RC
July 16, 2001	Decree 3.867 – Defines where the energy efficiency R&D resources will be deposited	EE
Sept 17, 2001	ANEEL394 Resolution – Criteria for projects that fight against waste	DS
Oct 17, 2001	Law 10.295 – National Policy of Energy Conservation and Rational Use	CS
Dec 19, 2001	Decree 4.059 – Minimum levels of efficiency for equipment	EQ
Dec 19, 2001	Law 10.334 – Regulates incandescent bulb manufacture and marketing	EQ
Feb 25, 2002	Decree 4.145 – Regulates emergency consumption goal	MC
Mar 15, 2002	Directive 113 – Establishes a consumption goal for public bodies	MC
Apr 29, 2002	Law 10.438 – Expansion of emergency electrical energy offer	O
July 26, 2002	Decree 21.806 – Book of charges for energy efficiency in public buildings	EE
Sept 3, 2002	ANEEL Resolution 492 – Criteria for resource allocation to energy efficiency	EE
Dec 11, 2002	Decree 4.508 – Minimum levels of energy efficiency of electric engines	EQ
Mar 18, 2004	CC-23 Resolution – Creates a technical group to study and propose best practices	EM
Jan 1, 2005	Law Project 518 – Municipal policy of incentives for using alternative sources	EM
Mar 30, 2005	Law 4.507 – Installation of solar heaters in Birigui	EQ
Sept 29, 2005	CC-64 Resolution – Technical group of the Public Management Quality Committee	EM
Nov 28, 2005	ANEEL Resolution 176 – Criteria for resource allocation to energy efficiency	EE
Dec 8, 2005	Inter-ministerial Directive 553 – Performance of electric 3-phase induction engines	EQ
Jan 1, 2006	Law Project 1.045 – Piping facilitating the adoption of solar heating system	EQ
Mar 28, 2006	ANEEL Resolution 215 – Changes in the efficiency program manual	EE
Jun 12, 2006	Inter-ministerial Directive 132 – Regulation for compact fluorescent lamps	EQ
Oct 24, 2006	ANEEL Normative Resolution 233 – Calculation of resources foreseen in Law 9.991	EE
Jul 1, 2007	Law 14.459 – Installation of solar water heating system	EQ
Jan 21, 2008	Municipal Decree 49.148 – Solar heating system in the municipality of São Paulo	EQ

EE: energy efficiency; RZ: rationalization; CS: conservation; O: offer; RC: reduced consumption; EQ: equipment; CM: crisis management; TR: tariff (billing); EM: energy management

Source: http://www.procelinfo.com.br and the National Energy Efficiency Plan (2011).

2.2 Risk Assessment Models

The risk is the probability of receiving a return on investment other than the expected amount (Fama and French, 2007). Risk does not include negative results, in other words, returns that are less than the expected amount alone, but also includes positive results, being returns that are more than the expected amount. Investors are expected to maintain a balance between risks and returns (Hung Cheung and Xu, 2003). Risk is represented by the variances of expected returns (Damodaran, 2010; Ghysels et al,. 2014).

According to Alexander (2005), the two variance models used to represent risk (volatility) are: *equally weighted moving average* - EQMA (Morgan, 1996) and *exponentially weighted moving average* - EWMA (De Santis et al, 2003). The first model assigns the same weight, considering present and past observations, while the second assigns greater weight to recent observations, considering the exponential decay. Variances of these models may be represented as follows:

$$\begin{aligned} &EQMA \quad \hat{\sigma}^2 = \sum\nolimits^{n}_{i=1} r^2_{t-i}/n \\ &EWMA \quad \hat{\sigma}^2 = (1-\lambda)r^2_{t-1} + \lambda\hat{\sigma}^2_{t-1} \end{aligned} \qquad (1)$$

According to Bueno (2011), such techniques may be applied if the series do not present trends or seasonality (Costantini and Martini, 2010), indicating the presence of self-correction and stationarity (Box et al., 1994). The augmented Dickey-Fuller test[28] is typically used to verify a series. Silva et. al. (2010) concluded that EWMA was the model that adapted better, considering the estimation of *value at risk*, and was based on a theoretical portfolio of stock price indexes from Argentina, Brazil, and Mexico.

Fama and French (2004, 2007) present the *capital asset pricing model* (CAPM) as one of the widely used models in the estimation of capital cost and return assessment of portfolios. The original model was proposed by Sharpe (1964), Lintner (1965) and Black et al., 1972, and was based on the efficient portfolio theory of Markowitz (1959). Markowitz (1952) emphasizes that risk in the financial area is measured by the variance of returns or the deviation from the average. Sharpe (1964) points out that asset prices have a close relationship with risk, measured by the beta coefficient, and that investment decisions are constructed from two variables: (i) the mathematical expectation of returns, and (ii) the standard deviation from the probability distribution.

In Brazil, this classic model was introduced by Alcântara (1981) and was viewed as a popular model in the European and American financial markets, which was subsequently used by select institutions in the Brazilian market. This study was selected as the base for raising questions regarding the objectives of this article, namely, the challenges involved in measuring risk and returns based on the selection of every possible event, and its implications in terms of risk and return. CAPM is based on certain essential concepts: (i) Efficiency of the capital market – the stock prices reflect all available information, which is the same as the fair price; (ii) Based on the utility theory, investors are opposed to risks, and make their rational combinations based on a logic of a map of indifferences that take risk and return into account; (iii) Existence of an efficient portfolio that is superior in terms of risk and return, which is represented by a market index; and (iv) risk-free assets. According to Alcântara (1981), this model can be represented as follows:

$$R_j - R_F = \alpha_j + \beta_{jM} \, (R_M - R_F) + r_j \qquad (2)$$

where, R_F is a risk-free asset; $R_j - R_F$ is the stock excess return; $R_M - R_F$ is the market excess return; α_j is the additional stock return when the market excess return is zero; β_{jM} is the sensitivity of stock return excess in relation to the market return excess; and r_j represents the uncertain portion of the extra market component of the stock return excess. According to Alcântara (1981), when the model terms are reorganized, we obtain the following:

$$R_j - R_F = \underbrace{\beta_{jM} \, (R_M - R_F)}_{\text{return component due to market}} + \underbrace{\alpha_j + r_j}_{\text{return component duee to extra} - \text{market factors}} \qquad (3)$$

Therefore, α_j represents the expected return excess portion that is not related to the market, while r_j represents deviations from the expected return that do not depend on the market. Extra-market risk (diversifiable or non-systematic risk) may be measured through the dispersion of return excess owing to extra-market factors. Essentially, they are deviations in linear regression. Based on

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[28] According to Gujarati and Porter (2011), the Dickey-Fuller test uses statistics (tau) r to observe whether the series is a random walk (with and without displacement or a temporal trend), considering the white noise of error values. Given a simple random walk $Y_t = \rho Y_{t-1} + u_i$ transforming $Y_t - Y_{t-1} = (\rho - 1)Y_{t-1} + u_i$, with $\delta = (\rho - 1)$, testing null hypothesis H_o: $\delta = 0$ is the same as testing H_o: $\rho = 1$. For cases in which errors are correlated, the values with deviations from the dependent variable are summed up. Currently, it is known as the augmented Dickey-Fuller test, represented in a complete equation with displacement and temporal trend as $\Delta Y_t = \beta_1 + \beta_2 t + \delta Y_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \varepsilon_t$.

the idea that a non-systematic risk can be diversified, the model places more emphasis on the systematic risk component, represented:

by β_{jM} or $^{Cov(R_M, R_j)}/_{\sigma^2 R_M}$, covariance between stock and market divided by market profits, and

such a model may be represented as follows:

$E_{R_j} = R_F + \beta_j(E_{R_M} - R_F)$, reorganized as $E_{R_j} - R_F = \beta_j\ (E_{R_M} - R_F)$ (4)

It should be noted that components $\alpha_j,\ r_j$ were not included in the equation above because they are part of the diversifiable risk. This equation can be interpreted as follows: the expected return of a stock depends on the risk-free return rate adopted and marked excess return weighted by the behavior of such stock in relation to the market behavior, which is measured by beta (Alcântara, 1981). This model receives strong empiric criticism by Fama and French (2004, 2007), who propose a model of three factors as an alternative. This study does not intend to discuss the model. However, Saito and Losso (2007) consider it valid, while others do not.

Several studies in the extant literature aim to test the proposals of the original CAPM. Figueiredo de Castro Junior and Yoshinaga (2012) propose an extension based on co-skewness and co-kurtosis, using a panel data technique; Araújo et al., (2006) test the GDP as a proxy for market portfolios; Tambose Filho et al. (2006) work with conditional models, with beta that varies along time. According to these authors, beta variation studies are not very common, probably because the conclusions of the studies conducted by Fama and MacBeth (1973), Black at al., (1972), suggest that beta is static, and indicating that the systematic risk would not change with time.

According to ANEEL's technical note 49/2013-SER, the CAPM and Weighted Average Cost of Capital - WACC (Modigliani and Miller 1958, 1963) models are used to establish the capital costs of providing electrical energy transmission services.

> *The cost of equity capital is the return rate that investors require to invest their capital in a company associated with a certain activity. ANEEL has adopted the CAPM to calculate the cost of equity capital (sheet 6 of Technical Note 49/2013).*

Although CAPM is the capital cost method used in beta calculations, even considering local bet as the ideal, the report uses mean beta from electrical sector companies in the United States, which have a levered beta of 0.7009 and unlevered beta of 0.27. According to the report, beta from the United States was used owing to the following: (a) data quality and quantity regarding energy transmission; (b) immature capital markets; (c) insufficiently extensive time series; (d) high volatility of stock; and (e) low liquidity in many cases.

3 Methodological Procedures

The proposed methodology has to be aligned with the availability of information and tools. The regulations and projects related to energy efficiency (energy saving) will be used as a secondary information source, as a *proxy* of energy efficiency measures, as well as to extract prices of historic series of stocks from the Economatica database (http://economatica.com). EQMA/ EWMA and CAPM were presented as risk/return assessment techniques. A central question that needs to be addressed at this stage is how to support the methodology? To answer this, two citations are presented below:

> *The challenges in measuring risks and returns may be understood if we imagined an analyst trying to outline every possible event (a stock price, for instance) and estimate its probability of occurring and the effect of every price on the investment alternatives* (Alcântara, 1981 p.56). *If general economic trends are stable, industry characteristics remain relatively unchanged, and there is a continuous management of companies, beta measurement will be relatively stable when calculated for different periods. If these conditions of stability do not exist, the beta value will also vary* (Alcântara, 1981 p.62).

By analyzing whether the Brazilian energy conservation program impacted the risks/returns of electrical energy companies, every regulation/program presented in Table 1 can be considered as an event, the following problem refers to, according to the citation above, estimating the probability of every event on the stock of every electrical energy company, and that may be tautological, as considering 2001, for instance, with many events occurring close to each other, how to identify which event is affecting the analyzed variable? Table 1 shows that most events take place in 2000–2001, which is a period of crisis, as analyzed mainly by Goldemberg and Prado (2003).

According to Damodaran (2010), in addition to the market risks that affect all companies and the risks taken by a specific company, as literature gap, we find risks that affect an entire sector. Therefore, this study essentially establishes that energy efficiency events affect the entire electrical sector. Therefore, the objective is to analyze the risk/return stability of the electrical sector during the period of intense energy efficiency measures to the present day.

3.1 Data Collection and Sampling

During the analyzed period, starting 2000, energy efficiency programs were intensified, as indicated in Table 1. Stock prices were extracted from the Economatica database, with sectorial classification as potential samples. An investigation of the energy sector generated 85 potential stocks for analysis, and of these, ten stocks with valid weekly data were found in the period from early 2000 to 2013. To assign other sectors as controls, the same technique was applied to all sectors of Economatica, using the sectors with four or more stocks negotiated with valid data, as indicated in Table 2.

Data of weekly saving accounts were also collected from the database as a proxy of the risk-free rate and IBOVESPA as a proxy of the market portfolio. Raw data were collected over a total of 729 weeks for every series, from January 7, 2000 to December 20, 2013.

Table 2 – Sample - Stocks by Sector

Sector	Stocks
Energy	Celesc PN, Cemig ON, Cesp ON, Coelce PNA, Copel ON, Eletrobras ON, Emae PN, Light S/A ON, Tractebel ON, Tran Paulist PN
Metallurgy	Ferbasa PN, Forja Taurus PN2, Gerdau PN, Gerdau Met PN, Sid Nacional ON, Usiminas PNA
Telecommunications	Embratel Part PN, Oi PN, Telebras ON, Telef Brasil ON, Tim Part S/A ON
Finance/Insurance	Amazonia ON, Bradesco ON, Brasil ON, ItauUnibanco PN

Source: Economatica[29]

3.2 Analysis Metrics and Model Variables

Given the proposed problem, a metric system that naturally emerges is the application of a panel analysis, or a data combination in temporal series with cross sections. Panel data can be used to capture a possible heterogeneity, either between groups or in time (Arroyo et al., 2014; Baltagi, 2005; Gujarati and Porter, 2010; Hill et al., 2010; Nauleau, 2014; Wooldridge, 2010).

Essentially, three methods are available to analyze panel data: the pooled model, the fixed effects model, and the random effects model, represented in the matrix forms below:

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[29] Even with the procedure referred above, the following missing data were identified in the sample: Coelce PNA [24/08/2001] – Emae PN [16/11/2012; 12/07/2013; 09/08/2013; 01/11/2013] – Amazonia ON [13/12/2002; 31/01/2003; 07/02/2003; 22/04/2005; 17/06/2005; 27/01/2006; 24/02/2006] – Ferbasa PN [15/02/2002] – Embratel Part PN [09/09/2011; 14/10/2011; 06/01/2012; 29/06/2012; 21/09/2012; 21/12/2012; 15/02/2013; 22/02/2013; 05/04/2013; 31/05/2013; 28/06/2013] – Telebras ON [04/05/2012; 11/05/2012; 18/05/2012; 12/07/2013; 06/09/2013; 13/09/2013; 20/09/2013], representing {31/(25*729)}*100 = 0.17% of total. The technique used to correct the problem was the assignment of closest value, according to Hair et al. (2009), where missing data are replaced with real values using the closest case. In this specific case, the stock price from the previous week was used.

$$
\begin{array}{llcl}
1 & Pooled\ Data & \equiv & y_{it} = \alpha + \beta X_{it}' + \mu_{it} \\
2 & Fixed\ Effects & \equiv & y_{it} = \alpha_i + \beta X_{it}' + \mu_{it} \\
3 & Random\ Effects & \equiv & y_{it} = \beta X_{it}' + (\varepsilon_i + \mu_{it})
\end{array}
\qquad (5)
$$

Where y_{it} is the vector of independent variable of $i - th$ individual in t time units; X_{it}' is the matrix of dependent variables of $i - th$ individual in t time units; α, β are the vectors of coefficients; and $\varepsilon_i + \mu_{it}$ are the vectors of errors, respectively.

As introduced by Baltagi, 2005; Gujarati and Porter, 2010; Wooldridge, 2010, Croissant and Millo, 2008; Katchova, 2013, model 1 (pooled data) consists of constant coefficients, where α and β present no variation between individuals or in time. In model 1, it is assumed that individuality is represented by μ_{it}. In model 2 (fixed effects), it is assumed that heterogeneity between individuals is represented by intercept α_i; in this model, variables not observed as represented by α_i are correlated with μ_{it}. In model 3 (random effects), heterogeneity between individuals is represented by error $(\varepsilon_i + \mu_{it})$, ε_i is randomly distributed, i.e., it is not correlated with regressors. If ε_i is correlated with repressors, the fixed effects model is the most appropriate.

There are at least five ways to estimate the models above based on (Croissant and Millo, 2008; Katchova, 2013ab):

(a) *Pooling* [uses both variation between and within groups];
(b) *Between* [uses variation between groups];
(c) *Within* [uses variation within groups];
(d) *Random* [uses the weighted mean between variations within and between groups];
(e) *First difference* [uses the first difference].

The model that better fulfills the needs of the proposed problem is model 2 (fixed effects), as this model may be estimated according to Gujarati and Porter (2010), through dummy variables, for both individuals and in time (one-way or two-way)[30]. As its purpose is to analyze how the sectorial risk behaved along time, 10 companies along 728 weeks, representing 14 years, a version of the one-way fixed effects model for time can be adapted as follows:

$Y_{10-14} = \alpha_{14} + \beta_{14} X_{10-14} + DT_{1\to13} + DTX_{1\to13} + \mu_{it}$ where:
(6)
$Y_{10-14} = E_{R_j} - R_F$ is the expected return from 10 stocks in 14 years;
$\beta_{14} X_{10-14} = \beta_j (E_{R_M} - R_F)$ represents beta from 10 stocks in 14 years;
$DT_{1\to13} + DTX_{1\to13}$ represents 26 dummy variables of intercept and time interaction.

Although this model is equivalent to the estimator within groups (Within), as introduced by Gujarati and Porter (2010), this study also presents other estimators with their respective statistical tests, for comparison purposes, as illustrated in Figure 2. A similar approach was adopted by Resende (2014).

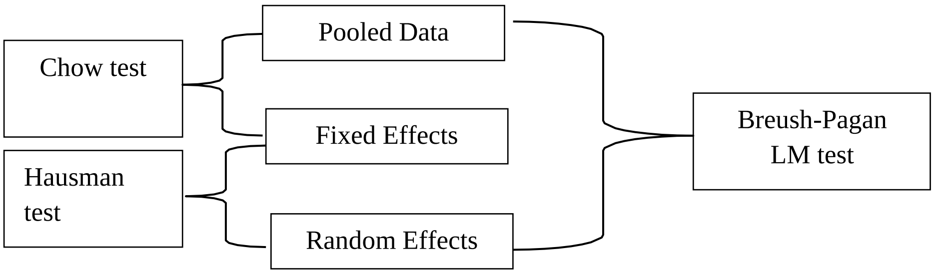

Figure 2 – Tests in Data Panel Models
Source: Developed by the authors

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[30] The problem of a two-way model with dummy variables recognized by both Gujarati and Porter (2010) and Baltagi (2005) is the large number of variables the model has to handle, which makes the analysis of a small sample not viable.

4 Data Presentation and Analysis

4.1 Evolution of risk

To begin explaining the problem, two questions are asked: How has the market risk represented by IBOVESPA volatility progressed during the analyzed period? How has the energy sector risk progressed by considering the stocks in Table 2? Figure 3 represents the evolution of market risk (volatility) represented by the IBOVESPA index.

Figure 3 indicates that at least two conclusions can be made: (i) the level of volatility is lower at the end of the period, and (ii) there are two periods of higher volatility as represented by the circles in the figure. The former refers to reduced volatility at the end of the period, i.e., a lower risk. The latter refers to exogenous shocks, which at first, does not establish an exact cause–effect relation, given the multiple events between 2000 and 2002. In the case of the subprime crisis, the cause–effect relationship is more evident owing to a higher volatility. Figure 4 shows the return volatility by considering the stocks presented in Table 2.

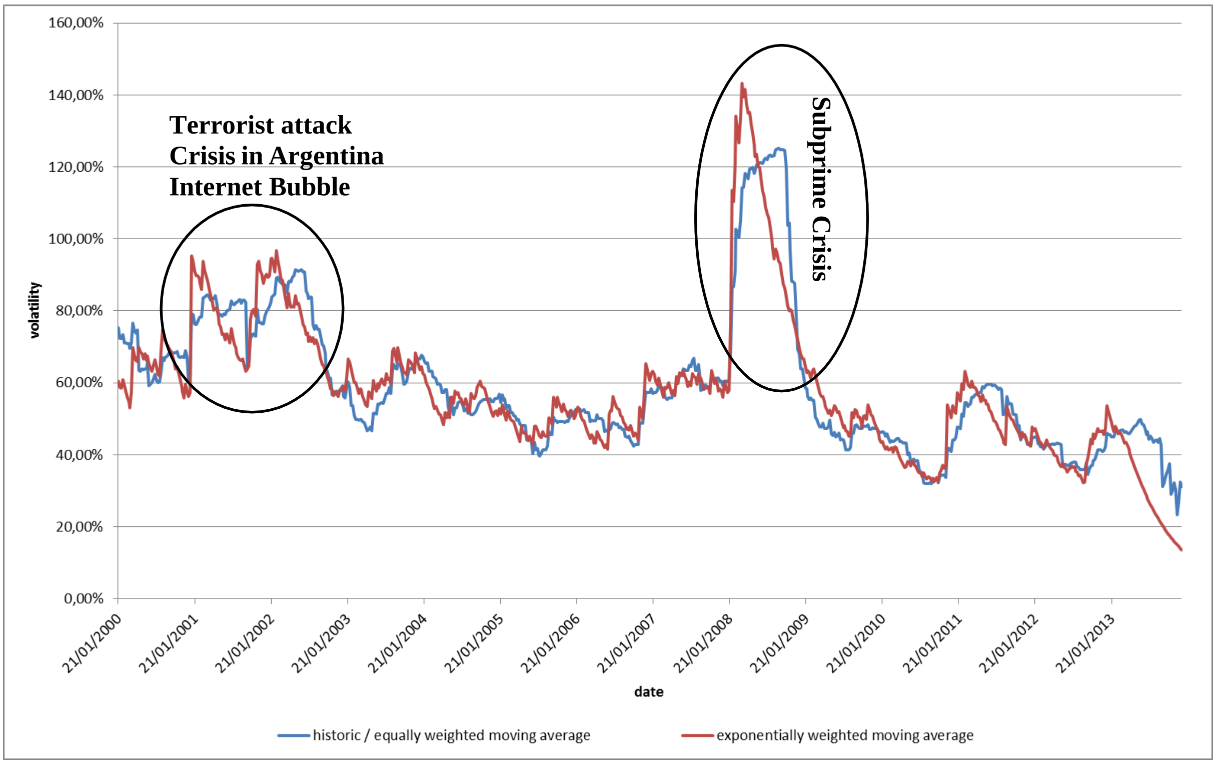

Figure 3 – Ibovespa Volatility through EQMA and EWMA[31] methods.
Source: Research data

Figure 4 shows return volatility for collective stocks presented in Table 2. Based on Damodaran (2010) study involving the sector risk component and market risk, one question that naturally emerges is: when analyzing Figure 4, what are the factors that can be attributed to sector risk and market risk?

Considering that the total risk is the sum of sector risk and market risk, the differences in Figures 3 and 4 can be attributed to the sector risk. The square in Figure 4 shows that between 2000 and 2004, the energy sector volatility represented by the sample stocks is greater than the market volatility. According to Table 1, this period had the creation of more than 50% of regulations related to energy efficiency. According to Gomes and Vieira (2009), owing to a lack of investment, a crisis period occurred in 2001, leading to rationing.

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[31] It is possible to implement these methods, because the series of Figures 3 and 4 did not present unit root at the level of 99% reliability, when using GRETL software. The tests were conducted under the following hypotheses: (a) Without Constant; (b) With Constant; (c) With Constant and Trend.

Goldenberg and Prado (2003) believe that the peak energy crisis was a result of reforms that occurred in the Fernando Henrique Cardoso (FHC) government, with respect to de-verticalization, privatization, and increased competition. According to Goldenberg and Prado (2003), there were differences between market interests and social interests, considering that Eletrobrás coordination was not in place anymore, and there was the absence of clearly developed regulation, resulting in reduced investment low levels of reservoirs in 2001, which resulted in the consequent instability of the sector (which experienced blackouts and rationing).

According to a report from the Brazilian federal accountability office (TCU), after the blackout, R$ 32.2 billion was invested in 2003, of which 60% came from tariff increases and the remaining from the National Treasury. Post investment, stock volatility significantly reduced, thereby worsening the subprime crisis and the 2012 crisis.

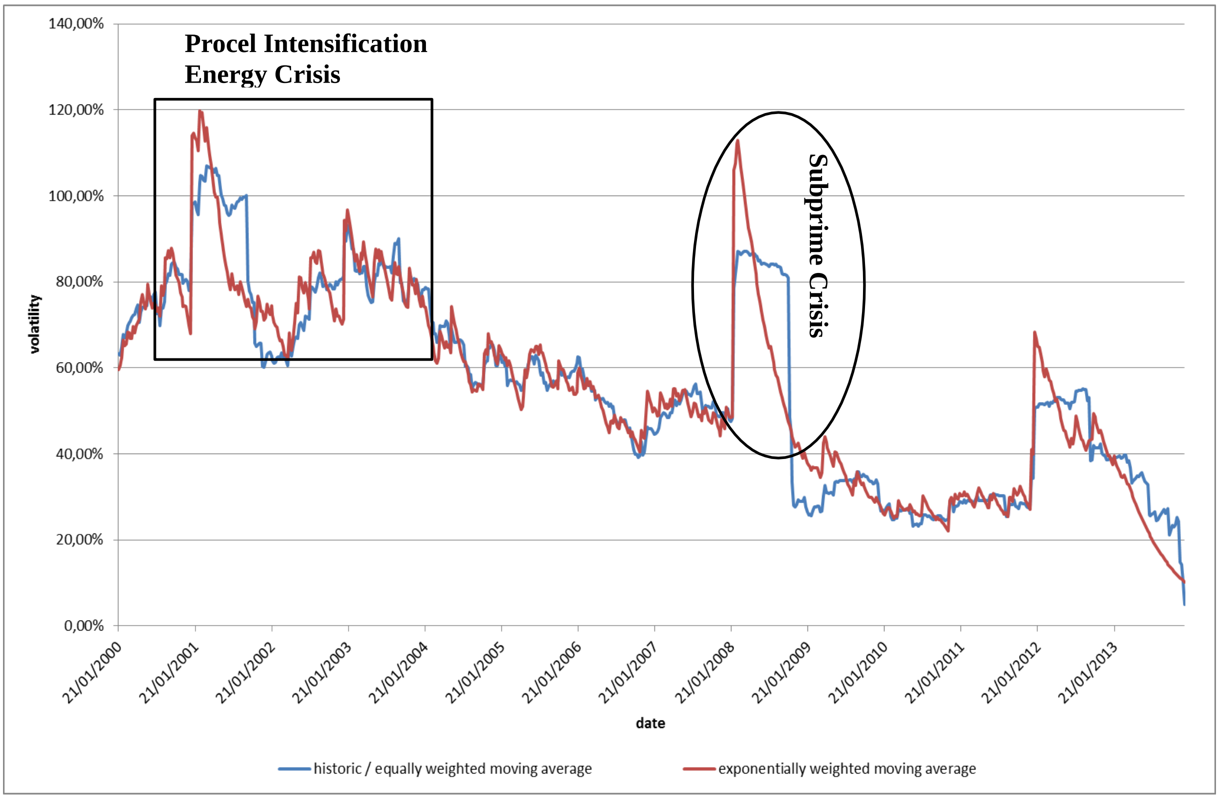

Figure 4 – Energy Sector Volatility through EQMQ and EWMA methods.
Source: Research data

4.2 Expected Return and Risk

The expected return measured via CAPM also indicates the risk, considering that to invest in an asset of greater volatility (variance), the investor requires a higher return rate, as presented in Alcântara's (1981) study. Equation 6 from data panel model was used to estimate the beta value in Box 2, with the saving rate as a proxy for risk-free assets.

Data from Box 2 were estimated using four different estimation techniques: least squares dummy variables (LSDV); ordinary least squares in first difference (OLSFD); random effects model (REM); and ordinary least squares with pooled data (OLSPD). The estimations were entered into the GRETL econometric software and in an R plm pack[32], and both systems provided the same results.

As beta represents systematic risk, the four estimation techniques showed that the energy sector risk is lower than the market risk, with high statistical significance. One interpretation of beta values obtained is that for every R$ 100 return required by the market, the energy sector requires around R$ 86 if using the fixed effects estimation (LSDV) is used and R$ 82 if REM is used.

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[32] R codes for Box 1 are presented in Appendix 1.

Models	**LSDV**		**OLSFD**		**REM**		**OLSPD**	
Constant	0.004*	[1.84]	0.001	[0.531]	0.001	[1.13]	0.001	[1.26]
Beta	0.867***	[23.09]	0.854***	[20.15]	0.822***	[81.07]	0.823***	[81.06]
DT1	-0.001	[-0.20]	-0.034	[-1.29]	-	-	-	-
DT2	-0.009**	[-2.54]	-0.044	[-1.19]	-	-	-	-
DT3	-0.006	[-1.62]	-0.083*	[-1.85]	-	-	-	-
DT4	-0.006*	[-1.81]	-0.089*	[-1.72]	-	-	-	-
DT5	-0.004	[-1.19]	-0.104*	[-1.79]	-	-	-	-
DT6	-0.003	[-1.03]	-0.127**	[-2.01]	-	-	-	-
DT7	-0.005	[-1.53]	-0.135**	[-1.96]	-	-	-	-
DT8	-0.003	[-0.85]	-0.190**	[-2.57]	-	-	-	-
DT9	-0.004	[-1.25]	-0.228***	[-2.91]	-	-	-	-
DT10	-0.004	[-1.28]	-0.226***	[-2.74]	-	-	-	-
DT11	0.001	[0.20]	-0.204**	[-2.36]	-	-	-	-
DT12	-0.008**	[-2.54]	-0.270***	[-2.99]	-	-	-	-
DT13	-0.003	[-0.80]	-0.316***	[-3.37]	-	-	-	-
DT1B	0.058	[1.23]	0.075	[1.47]	-	-	-	-
DT2B	-0.166***	[-3.14]	-0.149***	[-2.84]	-	-	-	-
DT3B	0.040	[0.81]	0.036	[0.64]	-	-	-	-
DT4B	0.161***	[2.78]	0.099	[1.63]	-	-	-	-
DT5B	-0.046	[-0.82]	-0.015	[-0.25]	-	-	-	-
DT6B	0.130	[2.47]	0.096*	[1.66]	-	-	-	-
DT7B	0.070	[1.17]	0.073	[1.10]	-	-	-	-
DT8B	-0.223***	[-4.60]	-0.19***	[-3.66]	-	-	-	-
DT9B	-0.159***	[-3.00]	-0.127**	[-2.28]	-	-	-	-
DT10B	-0.037	[-0.63]	-0.024	[-0.40]	-	-	-	-
DT11B	-0.107**	[-2.04]	-0.133**	[-2.38]	-	-	-	-
DT12B	-0.249***	[-3.99]	-0.302***	[-4.35]	-	-	-	-
DT13B	-0.055	[-0.71]	-0.046	[-0.56]	-	-	-	-
R^2 adjuste	0.48		0.47		0.47		0.47	
P value	0.000		0.000		0.000		0.000	
DW	2.18		3.07		-		2.17	

Box 2 – Beta value calculated through different data panel estimators.
Source: Research data

The results from statistical tests with these models are presented in Table 3 and Figure 5.

Table 3 – Chow Test for Data Structure

Stock	**p value**	**F-Statistics**
Celesc PN	0.036**	3.35
Cemig ON	0.021**	3.87
Cesp ON	0.214	1.54
Coelce PNA	0.725	0.32
Copel ON	0.051*	2.99
Eletrobras ON	0.002***	6.07
Emae PN	0.011**	4.57
Light S/A	0.004***	5.48
Tractebel ON	0.331	1.11
Tran Paulist PN	0.001***	6.90

Source: Developed by the authors based on research data

Table 3 presents the Chow test for beta structure division, i.e., series division in two, if the test is significant, evidence provided to state betas may differ along the time; according to the table, 7 out of 10 stocks presented significant values in the Chow test. Figure 5 summarizes the results of statistical tests as follows: both the Chow test and the Hausman test provide greater evidence for fixed effects, and the Breusch-Pagan LM test shows the supremacy of the pooled data model when compared to the random effects model. In summary, the tests indicate that the fixed effects model (LSDV) may be a proper estimation model.

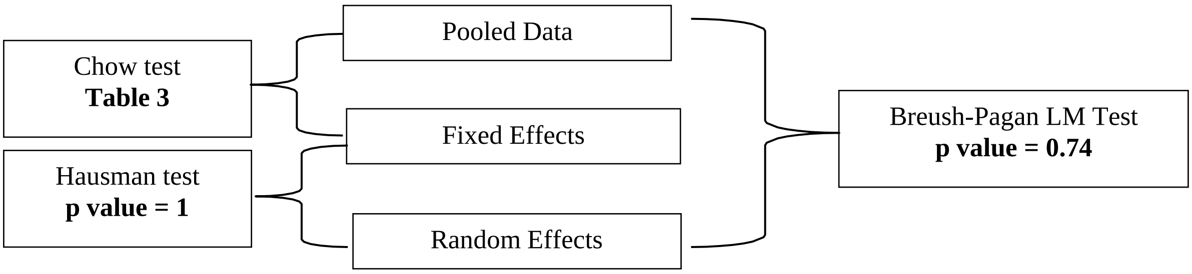

Figure 5 – Results from Statistical Tests
Source: Developed by the authors

Based on these considerations for a control factor, beta values were estimated for three other sectors: Metallurgy [0.826]; Finance/Insurance [0.855]; and Telecommunications [1.033]. Only the Telecommunications sector presented a slightly higher risk then the market risk, as indicated in Box 3.

LSDV	**Metallurgy**		**Finance/Insurance**		**Telecommunications**	
Constant	-0.001	[-0.50]	0.003	[1.05]	0.000	0.001
Beta	0.826***	[19.82]	0.855***	[18.23]	1.033***	[10.29]
DT1	0.007*	[1.92]	0.002	[0.43]	-0.002	[-0.25]
DT2	0.015***	[3.92]	-0.004	[-0.87]	-0.007	[-0.74]
DT3	0.006*	[1.66]	-0.003	[-0.79]	0.002	[0.23]
DT4	0.007*	[1.74]	0.000	[0.003]	-0.000	[-0.04]
DT5	-0.002	[-0.45]	-0.002	[-0.36]	-0.003	[-0.33]
DT6	0.004	[1.13]	-0.001	[-0.13]	0.001	[0.12]
DT7	0.008**	[2.01]	-0.002	[-0.42]	0.003	[0.28]
DT8	0.003	[0.68]	-0.004	[-0.83]	0.001	[0.19]
DT9	0.003	[0.78]	-0.003	[-0.58]	-0.000	[-0.05]
DT10	-0.001	[-0.22]	-0.003	[-0.65]	0.000	[0.00]
DT11	-0.004	[-1.16]	-0.002	[-0.51]	0.008	[0.94]
DT12	0.005	[1.34]	-0.002	[-0.48]	-0.003	[-0.36]
DT13	0.004	[0.98]	-0.000	[-0.10]	-0.004	[-0.43]
DTIB	0.085	[1.62]	0.063	[1.05]	-0.090	[-0.70]
DT2B	-0.041	[-0.75]	0.095	[1.53]	-0.158	[-1.20]
DT3B	0.092*	[1.69]	0.101	[1.64]	-0.052	[-0.39]
DT4B	0.1488**	[2.30]	0.034	[0.47]	-0.020	[-0.13]
DT5B	0.224***	[3.58]	0.045	[0.63]	-0.135	[-0.89]
DT6B	0.171***	[2.93]	0.173***	[2.64]	-0.006	[0.05]
DT7B	0.143**	[2.15]	0.262***	[3.50]	-0.038	[-0.23]
DT8B	0.278***	[5.16]	0.205***	[3.38]	-0.358***	[-2.76]
DT9IB	0.138**	[2.34]	0.061	[0.92]	-0.275*	[-1.94]
DT10B	0.292***	[4.46]	0.132	[1.79]	-0.262*	[-1.66]
DT11B	0.211***	[3.63]	0.096	[1.46]	-0.159	[-1.13]
DT12B	0.258***	[3.74]	0.125	[1.61]	-0.204	[-1.23]
DT13B	-0.087	[-1.00]	-0.025	[-0.26]	-0.321	[-1.54]
R^2	0.63		0.67		0.23	
P value	0.000		0.000		0.000	
DW	2.12		2.18		2.55	

Box 3 – Beta Values for the Data Panel LSDV Estimator for Different Sectors

The study question addresses risk variation, and whether such variations were influenced by energy efficiency programs. Boxes 2 and 3 tested risk variation via annual dummy variables. Box 2 shows a significant change in beta value in 7 of the total 13 compared[33]. Figure 6 depicts beta changes via a bar chart and energy efficiency events (regulations) in the inflection point chart.

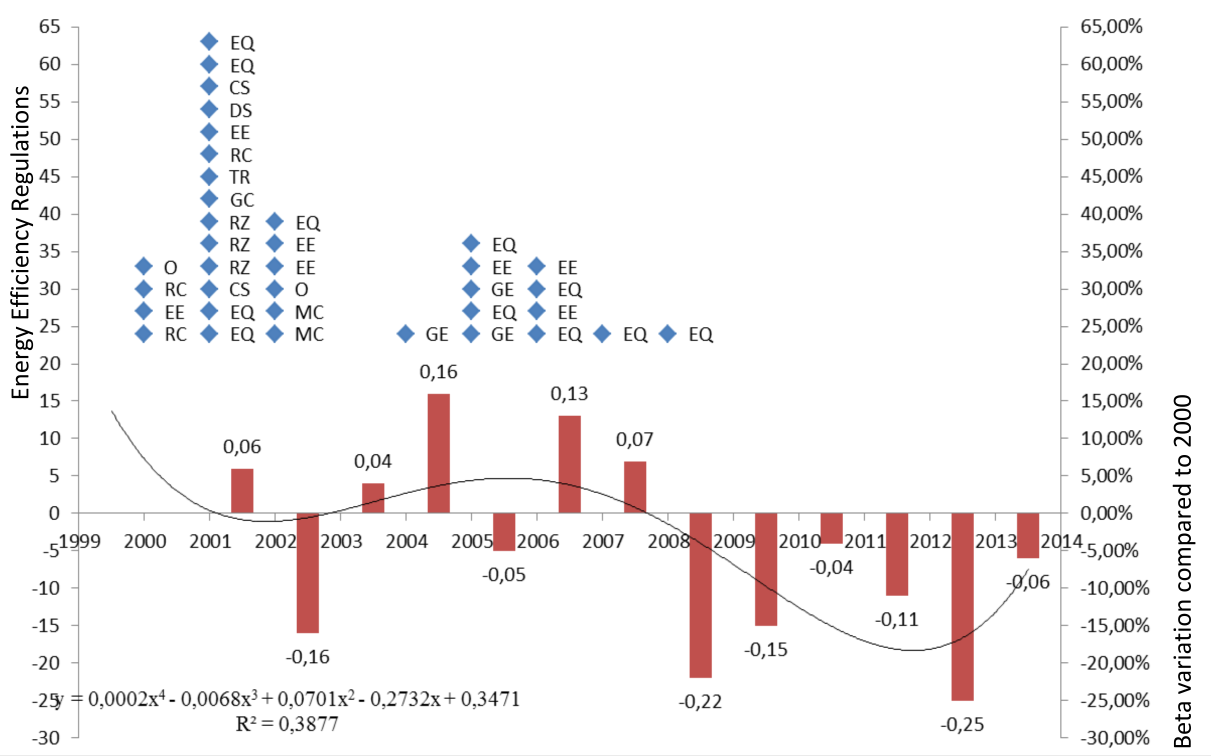

Figure 6 – Energy Efficiency Regulations versus Energy Sector Beta Variations
Source: Research data

Figure 6 shows that with more intense energy efficiency regulations, a trend was observed towards greater beta values when compared to the year 2000, and when the main energy efficiency program events stopped, the beta value was lower than that in the year 2000. Is it possible to state that the energy efficiency programs actually affected the risk taken by energy companies? In an attempt to answer this question, Figure 7 shows the differences in beta values for the Metallurgy, Finance/Insurance, and Telecommunications sectors, and, according to Box 3, the Metallurgy sector presents the best statistical significances.

Figures 6 and 7 show that when compared to baseline year of 2000, non-energy sectors represented in Figure 7 show higher or lower beta values, while Figure 6 shows higher beta values until 2008 and lower beta values in the following years. Standard deviations and R^2 of beta change polynomial adjustment are: Energy (0.131 – 0.39); Metallurgy (0.115 – 0.82); Finance/Insurance (0.077 – 0.79); and Telecommunications (0.118 – 0.71). The energy sector presented greater beta change variability represented by both variance and greater adjustment difficulty.

Figures 4, 6, and 7 are critical in studying the study question. According to the PNEE reports (2011), PROCEL invested around R$ 2 billion in energy efficiency programs. According to data from the TCU report, to mitigate the blackout crisis, almost R$ 40 billion was invested in 2003 alone. The evidence suggests that if the energy efficiency program had any impact on the risk taken by energy companies, the bar chart in Figure 6 would have to show a positive trend during or after the implementation of regulations; but both Figure 4 and Figure 6 indicate risk as a reducing trend. It is difficult to establish a cause–effect relationship, but the period with the highest risk coincides with that of crisis, which is probably a serious cause–effect relationship: the crisis increased the risk of energy companies, requiring a more stable regulatory environment (Table 1), and after the implementation of such more stable regulatory environment, risks were reduced.

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[33] This result confirms that the Chow test is significant even if the sample is divided into 14 equal portions, unlike that in Table 3.

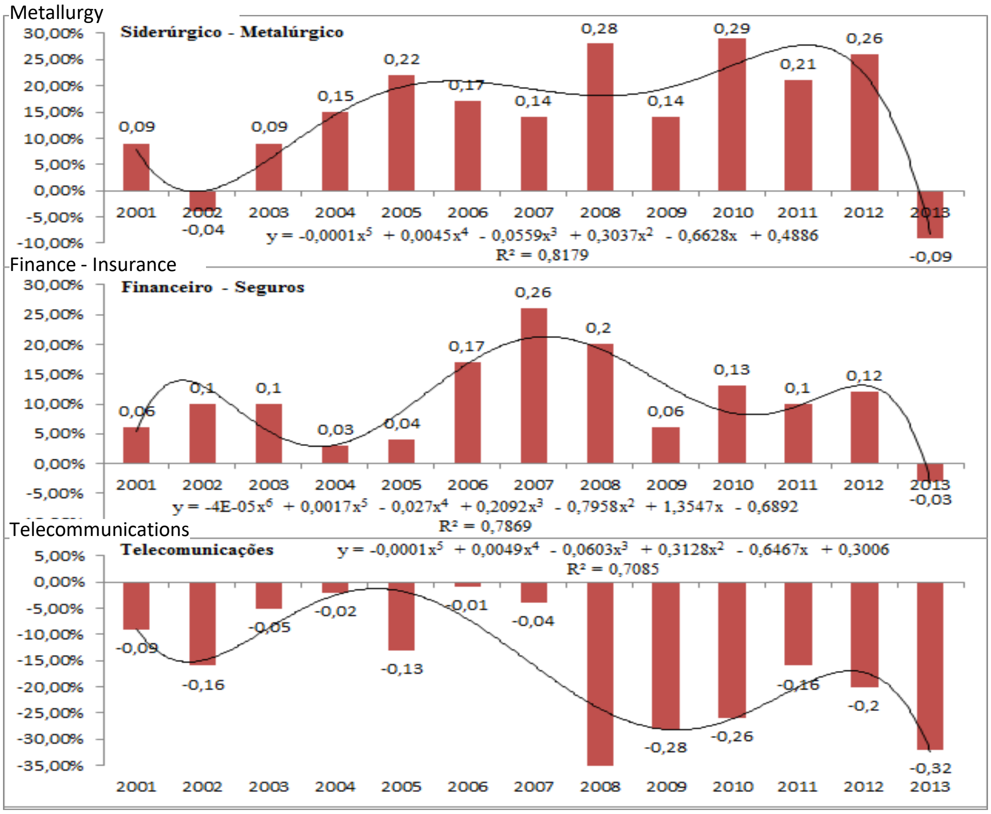

Figure 7 – Beta Variations for Control Sectors
Source: Research data

The first chart in Figure 7 shows a singular contradiction: while higher investments, increased tariffs and proper regulations favor reduced risks of energy companies. The scenario was different in the Metallurgy sector when compared to the baseline year of 2000, where the risk was always high. The year 2013 was an exception, which may be explained by the strong participation of energy in the sector cost.

5 Final Considerations

The objective this study was to analyze whether energy efficiency programs affect the risks of energy companies and attempt to define a possible fragility of the system, based on the following research question: Can we assume that energy conservation programs affect return risks to electrical energy companies?

Based on research findings, the evidence from Figures 4 and 6 indicates reduced risks of the energy sector, then, the energy efficiency programs did not present such dimension to affect the risk of companies. Energy efficiency and energy conservation are more popular during periods of moments of energy crisis. As electrical energy is a non-replaceable resource for many devices and machines, during periods of crisis and increased risk, government intervention was required to reduce such risks. This is a scenario where 93% of energy consumed by the National Interconnected Energy System are produced by hydroelectric power plants. In an alternative scenario with a more distributed electrical matrix, for instance: solar, wind, and biofuel energy, the results presented in Figures 4 and 6 would probably be different. This context, there are two limitations to be noted: (i) the sample in Table 2 does not represent all the companies in a sector, but the most negotiated stocks; and (ii) the analysis of energy efficiency effects on the risks taken by energy companies was an indirect analysis, as a variable not directly observed.

As a research contribution, the results obtained through risk assessment models, exponentially weighted moving averages, and the capital asset pricing model indicated that during periods of crisis, both volatility and required returns were higher, but during less difficult periods, risks taken were significantly reduced. Beside, eliminated the affirmative hypothesis that a possible increase in energy efficiency affects the risks taken by electrical energy companies. For future research, we suggest the analysis of the effect of regulatory events and programs affect return risks in other energy segments such as oil and gas companies.

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APPENDIX 1

R-Studio Code

```
# Energy Panel
# read library
library(plm)
# Load file
Energy <- read.csv("C:/rstudio/energia/EnergiaTempo.csv", sep=";", dec=","); attach(Energia)
# Recodifies variables for regression
Y <- cbind(Return)
X <- cbind(Ibov, DT1, DT2, DT3, DT4, DT5, DT6, DT7, DT8, DT9, DT10, DT11, DT12, DT13, DT1IBOV, DT2IBOV, DT3IBOV, DT4IBOV, DT5IBOV, DT6IBOV, DT7IBOV, DT8IBOV, DT9IBOV, DT10IBOV, DT11IBOV, DT12IBOV, DT13IBOV)
Z <- cbind(Ibov)
# Sets data as data panel
pdata <- plm.data(Energy, index=c("i","t"))
# Pooled data estimator - Pooled OLS [OLSPD]
pooling <- plm(Y ~ X, data=pdata, model= "pooling")
summary(pooling)
# First difference estimator [OLSFD]
pridif <- plm(Y ~ X, data=pdata, model= "fd")
summary(pridif)
# Fixed effects estimator – [LSDV]
fixo <- plm(Y ~ X, data=pdata, model= "within")
summary(fixed)
# Random effects estimator – [REM]
random <- plm(Y ~ Z, data=pdata, model= "random")
summary(random)
# LM test – random effects versus pooled data
plmtest(pooling)
# Hausman test – fixed effects versus random effects
phtest(random, fixed)
```

APÊNDICE H

APÊNDICE H: ARTIGO 3 - DEVELOPING A PROCESS MODEL FOR SYSTEMATIC LITERATURE REVIEW BASED ON PRINCIPLES OF CONTENT ANALYSIS: A SURVEY IN INDUSTRIAL ENERGY EFFICIENCY

CONGRESSO – POMS 26th ANNUAL CONFERENCE – WASHINGTON, D.C. USA 8-11 MAIO 2015.

Proposal of a Method for Review and Content Analysis of Literature: The Case of Industrial Energy Efficiency

ARTIGO ESTENDIDO – SUBMETIDO A REVISTA: SURVEYS IN OPERATIONS RESEARCH AND MANAGEMENT SCIENCE

Developing a process model for systematic literature review based on principles of content analysis: A survey in industrial energy efficiency

Marcos G. Perroni[a,*], Sergio E. Gouvea da Costa[ab], Edson Pinheiro de Lima[ab], Wesley Vieira da Silva[a], Dilmeire Sant Anna Ramos Vosgerau[a]

1. Introduction

It is common that the researcher updates the state of the art in relation to a specific research topic. This survey involves mapping the current scientific knowledge aiming to identify previous studies. The survey of previous studies is used by the researcher as a map for the existing intellectual territory assessment. This mapping provides conditions for the researcher to propose original research initiatives that advance the knowledge of a specific subject area [1,2].

With the advancement of information technology, the task of mapping has become easier because of the adoption of large scientific document databases; however, researchers face difficulty in choosing the right work as the objective of their research, primarily due to the large quantity of existing works, caused by the multidisciplinary and fragmentation of knowledge fields [1,3,4].

Systematic literature review (SLR), which is considered an approach to organize and develop a literature review process, is regarded as a solution to these difficulties. The development of the SLR process enables the identification, mapping, and analysis of relevant researches of a specific search topic or issue [1,3,5]. There is a range of studies that propose models for SLR; they usually use the process approach (input, processing and output) [6].

As described by Armitage *et al.*[7], there are ambiguities about the systematic review process, particularly by novice researchers, since the studies that propose processes for the systematic review [1,3] focus more on the objectives rather than procedures, especially in the analysis stage of the systematic review.

The objective of this article is to propose a process model for the systematic literature review that emphasizes the different level of procedures, termed as PM-SLR-CA (Process Model-Systematic Literature Review-Content Analysis). The systematic literature review (SLR) process is integrated with the approach of content analysis (CA) developed by Bardin [8]. Our study assumes that content analysis can be applied not only at the analysis stage but also at all the other stages of a systematic literature review. Therefore, content analysis is seen as a process that can engage (encompass) the

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systematic review phases and provide new terminologies, vocabularies, concepts, and techniques. To make the model operational at the procedural level, some methods such as Social Network Analysis [9-11], Concept Mapping [12-14], Text Mining [15-17] and Bibliometric Analysis [18-20] are related and integrated in the model.

The proposed PM-SLR-CA model offers specific procedures for document selection, information extraction by coding, matrix development, matrix representation in themed graphs and citations, as well as the relationship between the built graphs. In addition, we propose an index of the representation of *corpus* (IRPC), that measures the representation of a set of documents relating to a given field, when analyzing the number of citations. The model's main contribution is the provision of a procedure to organize the information within the systematic literature review process in order to map and analyze the areas of study. In addition to the development of a PM-SLR-CA model, a survey on industrial energy efficiency area was undertaken to demonstrate the validity of the proposed model.

Section 2 briefly discusses the systematic review process; section 3 shows the content analysis process model. In section 4, we describe the proposed PM-SLR-CA model as a procedural protocol for execution. In section 5, the applicability of the model is demonstrated via a survey on industrial energy efficiency. The last two sections present the results, discussion and the conclusions of the study.

2 Overview of systematic literature review

Literature reviews can be broadly classified into systematic and non-systematic reviews. Non-systematic reviews are also called traditional or narratives, and systematic may be associated with terms such as overview, systematic overview, research synthesis, research integration, systematic research synthesis, integrative research review, and integrative review [1,3,7].

The systematic review originates from the fields of Health [21-23] research, but it has been proposed in different fields such as Management [1,7], Systems Engineering [3,5], Information Systems [6], and Industrial Engineering /Operations Management [19,24]. The systematic review can be identified as a solution to the problem of eliminating biases, thereby enabling a safer, controllable, reliable, and replicable process as compared to non-systematic methods [1,3,21].

The process protocol for the systematic literature review (SLR) is generally divided into three stages: review planning (input); review run/conduction (processing); and review analysis/report (output). Table 1 shows an example of a systematic review process protocol according to Tranfield *et al.* [1], with three stages and ten phases. The process of systematic review is iterative, in which the planning stage involves phases such as the scope delimitation of studies based on the research question and the research protocol construction. The review conduction is the studies identification stage and involves a number of stages such as quality assessment, data extraction, and synthesis. In the analysis stage (report and dissemination), the objective is to identify the main categories and topics such as: Who are the authors? To which countries do they belong? What are the main articles? What are the main subjects? How are these subjects interconnected? [1,3].

Table 1
Stages and phases of the systematic literature review process

Stage I	**Planning the review**	**Stage II**	**- Conducting review**	**Stage III**	**Reporting and dissemination**
Phase 0	Identification for the need for a review	Phase 3	Identification of research	Phase 8	The report and Recommendations
Phase 1	Preparation of proposal for a review	Phase 4	Selection studies	Phase 9	Getting evidence into practice
Phase 2	Development of a review protocol	Phase 5	Study quality assessment		
		Phase 6	Data extraction and monitoring Progress		
		Phase 7	Data Synthesis		

Source: Tranfield *et al.*[1]

The three stages of the systematic review are divided into a variable number of stages or steps; for example, Khan *et al.*[23] and Biolchini *et al.[*3] identified five phases, while Gough *et al.* [24] identified seven phases. For example, the phases/stages identified by Biolchini *et al.* [3] are formulation of the research question, data source selection, study selection, information extraction, and presentation of results. Although the number of phases/stages is variable, it is important that the review process is clear and reproducible by other researchers, so that the initial assumptions can be refined to help create a future research agenda. [21]

Attempting to understand the challenges faced in the implementation of the systematic review process for undergraduate and graduate students, Armitage *et al.* [7] simplified the systematic review process by Tranfield *et al.*[1], and developed what the authors called Rapid Structured Literature Review, (RSLR). Even with a simplified RSLR method, a number of issues were faced by users; analysis of large quantities of articles (thousands), difficulty in maintaining focus of the research, theoretical mapping unrelated to the research objectives, difficulty in thematic analysis of literature, difficulty in dealing with text data that is naturally unstructured, and unfamiliarity with new methodological approaches.

3. Content analysis

Content analysis (CA) has been used for over 50 years in various areas such as Communication, Journalism, Sociology, Psychology, and Management [26] studies. According to Bardin [8], the origin of content analysis dates back to the early twentieth century, particularly in the field of journalism, which intensified in during the war era due to the spread of political propaganda. According to Neuendorf [26], there is no single definition of what can be regarded as content analysis. According to Berelson [27, p. 18] *"Content analysis is a research technique for the objective, systematic, and quantitative description of the manifest content of communication"*. According to Krippendorff [28, p. 21] *"content analysis is a research technique for making replicable and valid inferences from data to their context"*. For Bardin [8, p. 48], content analysis was, *“A set of communication analysis techniques to obtain description of the indicator message content (quantitative or not) that allow the inference of knowledge related to the production/reception conditions (inferred variables) of these messages via systematic procedures and objectives.*”

Based on the definition, we can infer that two of them use systematic words such as inference, while one mentions replicability, both of which are common to the systematic literature review process.

The content analysis model of Bardin [8] is shown in Fig. 1. Similar to the systematic review process (Table 1), content analysis can be divided into three stages. The first stage is the pre-analysis, which are established hypotheses (research question), selected documents (*corpus*), and the content analysis techniques (categorical analysis, discourse analysis, among others) to be applied by means of fluctuating readings. The second stage is simply the management of techniques in the *corpus*. In the third stage, statistical operations are employed in order to validate, synthesize, infer, and interpret the results, generating a theoretical framework as a guide for future analysis.

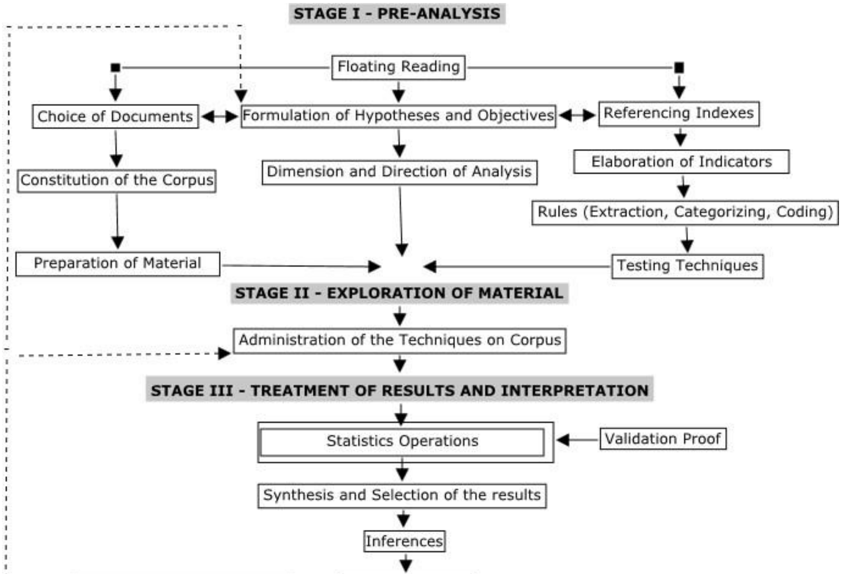

Fig. 1. Content analysis process model
Source: Bardin [8]

Researchers from various fields use the model proposed by Bardin [8]. Some recent studies cite Bardin [8] in the references and use the word "content analysis" in the abstract, key-words, and the article title can be highlighted: Nursing/Information [29]; Computers/Education [30]; Psychology/Economics/Management [31]; Psychology [32]; Engineering/Education/Geography [33]. These studies reveal the existence of a multidisciplinary nature in the use of content analysis, as well as the approach of the systematic review and can be used in several areas.

4. Developing a process model for systematic literature review

In this section, we propose the process model, and later on unfolded into a procedural protocol. The process model can be seen in Figure 2, making the stages junction of the systematic review process [1,3] in the Bardin model content analysis model [8]. To operationalize the analyzes in terms of procedures some methods are integrated as Social Network Analysis [9-11], Concept Mapping [12-14], Text Mining [15-17], Bibliometric Analysis [18-20].

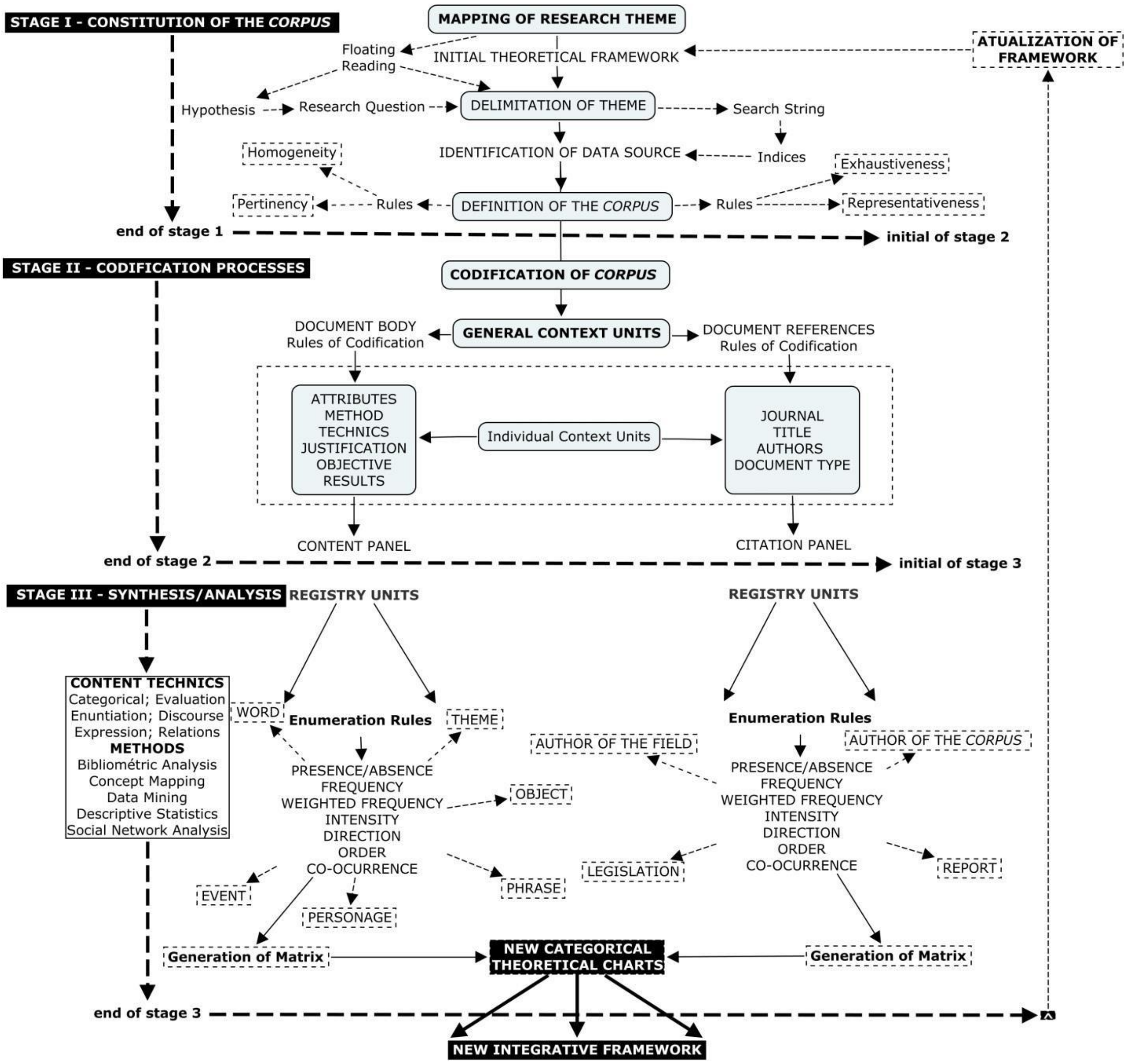

Fig. 2. Process model for the systematic literature review based on content analysis (PM-SLR-CA)

Source: The authors

As shown in Figure 2, the model is proposed in three stages (*corpus* constitution, coding process, synthesis/analysis). The objective of the stages is to support the construction of an integrative framework.

4.1. First Stage: Constitution of the *corpus*

The first stage starts with the constitution of the *corpus*, which is according to Bardin [8] is the set of all the selected documents to be submitted to analytical procedures. The constitution of the *corpus* involves choices, rules, and selection implementation. Initially, a topic is studied using a floating reading process in order to establish the research question and possible initial hypotheses, thus allowing the construction of an initial framework and the research topic delimitation. The reading is called floating because the objectives and rules have not yet been defined. The delimitation step crystallizes with the application of the search terms in the chosen databases. The search terms are a list of key terms that represent the research question, such as an index or presence indicator because they are the explicit mention of a term in a specific part of the message (abstract, title, body text, among others) [3,8].

Some common rules that can be applied in the *corpus* selection process are as follows:

- Exhaustiveness: Elements that may be important cannot be left out;
- Representativeness: The *corpus* selection should represent the universe;
- Consistency: The *corpus* elements should be homogeneous, obeying precise criteria of choices;
- Relevance: The *corpus* should be appropriate to the research objectives.

The four rules contribute to the selection process raised by Tranfield *et al.* [1] and Biolchini *et al.* [3] in the systematic review-planning phase.

4.2. Second Stage: Codification process

According to Bardin [8], coding corresponds to a transformation of the raw text data, allowing a content representation or its expression, susceptible to clarification by the analyst. According to Saldanã [34, p. 3] "*a code in a qualitative inquiry is most often a word or short phrase that symbolically assigns the summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based or visual data*". Coding is not a precise science, instead it is an interpretative action to condense the data instead of being simply reduced. Coding is a way to fix things in a systematic order that enables categorization. The relationship between code and category can is shown in Figure 3.

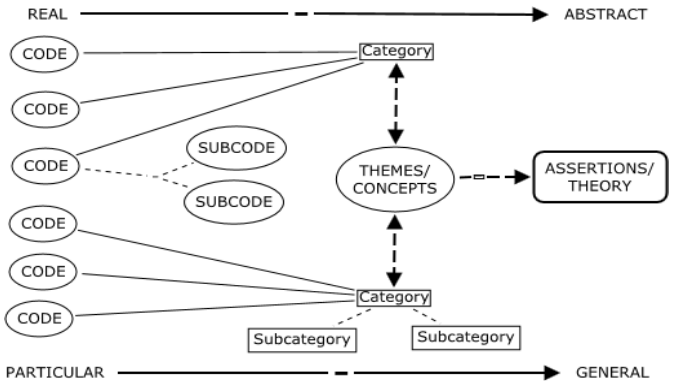

Fig. 3. A streamlined codes-to-theory model for qualitative inquiry
Source: Saldanã [34]

As shown in Figure 3, some categories may contain classified code groups, which can be further refined into subcategories. Comparison of categories makes consolidations possible, which facilitate the emergence of new concepts and theories.

Two useful units for the coding process organization are the context units and registry units. The context units can be understood as parts of the text where the registration units are (words, subjects, objects and others). As specified in the PM-SLR-CA process model in Figure 2, the cutout for the coding can be done using the context unit and the registry unit in a textual analysis process. In the textual analysis process, the context unit serves as comprehension unit to code the subsequent registry unit, corresponding to the message segment, whose dimensions are superior to the registry units.

At this stage, the documents (c*orpus*) are divided into two general context units, the document body and the document references. The coding process then generates individual connection units. The primary objective of coding for the document body is to extract the objectives, justification, method, techniques and results, in addition to some attributes such as department, institution, journal, city, and country (in case of a scientific paper). The coding for document references extracts author information, title, journal, and document type, thereby providing individual context units to the document references. The context units will later be analyzed by the selection of the registry units. The organization of document references can be applied to bibliometric analysis [18,19]. As extractions are being made, a content panel is being built for the document body while a citations panel is being built for the documents references. The content panel and citations panel can be built with the help of electronic resources, such as an Excel® spreadsheet, OpenOffice, a database table such as MySQL or directly into purpose-specific software such as atlas.ti.

4.3. Third Stage: Analysis and synthesis

The third stage is a continuation of the coding process where the registry units are established. The clarification of the following three elements is crucial in the analysis stage: Registry Unit, enumeration rules, and methods/analysis techniques that can be used. The registry unit is generally smaller than the context unit, being the meaning unit coded and aimed at categorization through the application of enumeration rules. The most used registry units are word, topic, object, character, and event; however, registry units are not restricted to these, as one can select other units in accordance with the research field and objectives. The most common enumeration rules are Presence/absence [may indicate or represent a sense], Frequency [the importance of registry unit increases with the appearance frequency], Weighted Frequency [may have registry units that may be more important than others for the context], Intensity [usually using qualitative attributes such as verb tense, adverbs and adjectives], Direction [can be positive, negative or neutral], Order [the order of appearance of the registry units may be relevant], and Co-occurrence [simultaneous presence of two or more registry units in a context unit].

There are methods that can be used from the same base, i.e., incidence matrices (term-document) and adjacency (co-occurrence). The similarities among these methods can be highlighted: Social Network Analysis [9-11] Concept Mapping [12-14], Text Mining [15-17], Bibliometric Analysis [18-20]. The use of enumeration rules are associated with the used analysis method, two examples are the frequency for text mining or co-occurrence in Social Network Analysis.

According to Prell [11], social network analysis has the task of discovering the relationship structure between the individual and the group. According to Trochim [12], the approach of concept mapping is a structured type of design that can be used by groups for the development of conceptual frameworks. Wittten *et al.* [16] define text mining as the process of textual analysis to extract information that is useful for a particular purpose. It can be considered that bibliometrics [18,35] studies the quantitative aspects of information related to bibliographic collection ranking, documents, authors, institutions, etc. By its very nature and definition, these methods were selected for possible applications in the data generated by the content panel and citations of the PM-SLR-CA model. The construction of matrices is an important procedure for applying the methods mentioned above.

4.3.1. Construction of matrices, graphical analysis and indicator IRPC

The matrices can be constructed and analyzed using different software. For the construction of the adjacency matrix (co-occurrence), the technique presented by Breiger [9] can be used, wherein the adjacency matrix is derived from the matrix product. Let us consider the matrices, $A = (a_{ij})_{m\times p}$ and $B = (b_{ij})_{p\times n}$ where the number of columns (p) of the first matrix (A) is equal to the number of lines from the second (B), the product is the result of $C = AB$ of size $m \times n$, represented differently as follows[36,37]:

$$[AB]_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \dots + a_{ip}b_{pj} = \sum_{k=1}^{p} a_{ik}b_{kj} \tag{1}$$

Based on [9,10,17], to obtain the P adjacency matrix from the A incidence matrix, it is only needed to substitute B for A^T, therefore

$$P_{ij} = \sum_{k=1}^{p} A_{ik}\, A_{jk} \quad rewrite\ P = A(A^T) \tag{2}$$

Figure 4 shows as hypothetical example with a binary matrix A:

$$\begin{array}{c|ccc|c}
 & I & II & III & \sum_{kj} \\
\hline
\alpha & 0 & 1 & 0 & \mathbf{1} \\
\beta & 0 & 0 & 1 & \mathbf{1} \\
\gamma & 1 & 1 & 0 & \mathbf{2} \\
\delta & 0 & 0 & 0 & \mathbf{0} \\
\varepsilon & 0 & 1 & 0 & \mathbf{1}
\end{array}
\qquad
\begin{array}{c|ccccc|}
 & \alpha & \beta & \gamma & \delta & \varepsilon \\
\hline
I & 0 & 0 & 1 & 0 & 0 \\
II & 1 & 0 & 1 & 0 & 1 \\
II & 0 & 1 & 0 & 0 & 0
\end{array}
\qquad
\begin{array}{c|ccccc|c}
 & \alpha & \beta & \gamma & \delta & \varepsilon & \sum_{kj} \\
\hline
\alpha & \mathbf{1} & 0 & 1 & 0 & 1 & \mathbf{3} \\
\beta & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} \\
\gamma & 1 & 0 & \mathbf{2} & 0 & 1 & \mathbf{4} \\
\delta & 0 & 0 & 0 & \mathbf{0} & 0 & \mathbf{0} \\
\varepsilon & 1 & 0 & 1 & 0 & \mathbf{1} & \mathbf{3} \\
\hline
\sum_{ik} & \mathbf{3} & \mathbf{1} & \mathbf{4} & \mathbf{0} & \mathbf{3} &
\end{array}$$

(a) incidence matrix A (b) incidence matrix A^T (c) adjacency matrix $P = AA^T$

Fig. 4. Incidence matrix and adjacency matrix

Source: The authors

Since the registry units are generated by the PM-SLR-CA model process, in the incidence matrix A in Figure 4(a), the Greek letters represent the registry units (theme, word, author, etc.) and the Roman numerals represent the documents (articles, reports, books, etc.). Each element of matrix A is the occurrence of registry units in the documents, and the sum of lines in matrix A is equal to the frequency that each registry unit received. After the operationalization of transposition, each element of adjacency matrix P in Figure 4(c) represents the co-occurrence of the registry units, and the sum of these co-occurrences by line or by column, indicates the co-frequency. Since matrix P caused by a binary matrix A, its main diagonal is equal to the frequency of registry units, or the sum of lines of matrix A. Another important factor is that matrix P will always be symmetric, generating symmetrical relationships between the registry units.

There are several tools and statistical techniques to extract and analyze both the incidence matrices and the adjacency matrices. Frequency analysis can be made using the algorithms present in Weka, such as StringToWordVector [16], the resources of atlas.ti [38] or R packages as the tm [39]. Concept mapping can be constructed by the method developed by Trochim [12] and Kane and Trochim [13], wherein multivariate techniques such as multidimensional scaling and cluster analysis are applied [40-42]. The perception of McLinden [14] is that the conceptual mapping data structures of Trochim [12] are similar to the structures found in the analysis of social networks. A range of software is available for analysis of social networks like NodeXL [10,43,44], igraph [17,45], UCINET [46] Gaphi [47], in addition to software such as Pajek, NetworkX, JUNG, statnet, and sna, [48,49]. In the PM-SLR-CA model in Figure 2, the registry units represent nodes or actors in social networks, therefore, the terms nodes, actors, registry units, and individual are used here interchangeably.

After the matrices are built, the packages for the analysis of social networks have the advantage utilizing the most common algorithms for drawing graphics, such as Kamada-Kawai [50] Fruchterman and Reingold [51] Fast Multi-Scale Method [52] Force Atlas [47], and Grid [10]. Several social networking statistics that describe the structure of networks are available, such as degree centrality, indegree centrality, outdegree centrality, eigenvector centrality, betweenness centrality, and density [10,11,53]. The function of both algorithms for the networks design as the statistics is the generation of subcategories that facilitate graphical analysis.

The degree centrality statistic is simply the number of connections that an actor has with other actors of the graph (network), and does not specify the direction of the connections, i.e. non-directional graphs. The indegree centrality statistic is the number of incoming connections, and the outdregree centrality statistic the number of calls sent to other chart actors. A larger connection number implies a larger communication channel to the actor, where the information can be spread easily. The degree centrality statistic is easier to be calculated since it is the sum of the lines or columns of the adjacency matrix such that the diagonal values are zero, i.e., minus the self-connections. According to Prell [11], Equation 3 represents the degree centrality;

$$C_D(i) = \sum_{j=1}^{n} x_{ij} = \sum_{j=1}^{n} x_{ji} \tag{3}$$

Here, x_{ij} is the connection of the *i* actor to the *j* actor, and *n* is the total number of actors.

The eigenvector centrality expands the notion of the degree of centrality, the sum of the actor's connection with other actors by taking into account the centrality degree of the other actors. An actor can have a high degree, but it is connected to actors with low degree, therefore the actor may have a low eigenvector, or a smaller communication channel. The idea of the eigenvector centrality is similar to the popular old algorithm of search engines, Google PageRank [54], where the centrality or popularity of the actors, as shown in Equation 4 is determined by υ eigenvector associated with λ eigenvalue (one), and M adjacency matrix with the weights of actors connected [55].

$$\lambda v = \mathrm{M} v \tag{4}$$

The betweenness centrality is the possibility that an actor has to mediate communication with others, since this actor has advantages in many situations when it is disconnected between groups. According to Prell [11], the betweenness centrality statistic can be presented as shown in Equation (5):

$$C_B(k) = \sum \partial_{ikj}/\partial_{ij}\, , i \neq j \neq k \tag{5}$$

where ∂_{ij} is the number of i a j e geodesic paths and ∂_{ikj} is the number of i a j geodesic paths passing by the k actor.

The closeness centrality statistic is related to the actor’s ability to bind all others in the graphic, being an actor's independence measure, since it has the ability to obtain the information without too many intermediaries. Mathematically, it can be calculated as shown in Equation 6 where d_{ij} is the distance connecting actor i to actor j[11,53].

$$C_c(i) = \sum_{j=1}^{n} d_{ij} \tag{6}$$

In the social networks analysis, density is a statistic that ranges from 0 to 1, describing the connections ratio present, or otherwise, the extent to which all individuals are connected to the network. Density is represented by the Equation 3 [10,11].

$$d = L/n(n-1) \tag{7}$$

Where *d* is the network density, *L* is the number of connections present, and *n* is the number of nodes in the network. In the PM-SLR-CA method, the calculation of two networks is possible through the citations panel, the field network (all *corpus* citations), and the *corpus* network (*corpus* authors that have been cited by other *corpus* authors). One way to compare the connection level of the *corpus* authors with the field authors is by the ratio of the networks density, as described by proposed Equation 4:

$$IRPC = (L_c/n_c(n_c - 1)/(L_{f100}/n_{f100}(n_{f100} - 1) = NDC/NDF \tag{8}$$

The *IRPC* is the index of the representation of *corpus* authors when the number of connections are compared, L_c is the number of connections in the *corpus*, L_{f100} is the number of connections in the field, n_c is number of nodes in the network *corpus*, n_{f100} is the number of nodes in the field network, *NDC* is the network density of *corpus*, and *NDF* is network density of field. In this calculation, the field is represented by the 100 most cited authors. Since network density can range from 0 to 1, the possible values of the index *IRPC* can be very close to 0 or greater than 1 if the *corpus* network density is greater than the field network density. In practice, the *IRPC* measures the proportion of the *corpus* connections in relation to the 100 most cited authors in the field, giving an idea of the relevance of the selected documents for the *corpus* constitution.

4.3.2. Procedural protocol

Figure 5 shows the procedural protocol of the PM-SLR-CA model developed in Figure 2, which has 12 procedures. The first four procedures are related to the *corpus* constitution; three are related to the construction of the data panels; the latest five are related to the graphic analysis procedures.

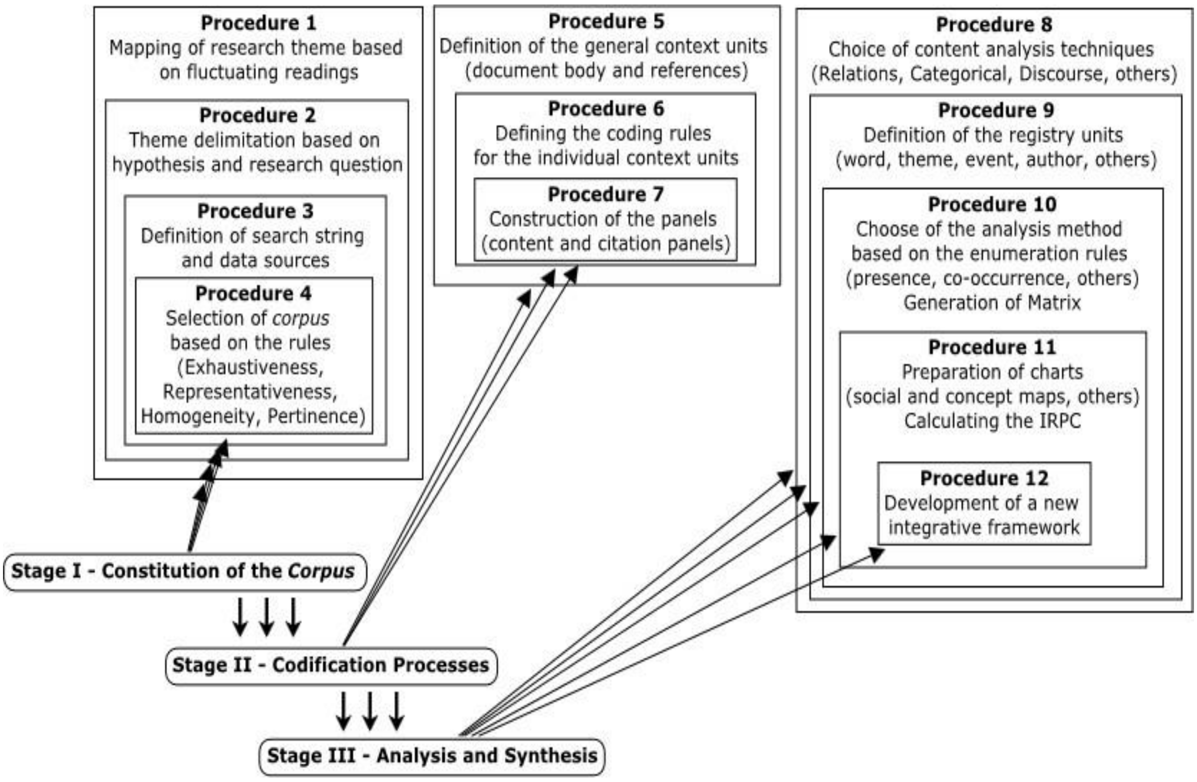

Fig. 5. Systematic literature review procedural protocol based on the PM-SLR-CA model
Source: The authors

The decision of allocation procedures in the three stages is based on the input-process-output logic. The inputs are the physical documents. The processing refers to the coding for data extraction. Finally, the analysis/synthesis refers to the construction of charts that will assist in the construction of an integrative framework. In the models for systematic literature review, the procedures are allocated differently. As shown in Table 1, the study selection task (procedure 4 of protocol in Figure 5) is in the second stage according to Tranfield *et al.* [1]. The models proposed by Biolchini *et al.* [3] and Levy and Ellis [6] also position the fourth procedure in the second stage. The second stage related to the three coding procedures is in accordance with the models proposed by Tranfield *et al.* [1] and Levy and Ellis [6], although Biolchini *et al.* [3] positioned the data extraction in the third stage. Both the models from Tranfield *et al.* [1] as from Levy and Ellis [6] identify the synthesis as a stage 2 procedure; however, for Biolchini *et al.* [3], the synthesis is a third stage procedure. The critical aspect is the replicability rather than the allocation of the procedures in the three stages.

5. Application of PM-SLR-CA: A survey in industrial energy efficiency

In the analysis of three bibliometric studies spanning the periods from 1993-2001 to 2002-2010, we can confirm the growing interest in specific areas in the field of industrial energy. In the field of biofuels [56], there was a 1310% increase in publications and 1946% increase in the number of citations; in the field of energy efficiency [57], a 278% increase in the number of publications and 396% increase in the number of citations; in solar energy [58], a 103% and 187% increase in the number of publications and citations, respectively. Based on these studies, research on energy efficiency has attracted relatively greater interest than solar energy.

The industrial energy efficiency field is understood to be a sub-area of energy efficiency. The survey presentation will demonstrate the stages of the PM-SLR-CA model without going into detail of what each author or topic is, since the objective is the proposition of the process model. This section presents an exemplification of the proposed model. The application of the PM-SLR-CA model has a narrower scope than the study made by Du *et al.* [57], which has the prospect of managing the energy efficiency in industrial processes. The application goal is to map and analyze research where energy efficiency is part of the management context in industries, especially the manufacturing industry. According to Bunse *et al.* [59], energy management is an activity pertaining to the control, monitoring, and improvement of energy efficiency.

5.1. Constitution of the *corpus* and codification process

In the first stage of the PM-SLR-CA model, with the objective of defining the research topic, initial research was conducted in books, government agency reports, the International Energy Agency and scientific articles through fluctuating readings. The initial question raised by the research was: " *How can the energy performance be measured, taking into account both efficiency and effectiveness in managing a manufacturing process?*"[60]. Through the construction of an initial theoretical framework, we verified the existence of a number of significant works in the field of Industrial Energy Efficiency; Science Direct was the foundation that brought together most important journals in the field, since it has more than 100 journals associated with the energy sector.

We decided to utilize Science Direct to focus on scientific articles, because they are able to reveal the frontiers of knowledge. After several tests, the selected search terms were: *[“industrial energy efficiency” OR “industrial energy management” OR “energy efficiency manufacturing” OR (“energy efficiency” AND “manufacturing”) OR (“energy management” AND “industry”) OR (“industrial symbiosis” AND “energy”) OR (“energy management” AND “manufacturing”)].* As scope of the presence indicator it was selected the title, abstract and keywords of the articles. The search was conducted during the month of May/2014, the search returned 574 articles, of which 178 were written off based on the analysis of the summary. Of the 178 articles, 104 were selected for the *corpus* constitution (Appendix B) as they were consistent with the search question to be answered based on the four criteria mentioned in the PM-SLR-CA model, i.e., exhaustiveness, consistency, representativeness, and relevance. The first stage of PM-SLR-CA model was completed in the period from April/2013 to May/2014.

The next stage in the PM-SLR-CA model is *corpus* coding. Coding is not an exact science, but rather an interpretive action, which depends on the researcher’s experience [34]. The initial objective of the coding process is the construction of the database content panel and citations panel. A full reading of the 104 articles was performed and extracted to an Excel® spreadsheet. In the content panel and the citations panel, the context units were registered according to the PM-SLR-CA model coding rules. The composition of the content panel was made with the extraction of 61,202 words, averaging 588 words per article, with a minimum of 288 words and maximum of 985 words. The citations panel was built by selecting the first author of each reference. The citations panel totaled 4,466 citations, where 1,255 were the journal authors. A partial view of the panels can be seen in Figures 1 and 2 of Appendix A. Approximately 400 hours were spent between June and December 2014 to implement the second stage.

5.2. Synthesis: Graphical analysis in industrial energy efficiency

There is no straightforward method to analyze the content panel and the generated citations panel discussed in the third stage of the PM-SLR-CA model. The following charts mainly present the analysis of categories and relations, in accordance with the PM-SLR-CA model content analysis techniques. Regarding the citations panel, we focused on the 1,255 citations of the journal articles.

Chart 1(a) shows the main countries and Chart 1(b) shows the journals based on number of articles. Charts 2(a) and 2(b) show the frequency in the form of word cloud built with the R wordcloud package [17];.

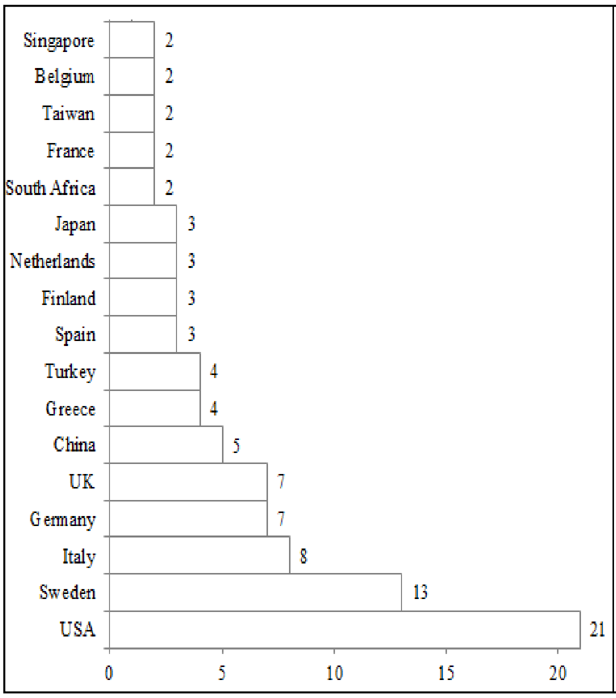

Chart1 (a). Articles by countries (91 of 104)
Source: The authors

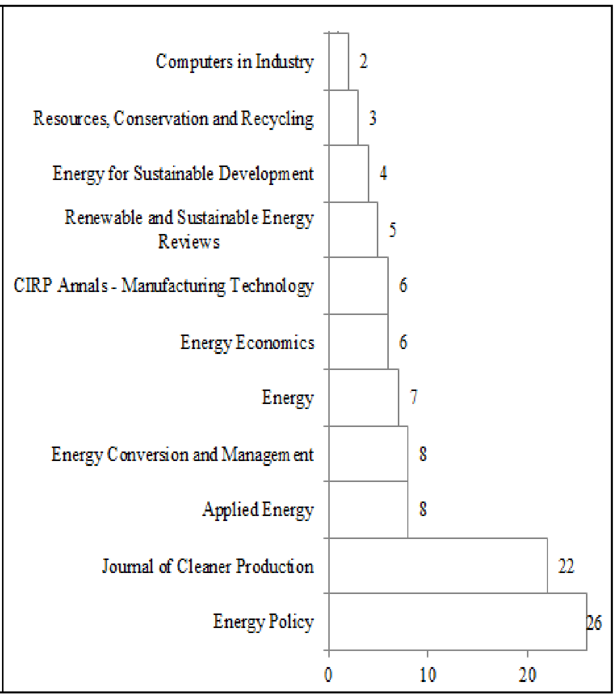

Chart 1 (b). Articles per journals (97 of 104)
Source: The authors

Chart 2(a) was built on the incidence matrix (author-document) of the 150 most cited authors. Given that the 104 articles cited 1,255 journals authors, Chart 2(b) shows the incidence matrix (term-document) of the 300 most cited significant words of the content panel of these articles, and the word energy was excluded in Chart 2(b) to be an outlier. The frequency analysis is an enumeration rule which shows the most important words and authors for the context, but does not show the relationship between the component parts. The relationship can be demonstrated through another enumeration rule, which is the co-occurrence, a result obtained with Equation 2.

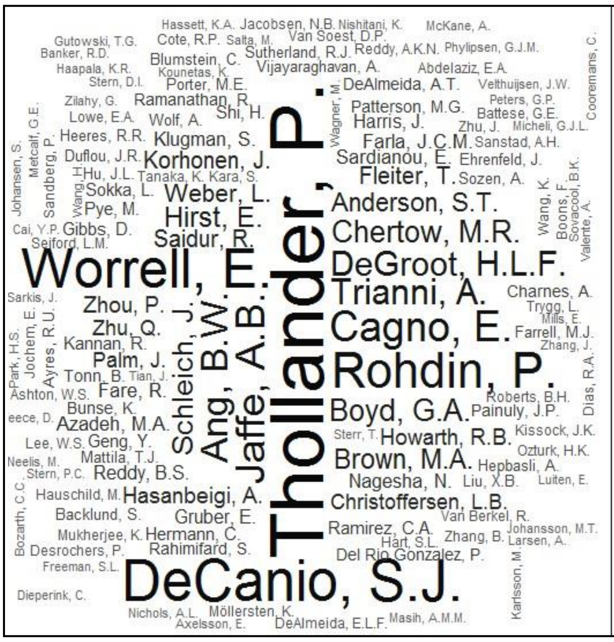

Chart 2(a). Frequency of authors
Source: The authors

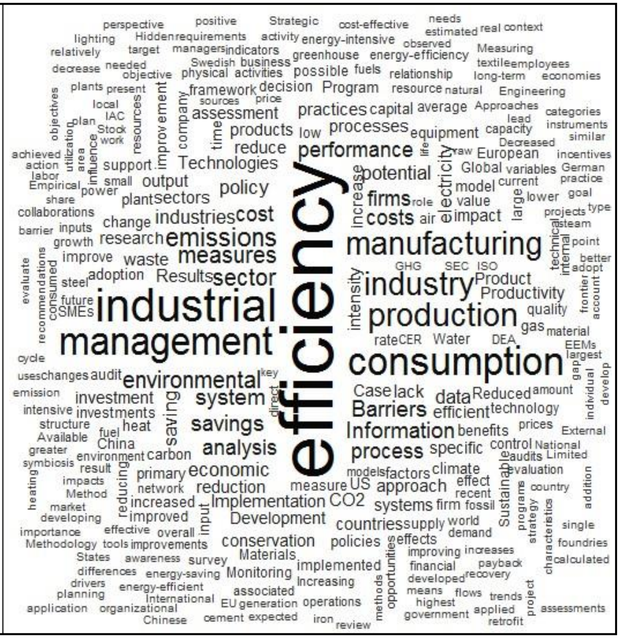

Chart 2(b). Frequency of words
Source: The authors

Chart 3 shows the relationship network (co-occurrences) of the more frequent 100 words (registry units). The network of words in Chart 3 represents a relative connection, considering that the statistical network density is nearly 100% between these words. To generate Chart 3, the software NodeXL was used by implementing the Grid algorithm to draw the graph, the size, and colors of the proportional vertices to the Eigenvector Centrality statistic. The words (registry units) with greater nodes, indicated by light orange, have greater importance for the context, since they are the most central. The thickness and opacity of the Edge (lines) are proportional to the weight of the Edge calculated by Equation 2 and indicate stronger relationships [10,11].

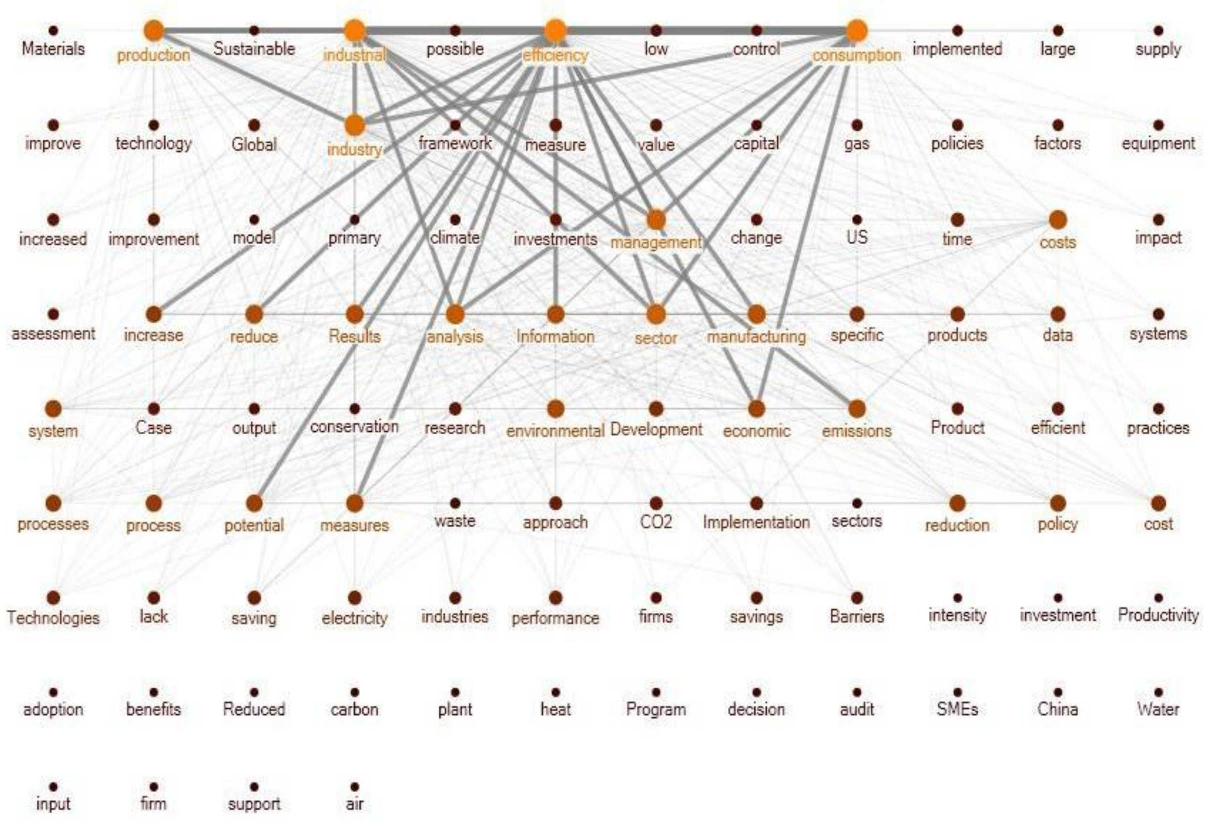

Chart 3. Relationship among the 100 most frequent words in the *corpus*
Source: The authors

Chart 4 shows the thematic network based on the extraction of two to five topics in each of the 104 articles that are dealt with. The thematic network was distributed by the Fast Multi-Scale algorithm [52], where the size and colors of the vertices are proportional to the Eigenvector Centrality statistic. Based on the distribution of the Fast Multi-Scale algorithm, three main groups can be seen in the network theme of Figure 4: Sustainability (triangle), management/energy efficiency (sphere), and performance (square). It can be understood that these groups form specific interest categories.

Chart 5 shows the relationship between 41 terms identified in reading that are tracked in the content panel. The nodes are classified by betweenness centrality statistic, which identifies the terms that serve as a bridge to the other terms, or otherwise the most common words (energy consumption and CO2) used by different groups.

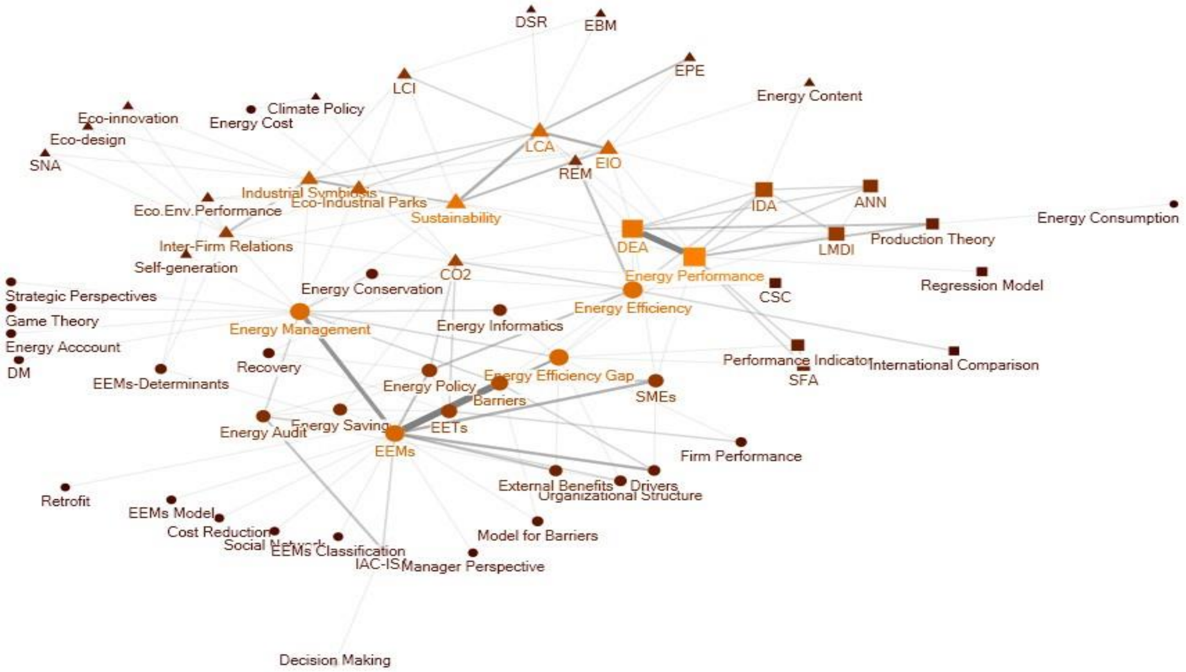

Chart.4 Relation among the 63 subjects identified in the *corpus*[34,35]
Source: The authors

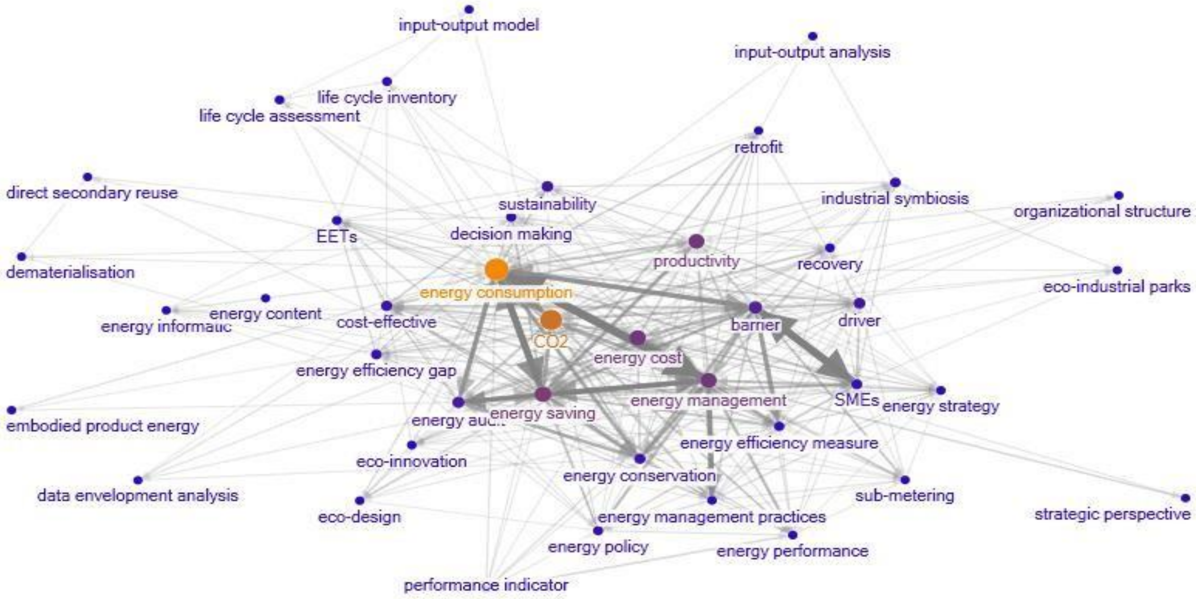

Chart 5. Relationship between 41 terms tracked in the content panel [36]
Source: The authors

Chart 6 shows the relationships (co - occurrence) between the 100 most cited authors among 1,255 journal authors in 104 articles, and the size and colors of the vertices are proportional to the Eigenvector Centrality statistic. It is possible to identify authors' cluster, by categorizing into three categories, Management/Efficiency, Sustainability, and Performance. Although the number of calls is

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[34] Categories - Sphere: Management and Efficiency in Energy; Square: Performance; Triangle: Sustainability.

[35] ANN - Artificial Neural Network; CED - Cumulative Energy Demand; CSC - Conservation Supply Curves; DM - Data Mining; DSR - Direct Secondary Reuse; EBM - Environmentally Benign Manufacturing; EEMs - Energy Efficiency Measures; EETs - Energy Efficient Technologies; EIO - Economics Input Output; EPE - Energy Product Embodied; IAC-ISA - Industrial Assessment Centers-industrial Saving Assessment; IDA - Index Decomposition Analysis; LCA - Life Cycle Analysis; LCI-Life Cycle Inventory; LMDI; Logarithmic Mean Divisia índex; REM - Resource Efficiency Manufacturing; DEA – Data Envelopment Analysis; SFA- Stochastic Frontier Analysis; SMEs - Small and Medium-sized Enterprises; SNA - Social Network Analysis.

[36] Example of formula in Excel® to count terms { SUM(LEN($B2:$F2)-LEN(REPLACE ($B2:$F2;U$1; "")))/LEN(U$1)}. There is a possibility to codify in software atlas.ti, for generation of incidence matrix.

increasing visually, the network density statistics among the 100 most cited authors is 34%, implying that the connections are a third of the maximum possible for the most cited authors.

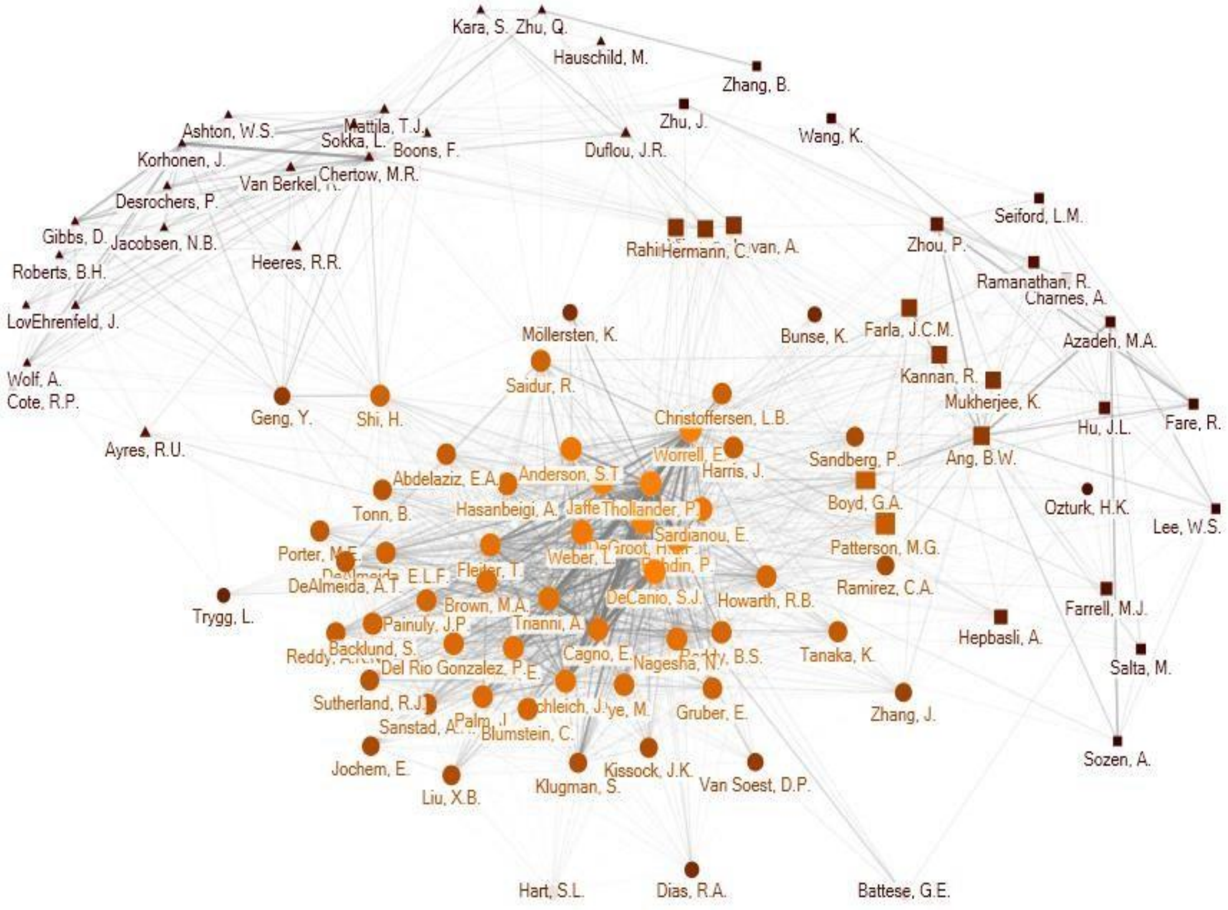

Chart 6. Relationship between the 100 authors most cited by the 104 articles of the *corpus* [37]
Source: The authors

Chart 7 shows the same network as Chart 6, but the node are classified according to the betweenness centrality statistic, which shows the authors who are connections or communication bridges between the groups. It can be clearly seen in Chart 7 that the author Shi *et al.* [61] is a communication bridge between the Sustainability and Management/Energy Efficiency group, while, Worrell *et al.* [62] and Worrell and Biermans [63] is a connection between the Performance and Management/Energy Efficiency group.

According to the PM-SLR-CA model, it can be considered that the authors of Charts 6 and 7 represent the research field since they are the most cited authors from among a total of 1,255 journal authors. Another proposed possibility by the PM-SLR-CA model is the construction of the author' network of the *corpus*, which can be seen in Chart 8. Chart 8 is generated from the construction of an incidence matrix that tells how each author of the *corpus* has been cited by the others. In Chart 8, from the 104 articles of the *corpus*, 60 articles (43 authors) were cited by others.

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[37] Categories - Sphere: Management and Efficiency in Energy; Square: Performance; Triangle: Sustainability.

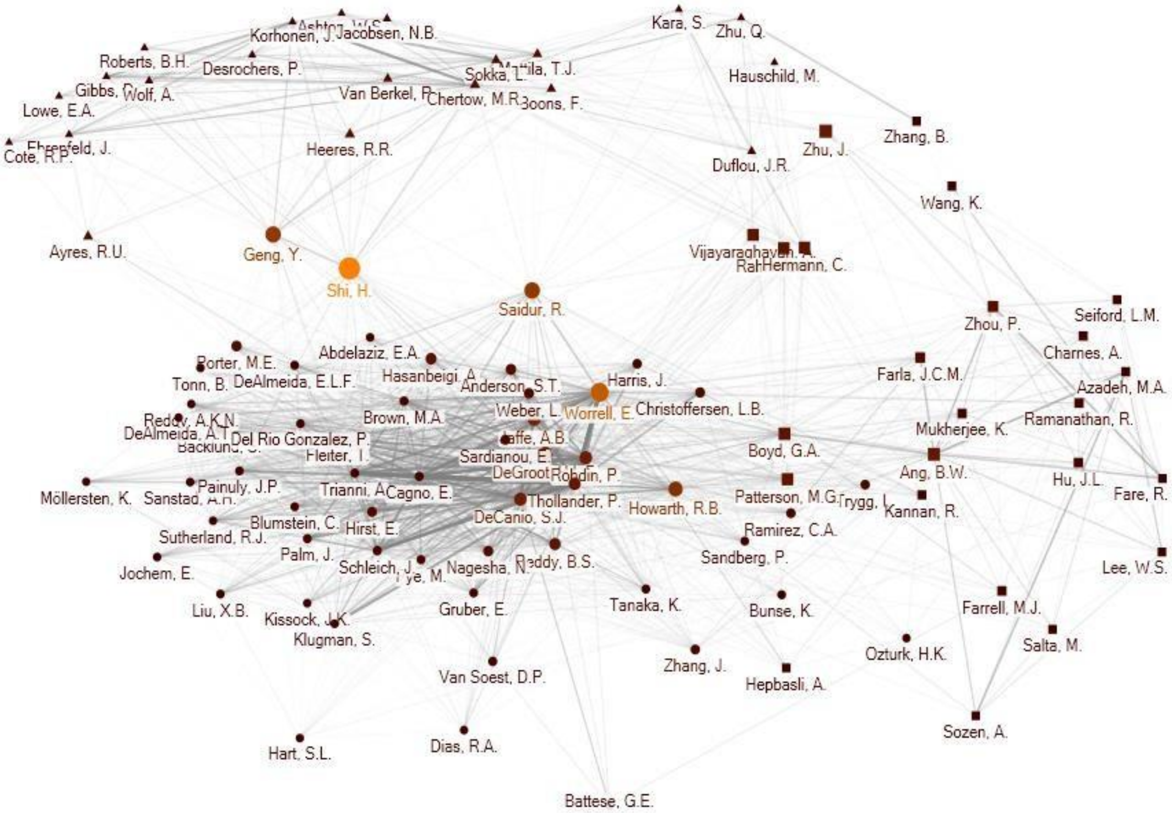

Chart 7. Intermediary authors of communication between the 100 authors categories[38]
Source: The authors

In order to draw a comparison between the *corpus* and the field, in the third stage of the PM-SLR-CA model, the *corpus* representativeness index was proposed in Equation 8 (IRPC), which is the ratio between the *corpus* network density and field network density (represented by 100 authors most cited in the field). As the *corpus* network density is 27% and the density of the 100 most cited of the field is 34%:

$$IRPC = NDC/NDF = 0.27/0.34 = 0.79 \qquad (9)$$

The 79% rate index implies that the total number of connections of the *corpus* authors is 79% of the possible connections among the 100 most cited authors in the field, indicating a good representation of the relationship. The representativeness of the *corpus* can also be analyzed by the statistics of centrality since many central authors in Chart 8 are also central in Chart 6.

The graphics shown in the application enabled the visual representation of the theoretical framework of industrial energy efficiency research field from the perspective of management. The nature of the systematic literature review is to provide an overview, thereby enabling the coherent integration of literature. The goal of the generated charts is to support the construction of an integrative framework, as shown in the PM-SLR-CA model of the Figure 2, by visually identifying the research groups, authors, concepts, and most important topics.

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[38] Categories - Sphere: Management and Efficiency in Energy; Square: Performance; Triangle: Sustainability.

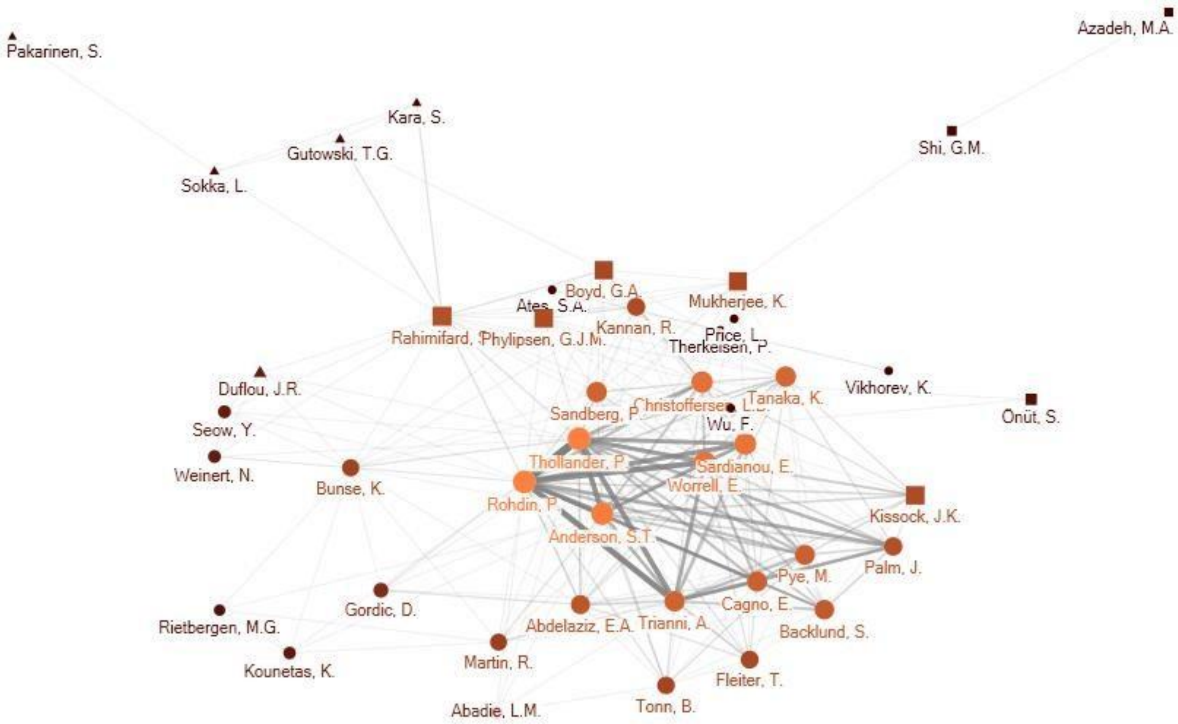

Chart 8. *Corpus* author relationship network[39]
Source: The authors

6. Discussion and results

The main contribution of the PM-SLR-CA model is the proposal of procedures to arrange information in the systematic literature review process in order to map and analyze different areas of study. The information offered by the PM-SLR-CA model has the function to help the construction of a literature integrated framework. The three-stage process of systematic literature review is reformulated using the content analysis approach proposed by Bardin [8]. For testing the proposed model, a survey on the Industrial Energy Efficiency field was performed, where the articles related to Energy Management were analyzed.

The objectives of the first stage of the PM-SLR-CA model, as shown in Figure 2, are to establish the procedures related to the constitution of the documents set (*corpus*), unfolding in four procedures as shown in Figure 5. The procedures of the first stage are not entirely different from those in the first stage of procedures for systematic review proposed in literature [1,3,6], since there are common compulsory steps that are related to inclusion and exclusion rules such as the research question, definition of search terms, and definition of the data sources. It is imperative that in the first stage the *corpus* meets the four selection criteria, i.e., exhaustiveness, representativeness, consistency, and relevance.

When applying the first stage in the field of industrial energy efficiency, we faced similar difficulties as experienced by Armitage *et al.* [7] because of the large amount of research work in the area of energy efficiency. The search term "energy efficiency" in the abstract title and keywords, for the Science Direct database on 03/25/2014 returned 8,141 articles. The selection of the search terms was an important element in defining the research topic. During the period from April/2013 to May/2014 majority of the time was spent in the selection of the research question and definition of search terms.

In the second stage of the procedure, the goal of the PM-SLR-CA model was to extract relevant information for analysis using the coding process of content analysis according to the three steps of the procedural protocol shown in Figure 5. The difference in the second stage between the models proposed by [1,3,6] and our proposed model is in the fact that they offer a specific procedure

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[39] Categories - Sphere: Management and Efficiency in Energy; Square: Performance; Triangle: Sustainability.

for the extraction and organization of the extracted information, supported by the division of documents in context units formed by the content analysis coding [8,34].

The second stage application time depends on the number of selected documents in the previous stage and the number of people participating; however, in general, it can be long (in the case of this application, approximately 400 hours), owing to the requisite for more detailed readings, as well as operationalizing of the coding process where Excel® spreadsheets were used to record data of the content panel and citations panel. In other studies, however, more specialized software can be used such as atlas.ti for the coding process.

In the third stage, the PM-SLR-CA model elaborates the procedures for synthesis and analysis of the content and citations panel built. It is the graphic construction phase of the relationship between registry units such as authors, terms, and topics, with the objective of identifying categories and subcategories. For visual representation, the qualitative data is transformed into quantitative data using coded registry units for the construction of matrices.

The similarity in this stage in relation to the model proposed by Tranfield *et al.* [1] refers to the types of question that this stage should answer such as, who are the authors? To which country do they belong? What are the main articles? What are the main topics? How are these topics interconnected? The difference lies in the fact that in Tranfield et al.'s study and other studies [3,6], there is no positioning at a procedural level on how to perform this analysis. The third stage procedures can help overcome the problems raised by Armitage *et al.* [7] such as the difficulty of unstructured text analysis and thematic literature analysis.

The application of this stage was represented by the construction of eight charts. Chart 1 shows the frequency of countries and journals, which is in accordance with other works, even when considering other research areas such as solar energy [58]. Chart 2 shows the authors and more important words for the context, and Chart 3 the relationship between the most important words. Chart 4 represents the thematic network and Chart 6 the network of the most cited authors in the field, and the other graphics some variant of these two. These charts are divided into three categories (Management and Efficiency in Energy, Performance and Sustainability) in addition to the subcategories within those categories. The general idea is that an integrated framework must take into account these three categories.

- Management and Efficiency in Energy: As shown in Charts 4 and 6, this group is more concerned about the barriers [64,65] and the implementation of measures for industrial energy efficiency (EEMs) [62,66,67]) at the micro level considering energy-efficient technologies (EETs) [68] or at the macro level considering the governmental energy policies [69], among many other topics.
- Performance: The performance group seeks to demonstrate ways of calculating the energy efficiency using a combination of different techniques such as envelopment analysis (DEA), neural networks (ANN), decomposition indicators (IDA) [69-71], frontier analysis (SFA) [72], among others.
- Sustainability: It correlates the demand for energy to broader aspects involving the life cycle of goods and services (LCI, LCA) and its environmental impacts [73-75], as well as energy savings through collaborative processes such as Industrial Symbiosis in Eco-industrial parks [77,78].

The developed IRPC indicator shows that the set of documents of the *corpus* has a good level of correlation (79%), even when compared to the most cited authors of the field.

Comparing the advantages and disadvantages with respect to the traditional models of systematic review [1,3,6], it may occur that in the first stage, there are no differences that may become a disadvantage because some additional criteria of *corpus* selection related to the impact factor of the journal, or others, can be added without problems. The first stage of the PM-SLR-CA model suffers from the same disadvantages in relation to the literature mentioned in Armitage et al. [7], since there is an implicit difficulty in adjusting or calibrating the four criteria mentioned in this stage: Exhaustiveness, representativeness, consistency, pertinence.

The combined advantages of the second and third stage when compared to the aforementioned works include the ease of replication, display, and the possibilities of correlation between concepts and authors. Another point is that the identification of concepts and authors is made in the third stage mainly by centrality mechanisms calculated based on adjacency matrices. A disadvantage in relation to the implementation of the PM-SLR-CA model is due to the lack of knowledge of different practices, techniques or software, even if rudimentary, by researchers, such as indexation mechanisms, classification, mounting of data panels or dynamic tables, extraction of words and terms, manipulation of matrices, even if rudimentary, visualization practices as well as network analysis or multidimensional scaling. Another limitation is that when concepts and authors are on the charts edge, it does not necessarily mean that they should be discarded. A proof of this fact was provided by the work of Granovetter [78], where the weak connections may be able to contribute to the innovation for the group.

The PM-SLR-CA model through its matrix procedures allows the context to develop more easily from a number of additional analyses that were not shown in the survey: Networks construction for the citations that show a temporal evolution when compared to the discussed topics/terms in its time, construction of social networks for authors according to some criteria such as universities, departments or countries to which they belong, relationships between research approaches and techniques used for the work, among others.

Future studies relative to the PM-SLR-CA model are related to its application in other areas in order to continue evolving and improving in the light of both past knowledge and new techniques that arise. For example, the possibility of integrating with meta-analytic approaches of Viechtbauer [79], because this starts from a systematic review to the compilation and comparison of different studies.

7. **Conclusion**

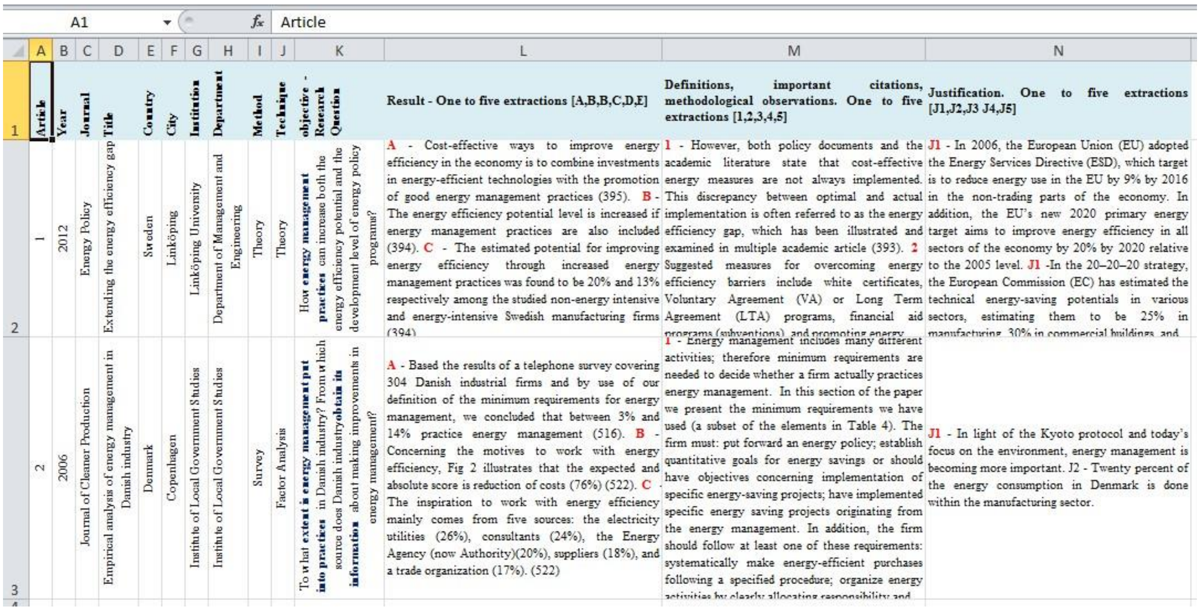
This article presented a PM-SLR-CA process model for systematic literature review using the content analysis approach. Content analysis was thought as a process concerned from documents selection to the presentation of the results. The benefit of using the model translates in providing a framework and new terminologies capable to aid with the implementation and analysis of a systematic literature review. In the construction model, greater emphasis was given to the analysis stage, since the planning steps are better documented in the systematic literature review.

The application of the PM-SLR-CA model was carried out by a *survey* in industrial energy efficiency area with management perspective. It was possible to visualize graphically the main authors, topics, categorical groups of the area, and their relationships. We proposed an index (IRPC) that measures the *corpus* representativeness in relation to the field of study.

Future studies may explore the relationship with other content analysis techniques mentioned in the method such as speech analysis or expression analysis. Based on the content and citation panels, new correlations are possible, depending on the goal of the researcher, including the generation of new complementary visual representations.

The PM-SLR-CA model is subject to the limitations found in the systematic review, especially in the planning phase due to the large amount of works; although with strengths in the analysis stage, it offers an easier way to visualize the relationships.

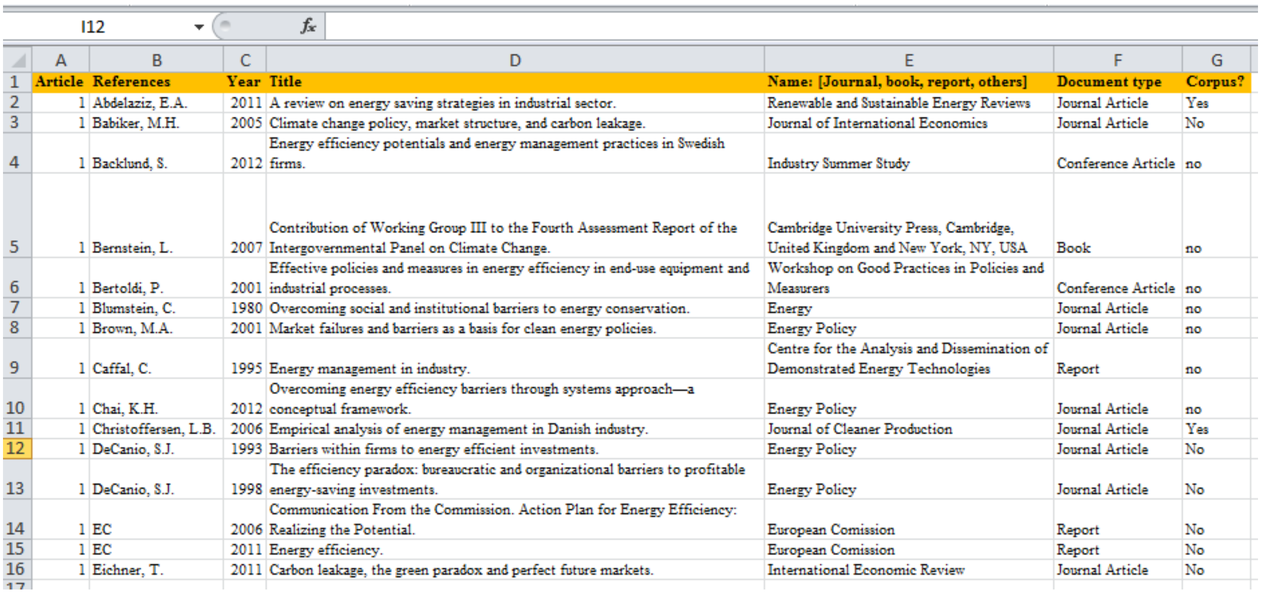
Appendix A: Content panel and citation panel



A1 Article

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Article**	**Year**	**Journal**	**Title**	**Country**	**City**	**Institution**	**Department**	**Method**	**Technique**	**objective - Research Question**	**Result - One to five extractions [A,B,B,C,D,E]**	**Definitions, important citations, methodological observations. One to five extractions [1,2,3,4,5]**	**Justification. One to five extractions [J1,J2,J3 J4,J5]**
2	1	2012	Energy Policy	Extending the energy efficiency gap	Sweden	Linköping	Linköping University	Department of Management and Engineering	Theory	Theory	How **energy management practices** can increase both the energy efficiency potential and the development level of energy policy programs?	A - Cost-effective ways to improve energy efficiency in the economy is to combine investments in energy-efficient technologies with the promotion of good energy management practices (395). B - The energy efficiency potential level is increased if energy management practices are also included (394). C - The estimated potential for improving energy efficiency through increased energy management practices was found to be 20% and 13% respectively among the studied non-energy intensive and energy-intensive Swedish manufacturing firms (394)	1 - However, both policy documents and the academic literature state that cost-effective energy measures are not always implemented. This discrepancy between optimal and actual implementation is often referred to as the energy efficiency gap, which has been illustrated and examined in multiple academic article (393). 2 Suggested measures for overcoming energy efficiency barriers include white certificates, Voluntary Agreement (VA) or Long Term Agreement (LTA) programs, financial aid programs (subventions), and promoting energy	J1 - In 2006, the European Union (EU) adopted the Energy Services Directive (ESD), which target is to reduce energy use in the EU by 9% by 2016 in the non-trading parts of the economy. In addition, the EU's new 2020 primary energy target aims to improve energy efficiency in all sectors of the economy by 20% by 2020 relative to the 2005 level. J1 -In the 20–20–20 strategy, the European Commission (EC) has estimated the technical energy-saving potentials in various sectors, estimating them to be 25% in manufacturing, 30% in commercial buildings, and
3	2	2006	Journal of Cleaner Production	Empirical analysis of energy management in Danish industry	Denmark	Copenhagen	Institute of Local Government Studies	Institute of Local Government Studies	Survey	Factor Analysis	To what **extent is energy management put into practices** in Danish industry? From which source does Danish industry **obtain its information** about making improvements in energy management?	A - Based the results of a telephone survey covering 304 Danish industrial firms and by use of our definition of the minimum requirements for energy management, we concluded that between 3% and 14% practice energy management (516). B - Concerning the motives to work with energy efficiency, Fig 2 illustrates that the expected and absolute score is reduction of costs (76%) (522). C - The inspiration to work with energy efficiency mainly comes from five sources: the electricity utilities (26%), consultants (24%), the Energy Agency (now Authority)(20%), suppliers (18%), and a trade organization (17%). (522)	1 - Energy management includes many different activities; therefore minimum requirements are needed to decide whether a firm actually practices energy management. In this section of the paper we present the minimum requirements we have used (a subset of the elements in Table 4). The firm must: put forward an energy policy; establish quantitative goals for energy savings or should have objectives concerning implementation of specific energy-saving projects; have implemented specific energy saving projects originating from the energy management. In addition, the firm should follow at least one of these requirements: systematically make energy-efficient purchases following a specified procedure; organize energy activities by clearly allocating responsibility and	J1 - In light of the Kyoto protocol and today's focus on the environment, energy management is becoming more important. J2 - Twenty percent of the energy consumption in Denmark is done within the manufacturing sector.

Fig. A.1 Partial view of content panel



I12

	A	B	C	D	E	F	G
1	**Article**	**References**	**Year**	**Title**	**Name: [Journal, book, report, others]**	**Document type**	**Corpus?**
2	1	Abdelaziz, E.A.	2011	A review on energy saving strategies in industrial sector.	Renewable and Sustainable Energy Reviews	Journal Article	Yes
3	1	Babiker, M.H.	2005	Climate change policy, market structure, and carbon leakage.	Journal of International Economics	Journal Article	No
4	1	Backlund, S.	2012	Energy efficiency potentials and energy management practices in Swedish firms.	Industry Summer Study	Conference Article	no
5	1	Bernstein, L.	2007	Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.	Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA	Book	no
6	1	Bertoldi, P.	2001	Effective policies and measures in energy efficiency in end-use equipment and industrial processes.	Workshop on Good Practices in Policies and Measurers	Conference Article	no
7	1	Blumstein, C.	1980	Overcoming social and institutional barriers to energy conservation.	Energy	Journal Article	no
8	1	Brown, M.A.	2001	Market failures and barriers as a basis for clean energy policies.	Energy Policy	Journal Article	no
9	1	Caffal, C.	1995	Energy management in industry.	Centre for the Analysis and Dissemination of Demonstrated Energy Technologies	Report	no
10	1	Chai, K.H.	2012	Overcoming energy efficiency barriers through systems approach—a conceptual framework.	Energy Policy	Journal Article	no
11	1	Christoffersen, L.B.	2006	Empirical analysis of energy management in Danish industry.	Journal of Cleaner Production	Journal Article	Yes
12	1	DeCanio, S.J.	1993	Barriers within firms to energy efficient investments.	Energy Policy	Journal Article	No
13	1	DeCanio, S.J.	1998	The efficiency paradox: bureaucratic and organizational barriers to profitable energy-saving investments.	Energy Policy	Journal Article	No
14	1	EC	2006	Communication From the Commission. Action Plan for Energy Efficiency: Realizing the Potential.	European Comission	Report	No
15	1	EC	2011	Energy efficiency.	European Comission	Report	No
16	1	Eichner, T.	2011	Carbon leakage, the green paradox and perfect future markets.	International Economic Review	Journal Article	No

Fig. A.2 Partial view of citation panel

Appendix B: *Corpus* in information extraction order

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APÊNDICE I

APÊNDICE I: ARTIGO 4 - A SYSTEMATIC LITERATURE REVIEW IN INDUSTRIAL ENERGY EFFICIENCY: A META-ANALYTIC FRAMEWORK

CONGRESSO – *POMS 27th ANNUAL CONFERENCE – ORLANDO, USA, 6-9 MAIO 2016*

A systematic literature review in industrial energy efficiency: an integrative framework

ARTIGO ESTENDIDO – *SUBMETDO PARA A REVISTA RENEWABLE & SUSTAINABLE ENERGY REVIEWS*

A Systematic Literature Review in Industrial Energy Efficiency: A Meta-Analytic Framework

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Abstract
A systematic literature review was accomplished in the field of industrial energy efficiency with an energy management perspective. We applied a content analysis based process model developed for the implementation and analysis of systematic reviews. Through a set of ex-ante questions, it was possible to identify the main categorical groups of authors in the field as well as to establish a relationship between these groups and the themes and methodologies in which they work. A series of ex-post questions were created to identify and analyze the main objectives, concepts, techniques, and results, guiding the presentation of the systematic literature review content. A meta-analytical framework for the measurement of energy performance is proposed, in order to represent the main ideas of the categorical groups found in the literature: (i) energy efficiency/management, (ii) quantitative performance and (iii) sustainable inter-firm relations. The energy performance in this framework depends on the dynamic-structure-performance condition.

Key-words – Systematic Literature Review, Industrial Energy Efficiency, Energy Management

1 Introduction

In the year 2011, 81% of the world's energy demand was supplied by fossil fuels. Considering that the estimated world population is going to be 8 billion by 2025, a heavy pressure on the energy system is expected and the investments needed in the transition to clean energy systems are about 1% of world GDP. The potential to reduce emissions by 2025 is 17 GtCO2 in buildings, 13 GtCO2 in transports and 11 GtCO2 in the industry. According to the International Energy Agency (IEA) report, 44% of emission reductions can be achieved by energy efficiency [1].

Industrial processes consume approximately one-third of global energy [2], but this rate varies between countries, e.g. 29% in Greece [3], 32% in the United States [4], 35% in Turkey [5], and 70% in China [6,7]. According to a broader classification made by DOE-EIA [8], which includes manufacturing, agriculture, mining and construction, the industrial sector consumption reaches approximately 50% of the world energy produced.

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These leading factors have made energy efficiency and industrial energy efficiency not only a macroscopic concern at government level but also a company concern through demand management and energy resources consumption, even turning it into a competitiveness factor [9].

Based on the literature, one of the first reviews on energy efficiency is the bibliometric analysis of Du et. al [10], which identified an increase of 278% in the number of articles published and 396% in the number of citations between the periods 1993-2001 to 2002-2010. A bibliometric study Du et. al [11] in the solar energy field showed a 103% and 187% growth in the same period and based on the same indicators. Also, the interest in energy efficiency was higher than in solar energy.

Our research has a more specific objective than the bibliometric analysis of Du et.al [10], we intend to present a systematic literature review (SLR) of industrial energy efficiency from the perspective of energy management. SLR can be considered an approach to organize and develop a literature review process, discussing problems deeper than a bibliometric study.

The development of the SLR process allows the identification, mapping and analysis of the relevant researches of a specific problem or themes [12, 13, 14]. The SLR performance in the industrial energy efficiency field was based on the use of a content analysis process model Perroni et.al [16] for the conduction of an SLR developed in [12, 14, 15, 17].

The presentation of SLR in industrial energy efficiency is divided into five sections: SRL process model stages; Graphical presentation of SLR; Categorical groups presentations of industrial energy efficiency; Discussion and Conclusion.

2 Process Model Stages for Systematic Literature Review

The systematic literature review in the industrial energy efficiency field was undertaken according to the process model presented in Fig.1. It is not the purpose of this work to detail the process model of the systematic review, but to use it as a methodological instrument. As in other works that propose models to implement SLR [12, 13, 14], the SLR process seen in Fig.1 occurs in three stages. The first stage is where the selection procedures of documents occurs, in order to comply with the rules of completeness, representativeness, homogeneity and pertinence.

The second stage involves the information extraction procedures, aiming to build a citations panel and a content panel. The content/citation panels can be analyzed in the third stage through various techniques such as social network analysis, text mining, and cluster analysis [18, 19]. The objective of this research is the construction of an integrative framework or a understanding related to the state of the art of the analyzed research field, with the integration between several works and themes.

With regard to the application of the process model of Fig.1 in the industrial energy efficiency field, in order to define the limits of the research theme, an initial search was made in books, government agencies reports, International Energy Agency and scientific articles, by floating readings. The initial research question raised was: "How does energy performance be measured, taking into account both efficiency and effectiveness in managing manufacturing?" [20].

After the survey and analysis among the main scientific bases, such as Wiley, ScienceDirect, InderScience, SciELO, Taylor & Francis, Emerald and JSTOR, it was verified the existence of a set of significant works in the industrial energy efficiency field with a management perspective, where Science Direct is the scientific base that gathers periodicals of relevance in the area, presenting more than 100 journals associated to the energy field, being many of them among the first in the SJR ranking of the energy field of Scimago. We decided to use scientific articles of the Science Direct platform, as they are able to reveal the frontier of knowledge. After several tests, the selected search terms were: ["industrial energy efficiency" OR "industrial energy management" OR "energy efficiency manufacturing") OR ("industrial symbiosis" AND "energy") OR ("energy management" AND "manufacturing")].

The title, summary and keywords of the articles were selected as a presence indicator for the search terms. The search was performed during the month of May/2014, returning 574 articles, of which, 178 were read and selected based on the analysis of the summary. Of the 178 articles, 104 were selected for the constitution of the corpus, always observing the four mentioned criteria in the model of Fig.1, that is, completeness, homogeneity, representativeness and pertinence, based on the research question to be answered. The first stage took place from April / 2013 to May / 2014.

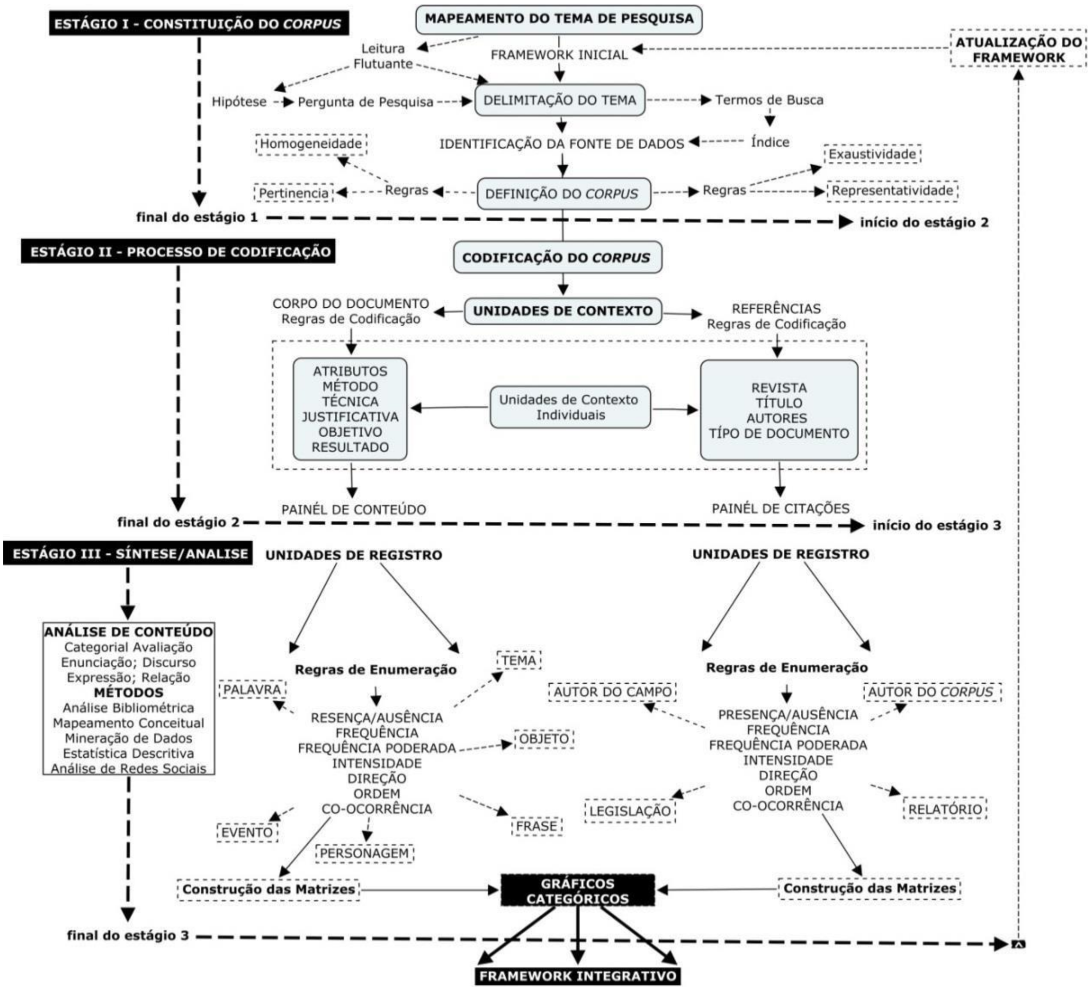


Fig. 1. Process Model for Systematic Literature Review.

According to the process model based on Fig. 1, the purpose of the second stage is to code the corpus. The coding process takes place with the construction of two bases: content panel and citations panel. A total of 104 articles were read and extracted to an Excel® worksheet. Context units (extraction of specific parts of the message) were recorded in the content and citation panel [16], according to the coding rules of the model in Fig.1.

The composition of the content panel occurred with the extraction of 61,202 words, having an average of 588 words per article, a minimum of 288 words and a maximum of 985 words. The citation panel was constructed by selecting the first author of each reference. The citation panel summed 4,466 citations where 1,255 are journal authors. During the second stage, approximately 400 hours were spent between June and December 2014.

The analysis will be performed in the next two sections of the paper. Based on Tranfield [12], the purpose of a systematic review is to provide answers to a set of ex-ante questions: Who are the most cited authors? The authors are from which countries, research institutes and departments? What are the main journals? What are the key themes and key words identified? What methods and techniques are used by the works? The analysis of these questions raised ex-ante will help in categorical analytical mapping with the formation of similarity groups. The indicators developed to answer these questions will help to clarify if the industrial energy efficiency studies actually represent a field of research.

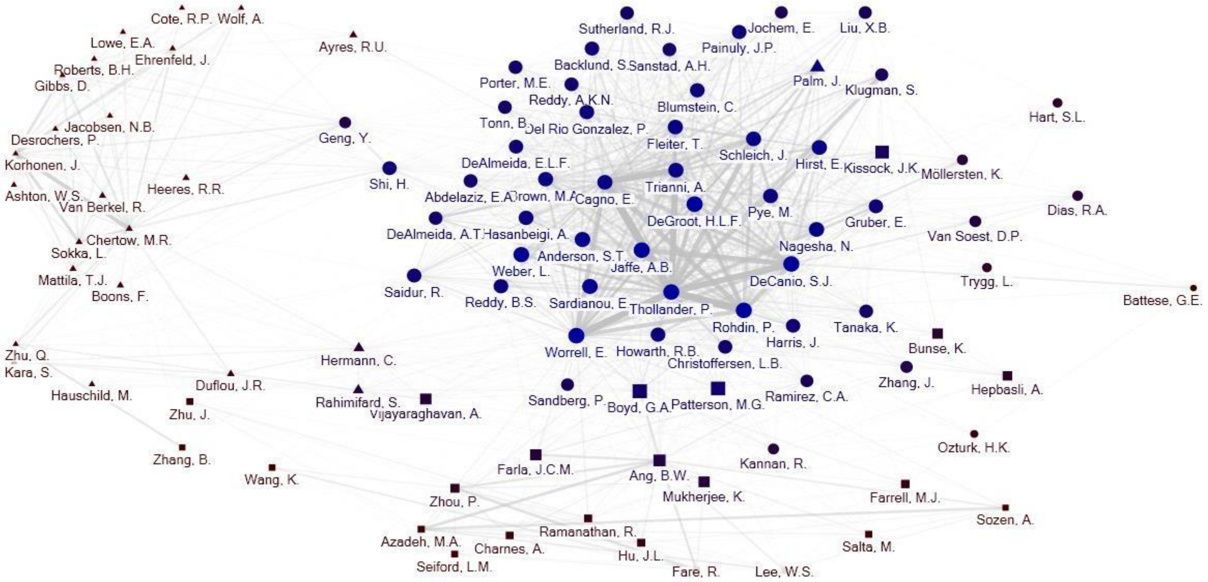
Once the ex-ante questions have been answered, through the categorization of the research themes, it was possible to establish a series of ex-post questions that could aid in future research presented in the fourth section. Why Study Energy Efficiency? What are its main determinants and limiters? What kind of measures can be taken? What is energy management? What types of practices are being investigated and what are the difficulties? What kinds of frameworks have been proposed for energy management? What types of policies can be adopted by governments? Did the energy policy actions give the expected result? What is energy efficiency? What is energy performance? How is energy performance being measured? What kinds of concepts and techniques have been used to study energy efficiency when more than one actor (interrelationship between companies) is involved? Did the relationship between companies have been successful in energy efficiency?

The goal is not only to provide definitive or complete solutions to the issues raised ex post, but also to offer a boundary situation that helps both the SLR presentation and future researches.

3 Charts in Systematic Literature Review of Industrial Energy Efficiency

The application of the process model of Fig.1 allows the identification of the main theoretical aspects along with the identification of the categories and themes that the researchers worked with, turning possible an update of the existing framework, as well as highlighting trends for future researches. This section goal is to answer some questions graphically, such as: Who are the most cited authors? Which countries, research institutes and departments are they from? What are the main journals? What are the key themes and key words identified? What methods and techniques are used? Graph 1 shows the relationship (co-occurrence) of the 100 most cited authors among the 1,255 journal authors of the 104 articles, where the size and color of the vertices are proportional to the Eigenvector Centrality statistics. The distribution of the network in Graph 1 was done by the Fast Multi-Scale algorithm [18, 19, 21].

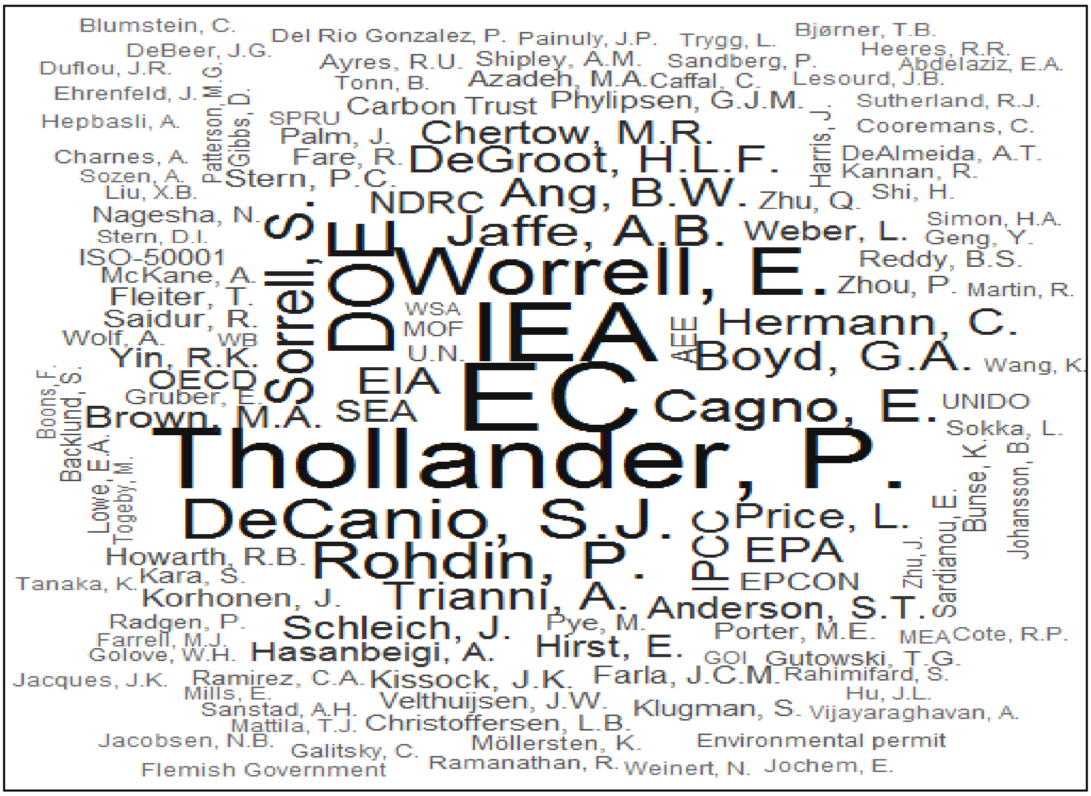
Based on the distribution provided by the algorithm and on the interest subjects of the authors, the network of Graph 1 was classified into three categories, according to its geometric form: Sphere: Energy Efficiency/Management; Square: Quantitative Performance; Triangle: Sustainable Inter-Firm Relations.



Graph 1. Relationship between the 100 most cited authors by the 104 articles in the *corpus*

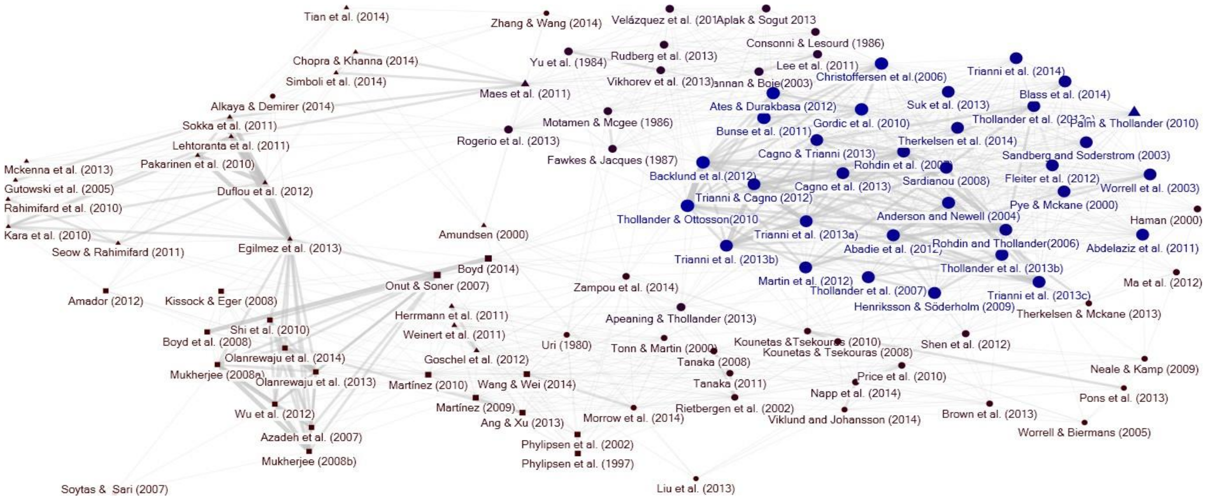
Note: (a) Energy Efficiency/Management (sphere); Quantitative Performance (square); Sustainable Inter-Firm Relations (triangle); (b) Algorithm: Fast Multi-Scale (c) size / color of vertices: Eigenvector Centrality

The Graph 2 shows the 130 most cited articles of a total of 2,411, cited 4,466 times. Unlike Graph 1, where only the authors of the journal appear, Graph 3 includes all types of documents: journal articles, congress articles, reports from government agencies, academic papers, among others. It may be noted that among the most cited reports are the ones from European Commission (EC), International Energy Agency (IEA), Department of Energy (DOE), American Energy Information Administration (EIA), Intergovernmental Panel on Climate Change (IPCC), American Environmental Protection Agency (EPA), Swedish Energy Agency (SEA), and many others.



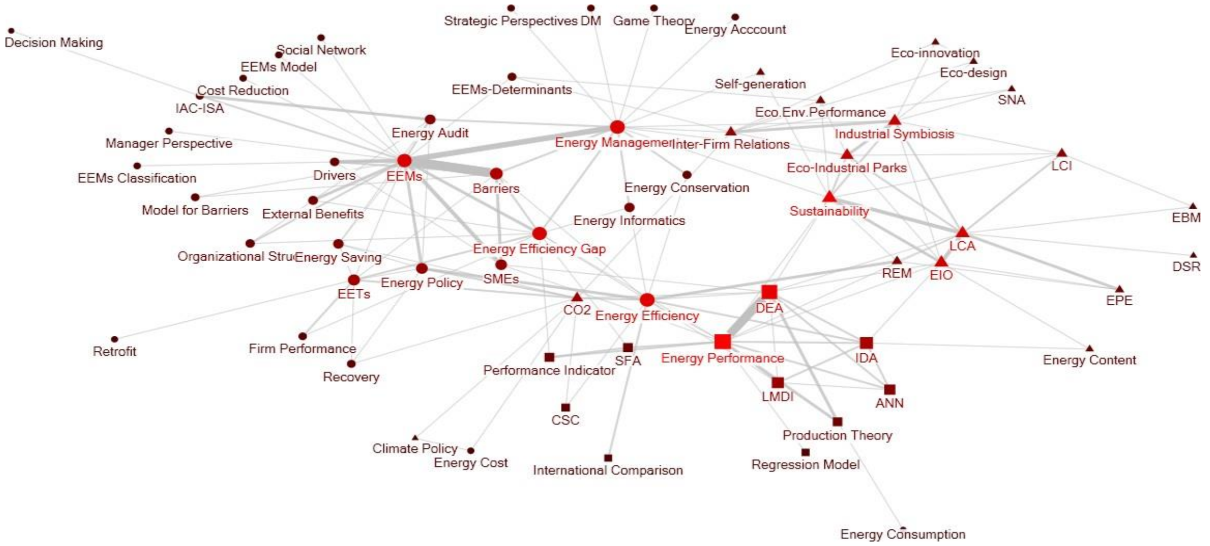
Graph 2. Most cited authors considering all the documents
Note: Constructed from the incidence matrix (frequency) of the citation panel of the process model of Fig. 1.

Note that the Graph 3 is not an analysis of co-citations, but a network created from the thematic relationship, i.e. common themes that the authors of the 104 articles selected to constitute the corpus and can also be divided in three identified categories, according to the geometric form selected to represent the categories.



Graph 3. Relationship of authors of the corpus considering the research themes
Note: a) Energy Efficiency/Management (sphere); Quantitative Performance (square); Sustainable Inter-Firm Relations (triangle); (b) Algorithm: Fast Multi-Scale (c) size/color of vertices: Eigenvector Centrality.

The Graph 4 shows the network of themes in which the 104 articles had their main focus. We selected two to five themes per article. Keeping the pattern of Graph 1 and Graph 3, the themes in Graph 4 are distributed according to the three identified categories.



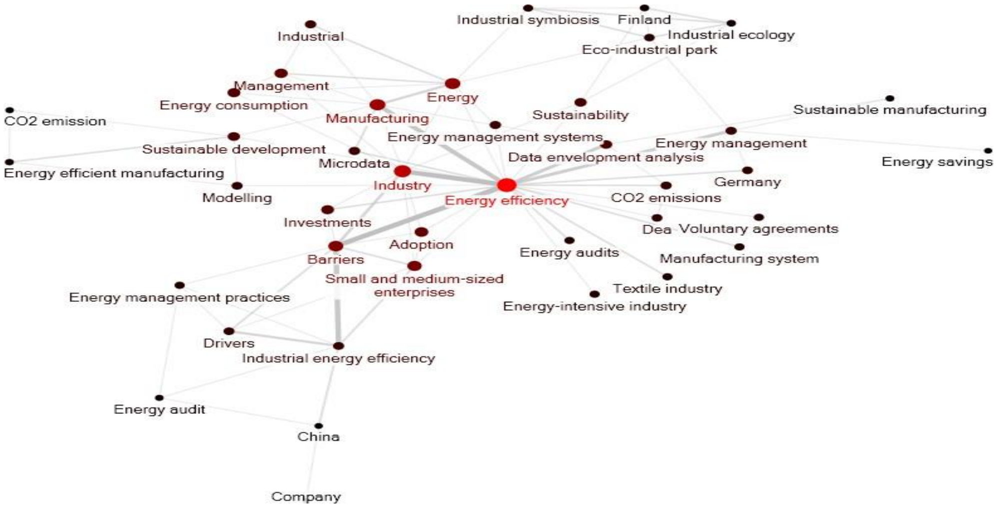
Graph 4. Relationship between the 63 identified themes in the corpus

Note: Acronyms: ANN - Artificial Neural Network; CED - Cumulative Energy Demand; CSC - Conservation Supply Curves; DM - Data Mining; DSR - Direct Secondary Reuse; EBM - Environmentally Benign Manufacturing; EEMs - Energy Efficiency Measures; EETs - Energy Efficient Technologies; EIO - Economics Input Output; EPE - Energy Product Embodied; IAC-ISA - Industrial Assessment Centers-industrial Saving Assessment; IDA - Index Decomposition Analysis; LCA - Life Cycle Analysis; LCI-Life Cycle Inventory; LMDI; Logarithmic Mean Divisa index; REM - Resource Efficiency Manufacturing; SFA- Stochastic Frontier Analysis; SMEs - Small and Medium-sized Enterprises; SNA – Social Network Analysis.

The energy efficiency/management category involved 66 of 104 articles. The most central or most influential themes of this group are: (i) Energy Efficiency Measures (EEMs); (ii) Barriers; (iii) Energy Efficiency Gap; and (iv) Energy Management [19]. The strongest linkages occur between Barriers, EEMs and Energy Management as can be seen in Graph 4 .

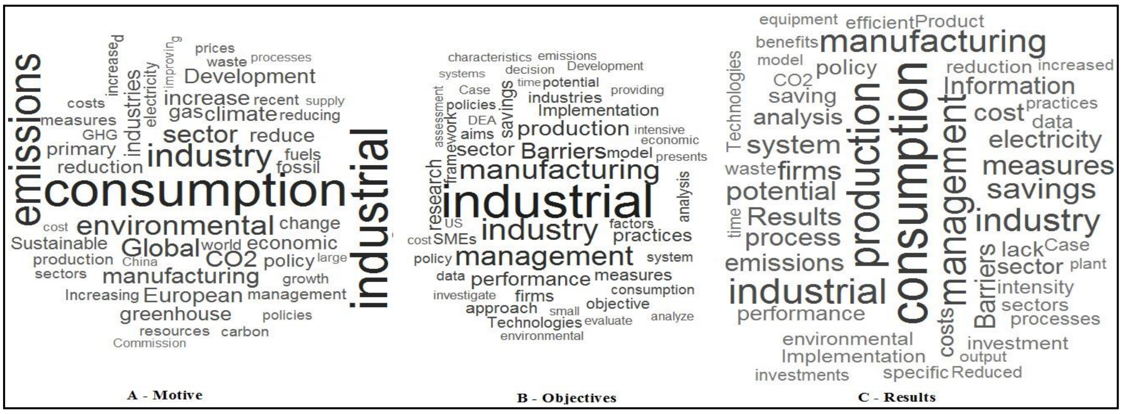
Data envelopment analysis has the greatest centrality in the efficiency group and in the other hand, sustainability, economic input-output (EIO) and life cycle analysis (LCA) presents the largest centralities in the sustainable inter-firm relations categorical group.

The Graph 5 shows the keywords network that appears in at least 2 times in the 104 articles. The 104 articles used 286 keywords, represented in Graph 5, of which 40 were mentioned more than once. As expected, energy efficiency is a central keyword and it has a stronger relationship with the industrial sector/manufactures, barriers, Energy management and data-invariant analysis (DEA) themes.



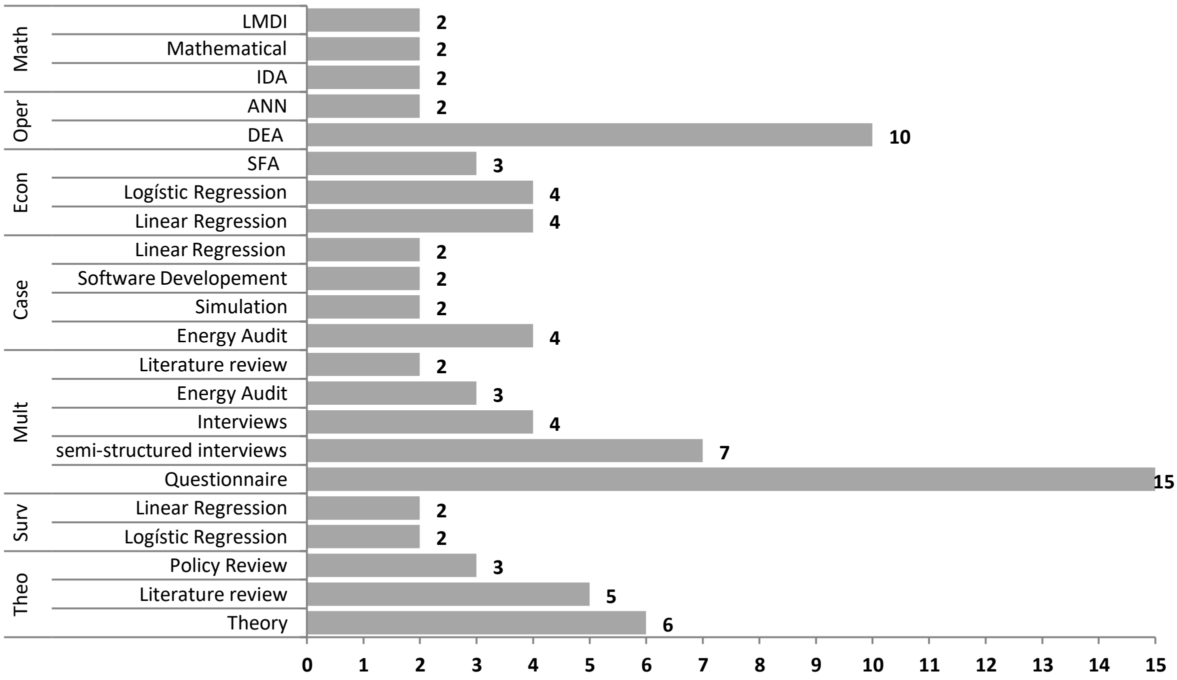
Graph 5. Relationship between keywords.

The Graph 6 shows the 50 most frequent words that appeared in the problem description, objective and result section (excluding the words energy and efficiency). It can be noticed that the words used to justify the researches have a greater environmental appeal.



Graph 6. 50 most frequent words in the problem description, objective and results in the 104 articles

The Graph 7 presents the research approaches and the techniques or methods used by these approaches. Only techniques/methods with more than one occurrence were presented. As expected, qualitative approaches such as case study/multiple are related to questionnaires and interviews techniques and the research approach such as operational, econometrics and survey researches generally uses data envelopment analysis and logistic regression techniques.

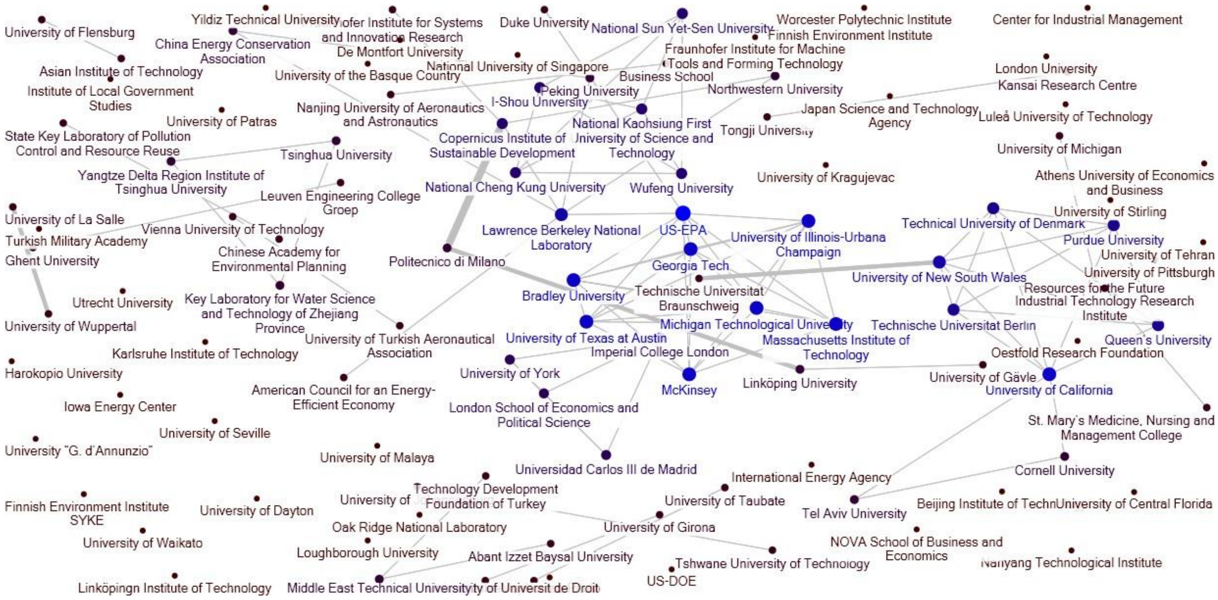


Graph 7. Research approaches and techniques used

It is possible to elaborate a set of graphs to visualize the attributes of the articles, represented in Graph 8, Graph 9, Graph 10 and Graph 11. Graph 8 shows the network of the research centers based on the information that authors and co-authors declared in the articles. The lines in Graph 8 show the cooperation between institutions, with the most central institutions based in the United States led by the US Environmental Protection Agency (US EPA). This fact may mean that within the United States there is a greater cooperation network working on this theme. We can also observe that for the set of corpus articles the major links (cooperations) are between Italy and Holland (Politecnico di Milano/Copernicus Institute of Sustainable Development); Italy and Sweden (Linköping University) and Germany and Australia (Technische Universität Braunschweig / University of New South Wales).

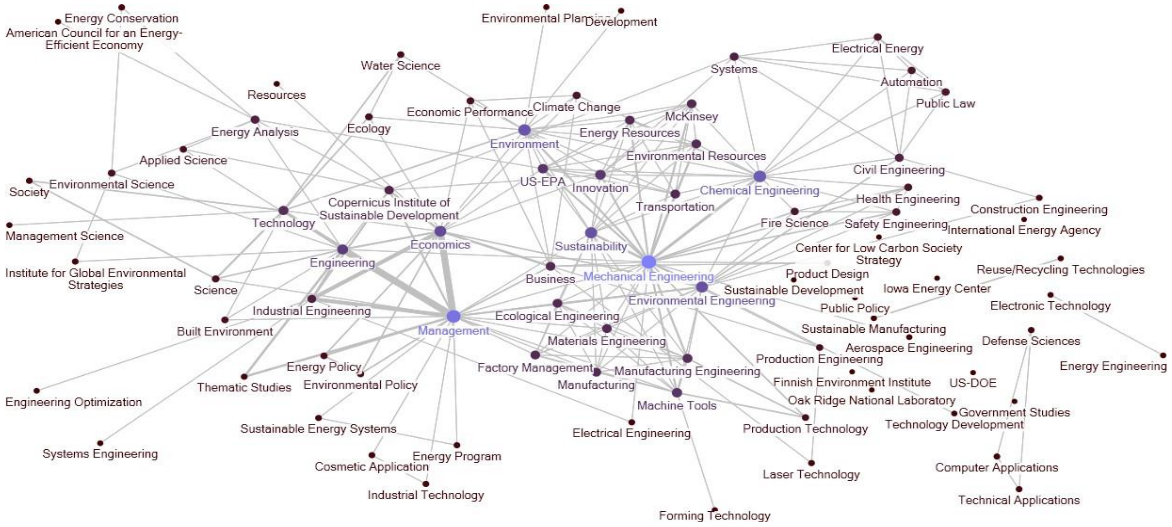
In Graph 7 we can note the large number of institutions in which the authors and co-authors belong, since the 104 articles had contributions of 107 institutions from 30 different countries (see also Graph 11).

As in Graph 8, Graph 9 shows the network of departments in which the authors and co-authors belong. Two issues can be highlighted in Graph 9, the first is the large number of departments that study the field of industrial energy efficiency, where 83 departments were identified, including the creation of new departments or centers such as Sustainability, Ecological Engineering, Climate Change, Environmental Resources, Energy Resources, among others. A second issue is the information of which departments are most central in the study of industrial energy efficiency considering the selected energy management studies. The largest centrality indicates which departments are most interested in the area of industrial energy efficiency.



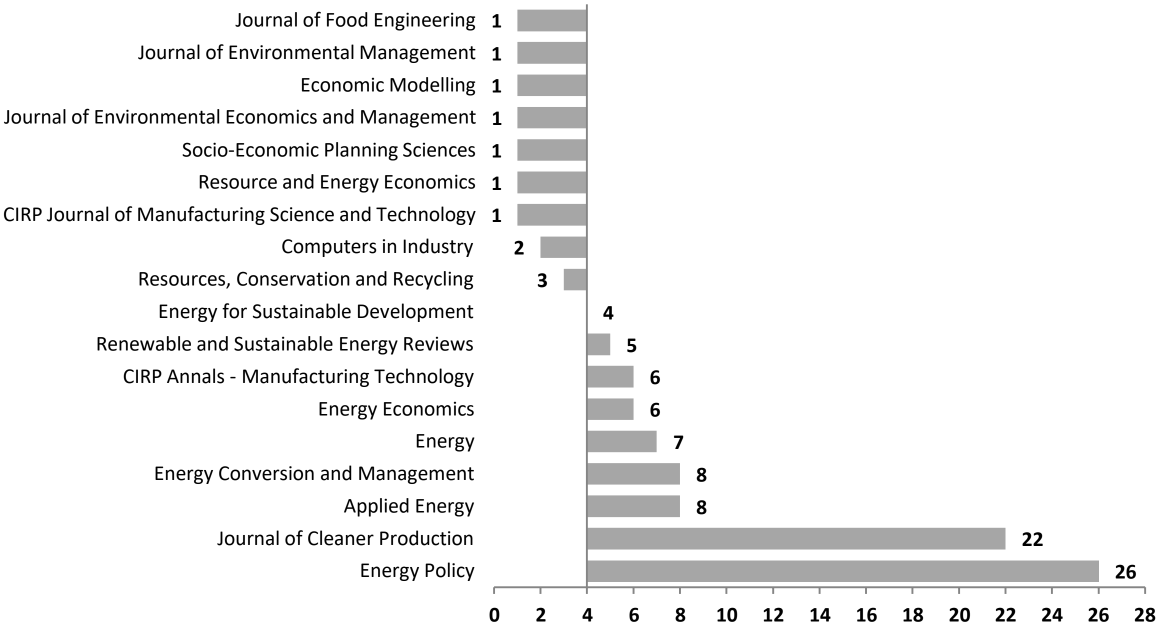
Graph 8. Collaboration network among research centers' corpus

The most central departments involve the areas of Engineering, Management and Sustainability. The departments of Mechanical Engineering and Management carry out the largest information intermediation because they have the highest statistical centrality. The most frequent links are among the departments of Engineering, Management, Economics and Industrial Engineering.



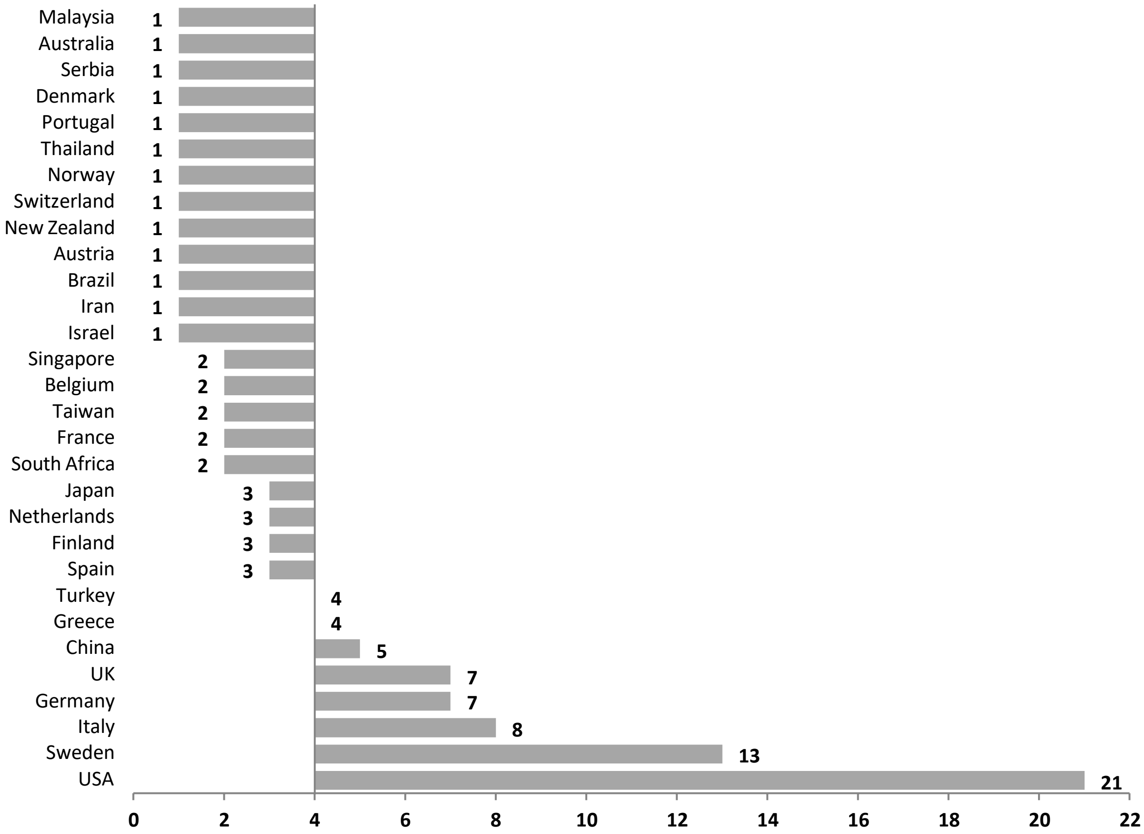
Graph 9. Network of departments that authors and co-authors declared to belong

Graph 10 gives information about which journals they were published. Based on Graph 10, eight journals had more than five articles. The eight journals are among the 50 with Scimago's best SJR ranking, considering a total of 753 journals registered in the energy field.



Graph 10. Number of articles by journals.

Graph 11 shows the number of articles considering the country which the first author belongs. A first point that stands out is that it is a theme discussed internationally, although only six countries have five articles or more, representing (58/104) approximately 60% of the total.



Graph 11. Number of articles by country

3.1 *Considerations based on graphical analysis of systematic literature review*

It was possible with the graphical mapping presented in this section to visualize categorical variables related to the frequency or co-frequency (co-occurrence) found in the systematic literature review process in the field of industrial energy efficiency. The 11 (eleven) graphs of this section relate frequency or co-occurrences the objects of ex-ante questions: authors, research themes, keywords, research methods, research centers, departments, journals, and countries.

The main insights of the analysis of all graphs was that the area of industrial energy efficiency can be divided into three categorical groups: (i) energy efficiency/management; (ii) Quantitative performance; (iii) Sustainable Inter-Firm Relations. A more in-depth analysis of the content of the articles in each group will be conducted in a way that makes it possible to answer ex-post questions that are beyond the categorical analysis.

4 Presentations of Categorical Groups in Industrial Energy Efficiency

According to the methodology proposed in section 2, through the SLR process presented in Fig. 1, it was possible to identify three highlighted categories based on Graph 1, Graph 3 and Graph 4. The main category is the energy efficiency/management studies, being the most denser categorical group of authors. Their vertices are represented as spheres in Graph 3. In order to facilitate the presentation, the energy efficiency/management category was codified in five subcategories: (i) energy efficiency; (ii) energy saving/energy efficiency measures (EEMs); (iii) management; (iv) energy police; and (v) other factors related to energy efficiency. A second category of articles is the ones which work with quantitative measurement of energy performance. Its vertices are identified as squares in Graph 3. The category of the sustainable inter-firm relations is represented as triangles at the vertices of Graph 3 and is the third to be presented.

As explained before in section 2, it was possible to establish a series of ex-post questions that will guide the presentation of how the literature solves these issues. These issues can be seen in Chart 1. Since each article of the corpus presents at least one research question, there are at least 104 questions and the ex-post questions are representative of these questions.

•	**Energy Efficiency / Management**
EPQ1	✓ Why Study Energy Efficiency?
EPQ2	✓ What are the main factors and constraints in energy efficiency?
EPQ3	✓ What types of measures can be taken?
EPQ4	✓ What is energy management?
EPQ5	✓ What types of energy management practices are being investigated and what are the difficulties?
EPQ6	✓ Which frameworks have been proposed for energy management?
EPQ7	✓ Which policies can be adopted by governments?
EPQ8	✓ Did the energy policy actions give the expected result?
•	**Quantitative Performance**
EPQ9	✓ What is energy efficiency?
EPQ10	✓ What is energy performance?
EPQ11	✓ How is energy performance being measured?
•	**Sustainable Inter-Firm Relations**
EPQ12	✓ Which concepts and techniques have been used to study energy efficiency when more than one actor (inter-relationship between companies) is involved?
EPQ13	✓ Is the relationship between companies successful in energy efficiency?

Chart 1. Representative Ex-post (EPQ) questions of the corpus.

4.1 *Energy Efficiency/Management*

The 66 articles in this group were classified into 13 themes, according to the research problem that these articles sought to solve, in which authors and themes can be seen in Fig. 2. In addition, the category was divided into five subcategories to facilitate visualization (Energy efficiency, energy savings/EEMs, energy management, energy police and other factors related to energy efficiency). One peculiarity is that only four articles in this group date back to the year 2000 and approximately 70% of articles are from 2010 or higher.

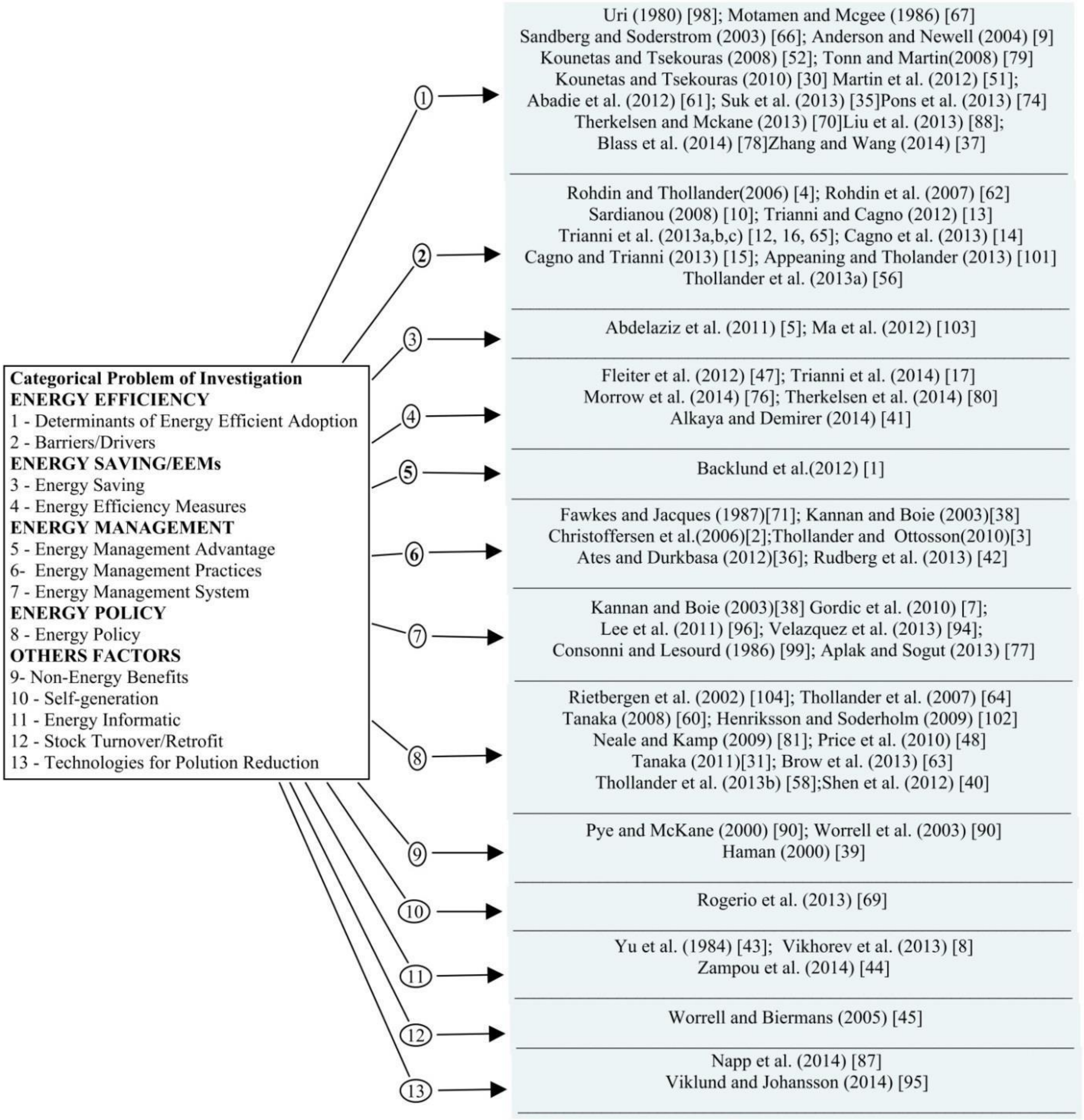


Fig. 2. Subcategories of the energy efficiency/management group.

4.1.1 *Energy Efficiency*

The ex-post questions defined for this subcategory were: Why Study Energy Efficiency? What are the main determinants and barriers? The main reasons for studying energy efficiency revolve around two themes: Nonrenewable resources scarcity and their impacts on the environment.

There is the fact that literature has recognized the so-called energy efficiency gap since the 1980s. Based on Jaffe e Stavins [22], who is among the most cited authors in Graph 2 and co-cited in Graph 1, the gap refers to the discrepancy between the optimal energy efficiency implementations and the actual implementations. The work of DeCanio [23] appears as one of the most cited and co-cited in Graph 1 and Graph 2. He found that a paradox still exists since many companies present the opportunity to maximize results through investments in energy efficiency, but they do not do it. From this scenario and government and social political leaderships pressures, the energy efficiency topic has been investigated more vehemently, especially since the end of the first decade of the 21st century.

One of the first issues to be presented is the determinants and limitations for energy efficiency. The authors presented in Fig. 2 were categorized as those that studied the determinants of energy efficient adoption, usually adopting statistical/econometric methodologies, which can be visualized in Graph 7. The authors who discuss the limitations (Barriers/Drivers) have adopted qualitative methodologies, especially case studies, which can also be observed in Graph 7.

In the studies on the energy efficiency determinants, many hypotheses are proposed to establish a relationship between the lower energy use and several other aspects. Energy efficiency is affected by technological innovations, access to capital, variation in consumption capacity and increase in energy prices [24]. Energy conservation projects are insufficient [25], wherein the next discussions give hints that this still is the problem. Energy efficiency can be promoted by supplying informations to stakeholders, government support, energy audit, housekeeping, capital investments, energy flow monitoring, benchmarking, and connections to other investments [26].

Through an analysis of energy efficiency audits for small and medium-sized companies in the US, it was found that approximately 50% of the projects are implemented and the adoptions are guided by cost metrics (lower cost, lower payback and higher energy price) [4. 27, 28]. It is also identified that the audits had a positive correlation with later investments [29]. In the work of Blass et. al [30], who also investigated with DOE-IAC information, the operation managers' involvement is essential to improve the adoption rate of energy efficiency practices.

The most likely companies that adopt these practices are the ones that received subsidies, companies with greater energy intensity and higher fixed capital. Energy efficiency technologies (EETs) positively affect the technical efficiency of the companies investigated [31].

When considering the political and environmental factors, Suk et.al [32] did not find a relationship between regulation, competitors, associations, and energy savings, even for energy-intensive companies. Energy savings are determined by high-level managers' support, economic incentives and training. In Liu et.al [33], the higher carbon rates acceptance are determined by subjective perceptions and self-motivation, probably due to the lack of internal capacity. In Liu et. al [34], it was found that the collaboration to reduce carbon emissions (Industrial Symbiosis) has a positive relationship with economic performance. But the authors in Zhang and Wang [35] did not find a relationship between economic performance and energy efficiency, they identified a positive relationship between energy efficiency and environmental performance.

Another set of authors sought to investigate the problem by directly questioning the industrial companies. What are the main limiting conditions and diffusion factors to get greater energy efficiency? A synthesis of the main constraints (barriers) and the work of Cagno et. al [36] is presented, identifying a number of internal barriers (Economic, Behavioral, Organizational, Competencies/Awareness) and external barriers (Market, Government/politics, Technology/services suppliers, Designers and manufacturers, Energy suppliers, Capital suppliers).

Through qualitative techniques, such as interviews and semi-structured questionnaires, several studies investigated barriers and drivers. Among the main empirical barriers in energy-intensive and non-intensive industries, it can be highlighted: (i) cost and risk of production disruption; (ii) lack of time; (iii) other priorities; (iv) cost of time to get equipment energy information; (v) other priorities for capital investment; (vi) lack of sub-meters; (vii) incentives division with ESCOs [37, 38, 39].

For the Greek industries, Sardianou [3] identified that energy investments are not a priority, 70% of the companies were not updated about the new technologies, but considering that if competitors do, they are willing to do as well.

Investigating the framework of Cagno et. al [36] for 48 manufactures from Italy, Trianni et. al [40] identified the main economic barriers (high cost of investments, hidden costs, intervention not profitable enough), information (energy contract information, unclear information by technology suppliers, cost benefit information), and they concluded that energy management is marginal in the assessed companies. Trianni et. al [41] also identified for 65 European foundries that companies were concerned with ensuring business continuity and their risks. Additionally, for the metalworking industries, Trianni et. al [42] have also identified the lack of interest in energy efficiency by companies that already believe to be efficient. Appeaning and Thollander [43] have identified in a large industrial area the lack of qualified people to evaluate the performance of EETs.

Among the drivers or facilitators, it was identified long-term strategy, energy price increase, necessity of personnel with real ambition [37, 38, 43]. They also identified as drivers public funding, external pressure, long-term benefit, cost reduction and senior managers support [44, 45].

4.1.2 Energy Saving / EEMs

Another question is: what types of measures can be identified? In a literature review, Abdelaziz et.al [46] identified that energy savings can occur in three ways: (i) energy management (historical data analysis, energy audit, engineering analysis, information/training); (ii) EETs (variable speed drive, waste heat recovery, high efficiency motors, leak prevention in air compressors); and (iii) policy (regulations, fiscal policy, agreements and goals).

According to Fleiter et. al [47], the EEMs depend on three factors: (i) relative advantage (internal return rate, payback, investment expenditure, non-energetic benefits); (ii) technical context (central process distance, modification type, impact scope, life time); and (iii) information context (transaction cost, planning and implementation knowledge, diffusion progress, sectorial applicability).

Several advantages of indirect EEMs are introduced: internal environment improvement, noise reduction, work and time savings, process control improvement, convenience improvement, water saving and waste minimization, equipment miniaturization, emission reduction, maintenance necessity reduction, productivity increase [48].

As presented by Abdelaziz et. al [46], as well as in DOE-IAC [49], which has approximately 700 practices related to energy management, the measures identification is a specific case. Based on the literature, some researches seek to identify measures for specific cases. Morrow et.al [50] identified 22 measures for the Indian cement industry, Therkelsen et. al [51] identified 23 measures for the bakery sector, Alkaya and Demirer [52] identified 5 general measures for a textile mill in Turkey. It is important to notice that in the textile factory, with an investment payback of 1.5 month, water consumption was reduced by 43% and energy consumption by 13.5%.

4.1.3 Energy Management

Regarding the Subcategory of energy management, some questions can be answered based on literature: what is energy management? What types of practices are being investigated and what are the difficulties? What kinds of frameworks have been proposed for energy management? As reported in Backlund et.al [53], there is no precise definition of what is energy management, Amundsen [54] claim energy management does not differ from other management systems and can be easily integrated with other management systems.

The authors Christoffersen et. al and Ates e Durakbasa [55, 56] associate energy management with certain procedures for energy savings (training, controls, goals, plans, estimates, communications, evaluations, etc.) that companies can adopt. Lee et.al and Gordic et.al [57, 58] suggest that energy management is multidisciplinary by nature, with engineering and management areas involvement, where its objective is to maximize energy efficiency in favor of competitive performance continuous improvements. In accordance with Kannan and Boie [59], energy management is a continuous improvement system, with the use of planned procedures, periodically reviewed. Energy management is related to control activities, monitoring and improving energy efficiency [9].

In contrast to Amundsen [54] and Vikhorev et. al [60] declares that the industrial energy management is context specific, depending on local factors such as product design, process choice, national energy matrix, among other factors. This latter approach means that it is difficult to replicate solutions for industries and different locations, requiring a plan-do-check-act (PDCA) approach.

What types of practices are being investigated and what are its difficulties? The authors Fawkes and Jacques [61] in studied energy management in terms of consumption monitoring intervals, existence of goals and control by cost centers. Of the 49 beverage companies, 11 companies practiced energy management. The work of Christofersen et. al [55], through a survey, investigated 304 industrial companies in Denmark, they concluded that between 3% and 14% practice energy management. With regard to the reasons, 76% are motivated by costs. To be energy management practitioners, the companies would have to employ the following requirements: (i) Implement energy policy; (ii) Establish quantitative energy management and energy saving projects implementation goals; (iii) Implement specific energy saving projects originated from energy management. They would also have to employ at least one of the following requirements: (i) Specific procedures for the energy efficient purchase; (ii) Organize energy activities by clearly allocating responsibilities and tasks; (iii) Engage employees in energy saving, informing, motivating and educating.

The research of Thollander and Ottosson [62] in the paper/pulp and foundry industries in Sweden has identified that energy management is not a major activity. They have found a payback criterion of up to three years. Success factors for energy management are: Senior management support, strategic approach, initial energy audit, energy consumption monitoring, energy policy, energy management project follow-up, training and motivation of support staff. In the work of Ates and Durkbasa [56], only 40% of the studied companies have a formal energy policy, concluding that 24% of companies practice energy management. A major problem identified is the position and task of the energy manager, generally in an administrative position. Even for energy-intensive companies, energy management is not discussed at a strategic level [56, 63].

What kinds of frameworks have been proposed for energy management? As reported by Bunse et. al [4], there is a need to develop decision making frameworks. Frameworks in the area of energy are scarce. The 1980s work of Consonni and Lesourd [64], was concerned with developing an accounting system to reveal the costs and benefits of energy savings. Some authors have used game theory approach considering industry and environments as competitors Aplak and Sogut [65] and others apply data mining approaches in the development of an energy management system using flow diagrams, discriminant analysis and regression analysis [66]. In the IT industry, Lee et.al [58] identified that 80% of companies (out of 66) lacked appropriate energy management functions, the authors propose a real-time monitoring system.

The proposals of Kannan and Boie [57, 67] develop a continuous improvement process for energy management. There are four phases: (i) Energy Audit; (ii) Identification of EEMs; (iii) Implementation of EEMs; and (iv) Evaluation and Monitoring [57]. For a bakery in Germany, the expected reduction in energy consumption was 6%. The system begins with the definition of an explicit energy management policy, energy audit, action plan, implementation and performance evaluation [67]. The improvement occurs in six pillars of the energy management matrix: Policy, organizational structure, motivation, monitoring, awareness and investment. After the system installation in an automobile factory, there was approximately 25% reduction in energy consumption in the 2005-2008 periods [67].

4.1.4 Energy Policies

What types of policies can be adopted by governments? Did the energy policy actions give the expected results? The need for an industrial energy policy mainly comes from the presence of inefficiencies and information asymmetries [68]. The policy for efficiency and industrial energy management is presented in three groups Tanaka [69]: (i) Prescriptive (equipment efficiency regulation, process configuration and efficiency regulation, energy management regulation, agreements); (ii) Economic (Energy costs, direct reduction of energy consumption costs, direct financial incentives, cap and trade schemes, energy cost discrimination); and (iii) Support (identification of energy efficiency opportunities, cooperative measures, training and capacity building). Another issue brought up by Tanaka [69] is if boundaries are not defined for the performance of energy policies, there may be differences in the measurement of results.

The results of energy policies are not always simple to assess due to direct (reduction of energy consumption) and indirect effects (non-energetic benefits such as improved productivity). In the study of Rietbergen et .al [70] in Netherlands, between one-quarter and one-half of energy savings are attributed to long-term agreements. Although there is a low priority in small and medium-sized enterprises, the Highland program had a 40% adoption in Sweden.

Some articles analyze specific programs potentials and gaps in several countries. In New Zealand, compressed air systems programs have some gaps Neale and Kamp [71], like new instruments and procedures for airflow analysis, air leak detection, data analysis training, and detection of energy saving opportunities.

The potential of the Chinese program to reduce the energy consumption of the 1000 largest Chinese companies is enormous, Price and Wang [72] estimates a reduction of 148 Mtce (4.3EJ), which is equivalent to Poland CO2 emissions. Evaluating energy audit programs also in China, Shen et.al [73] identify gaps that need to be improved: long-term policy mechanisms, national organization, corporate motivation, limited technical scope, economic feasibility analysis, proper incentives, standardization, energy assessment tools, and training. Brown et.al [74] identifies that a CHF (Combined Heat and Power) fiscal stimulus policy could generate a return several times higher to the investment made in the United States.

The European 2020 goals of reducing energy consumption by 20% by 2020, was analyzed by Thollander et. al [75] for Sweden's industrial sector, concluding that the adopted measures (voluntary agreements, long-term agreements, energy audit programs) would not be sufficient to meet Sweden's goals. According to the authors, the goal can be achieved by three factors: energy management, energy efficient technologies (EETs), and energy supply measures.

4.1.5 Other related factors to energy efficiency

The works of Pye and McKane, Haman and Worrell et. al [76, 77, 78] identify, the non-energetic benefits of energy efficiency, e.g. productivity increase, pollution reduction, costs reduction, among other benefits. The work of Rogerio et.al [79] analyzes self-generation in a Brazilian aluminum industry, which has been identified as a viable competitive strategy.

A set of three works Yu et.al, Zampou et.al and Viklund et.al [80, 84, 81]) proposes computerized systems for the monitoring of consumption and energy efficiency.Regarding technologies, Worrell and Biermans [82] assumes that energy intensity can be reduced by replacing equipment or by retrofit. Napp et.al [83] reviews the technologies for reducing CO2 emissions and Viklund et.al [84] technologies to use excesses to reduce CO2 emissions.

4.2 Quantitative Measurement of Energy Performance

What is energy efficiency? What is energy performance? How can energy performance be measured? Basically, it can be understood that energy performance is related to the measurement of energy efficiency indicators. It must be emphasized that energy efficiency is not the only variable to be controlled in the measurement of energy performance, since that Vikhorev et.al [60], industrial energy management is a context specific. In this way, it may be necessary and feasible to measure the performance of the so-called associated resources consumption such as water, energy-intensive materials use, pollutant emissions, and many others, depending on the local production conditions and processes. As perceived by Soytas and Sari [85], the relationship between production and energy was not always clear due to the marginalization of this input as a production factor.

A first issue is the definition of energy efficiency. According to Patterson [86], who appears among the main co-citations and citations presented in Charts 1 and 2, energy efficiency is a generic term and there is no quantitative way of measuring it without incurring in some kind of assumption. In general, greater energy efficiency is associated with less energy consumption to produce the same amount of good or service. Energy efficiency can be measured as the ratio (useful output of process / energy input into a process). The investigation of Patterson [86] indicates that the variables selection that compose the indicator can fall into four types of indicators: (i) thermodynamic; (ii) physical thermodynamic; (iii) economic thermodynamic; and (iv) economic. For Phylipsen et al [87], the indicator also consists of a numerator and denominator relationship, denoting the existence of two types of indicators: economic and physical. Based on Phylipsen et al [87], two commonly used indicators are: (i) Energy Intensity (EI), in which the numerator is a thermodynamic energy variable (Joule, kilocalorie, among others) and the denominator is a variable of production measured in economic terms; (ii) Specific Energy Consumption (SEC), where the numerator is also a thermodynamic energy variable, the denominator is measured in terms of physical production (tonnes, km, among others). It is recognized that these indicators practically measure the inverse of efficiency, because the ideal situation is to not use the indicator [87].

The International Energy Agency (IEA) reports are among the most cited according to Graph 2. Some points still need to be clarified due to doubts about energy efficiency indicators. The first issue is that energy performance has several dimensions, where indicators of a specific process can be created for the industrial system as a whole. For the IEA, the amount of energy consumed divided by the activity or product is an indicator of energy intensity. Generally, the value of the activity / product variable is given in monetary values. This definition is in accordance with the ones given by Patterson and Phylipsen et al [86, 87] with the exception that the more an energy intensity indicator is aggregated (several industrial fields) the more the indicator becomes an energy efficiency approach because other factors are becoming relevant (structure of the economy, type of industry base, exchange rate, affordability of energy services, size of a country, climate and behavior). For aggregated indicators, the IEA uses decomposition indices for energy consumption, generally separating into three effects: (i) Activity (economic activity); (ii) Structure (mix of activities / processes within a sector); and (iii) Energy Intensity (energy efficiency) [1]. The most known algorithm of decomposition is the Logarithmic Mean Divisia Index (LMDI), which was developed by (Ang, W.B.), this author also appears among the most cited in Graph 2.

Another difference that causes confusion among the authors is the differences between energy efficiency and energy conservation. Energy conservation refers to a change in lifestyle, generally not consuming a particular product / service. Energy efficiency is related to the consumption of the same energy-saving product / service, i.e. the use of EEMs measures for energy efficiency (technology, energy management, energy policy) [1, 46].

Several works in the SRL seek to develop ways to measure energy performance, creating a particular category, which is concerned with the measuring ways. The authors and categorization of themes can be seen in Fig. 3.

The works of Boyd et. al and Boyd [89, 90] make empirical estimations of the best observed performances, i.e., an empirical distribution of efficiency based on the differences between the best estimated practices (as each plants distance from the frontier). The estimation of the frontier in this model is done by the Stochastic Frontier Analysis (SFA), in which two forms of improvements are possible: best practices and efficiency changes. The Olanrewaju et.al [91] model creates an energy performance indicator (EPI) to compare industrial plants in the USA, which is given the Energy Star label for the most efficient plants.

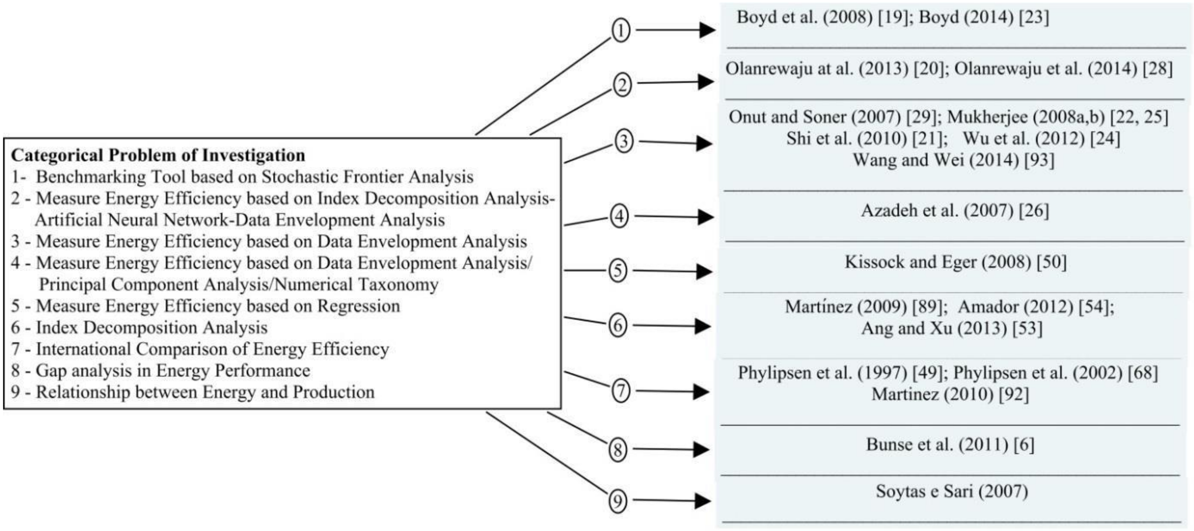


Fig. 3. Category of quantitative performance.

For energy analysis, Boyd and Olanrewaju et.al [90, 91] integrate the decomposition methods Index Decomposition Analysis- Logarithmic Mean Divisia Index (IDA-LMDI), Artificial Neural Networks (ANN) and Data Envelopment Analysis (DEA). The idea of the model is to use the DEA to compare the expected energy consumption (from the effects of the decomposition estimated by ANN) with the observed consumption. The work of Olanrewaju et.al [92] presents an approach based on DEA, principal component analysis (PCA) and numerical taxonomy (NT) for the evaluation of total energy efficiency. The application is made in Iran and in some other OECD countries using aggregate data. Azadeh et.al [93] presents a method for the measurement of the energy saving based on regression using temperature, production and energy consumption as variables.

According to Bogetoft and Otto [94], the DEA is a method that comes from mathematical programming and management science. Several SRL works employ DEA to analyze energy efficiency. Onut and Soner [5] estimates the efficiency of medium-sized companies (50-250 employees) in Turkey using DEA. The main difficulty was the data collection (electricity, gas, oil, LPG and annual sales) that was done through a questionnaire. Bogetoft et.al and Mukherjee [95, 96] uses DEA to measure energy efficiency in US manufactures and Indian manufactures in different states. The intertemporal boundary was also analyzed. The works of Shi et.al and Mukherjee [6, 97] use DEA with unwanted outputs (C02 emissions) in some regions of China. Finally Wu et.al [98] applies DEA to evaluate energy savings as well as emission efficiencies of the 30 largest Chinese industrial sectors.

The previously mentioned IDA-LMDI decomposition approach was used by Charnes et.al [99] to evaluate the effect, structure and intensity effects between Germany and Colombia. Comparing the exports energy content from 30 industrialized and developing countries, Wang and Wei [100] uses the EIO matrices and the IDA approach.

The objective of Phylipsen et.al ,Martínez and Amador [87, 101, 102] was even broader, to compare energy efficiency between countries. They present a methodology that eliminates the structural problem (mix of activities and products within a sector) between countries to compare energy efficiency indicators [101].

The review by Bunse et. al [9] investigates energy performance in production management, noting that the existence of energy efficiency indicators is limited at the national and sectorial level. The industry needs standardized energy efficiency metrics at the machine, process and plant levels. There are also systems for benchmarking, continuous process measurement technologies, conceptual frameworks, and computational visualization mechanisms for the indicators.

4.3 Sustainable Inter-Firm Relations

The reason of most of the articles that study energy efficiency focusing management is directly or indirectly related to the three pillars of sustainability (economy, environment, and social). The Sustainable Inter-Firm Relations category, in which the main authors and research topics can be observed in Fig. 4, is the understanding that the problem of efficiency or energy management is not a problem of a company and that energy performance may be greater in a sustainable collaborative process involving several actors with similar interests, such as reducing energy consumption, emissions, and increasing efficiency, among others [54].

Gutowski et. al [103] concludes that major global companies like Sony, Toyota, Hitachi, Volvo, Daimler, Chrsler, IBM, Motorola, Ford and Dupond are really worried about environmental issues, being their main concerns energy conservation, waste disposal, and water use. The questions that emerge are: What kinds of concepts and techniques have been used to study energy efficiency in this research category? In which cases has this technique been successful?

The presented concepts refer to the relationship of more than one company, where it can be a chain or a group of companies working in harmony. The general idea is that the complexity is increased, since each participating actor in this category has the same problems identified in the previous categories. The survey by Duflou et.al [104] identified environmental impact reduction technologies and methodologies at five levels: (i) Unit / machine process (machine redesign, selective control, optimization); (ii) Multi-machine (energy reuse, peak control); (iii) Factory level (energy flux simulation system, layout, building standards, facilities); (iv) Multi-factories (Co-location / Industrial Symbiosis / IS, use of input-output analysis); and (v) supply-chain (regional energy generation, location, climatic conditions, use of Life Cycle Analysis/LCA).

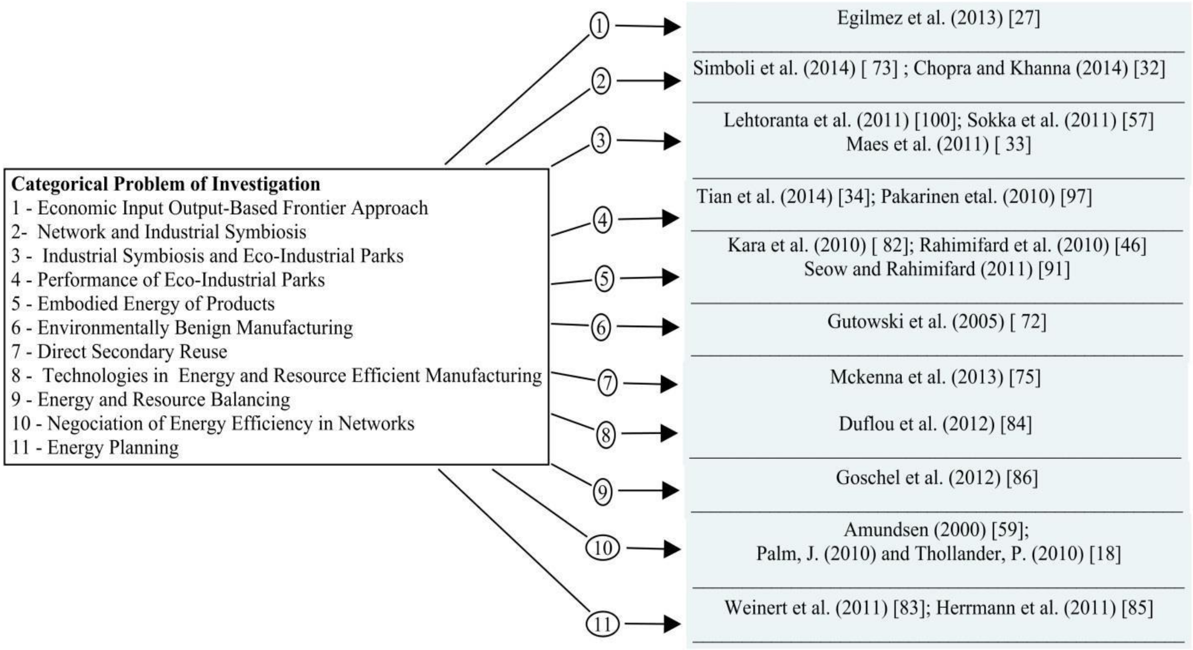


Fig. 4. Category of sustainable inter-firm relations.

One of the first emerging concepts is the Industrial Symbiosis (IS), being a concept of Industrial Ecology, it uses a systemic approach to study the physical flows of materials and energy of a local industrial system. Another similar concept is Eco-Industrial Parks (EIP), which has the same propositions, but it has a broader concept, and may involve service providers [105, 106].

Two energy data analyses techniques used and recognized by several authors are life cycle analysis (LCA) and economic input-output (EIO) or input-output analysis (IOA). The LCA according to ISO 14.040 is a compilation and evaluation of the inputs / outputs and the potential environmental impact of the productive system in its life cycle. The IOA is a matrix approach developed by economist Leontief for economic planning.

In the literature, some papers have dealt specifically with IS and PIDs together. In the analysis of a motorcycle industry in Italy involving a large company and 18 small and medium enterprises, Lehtoranta et.al [107] showed that without the development of IS, inefficiencies would be present (e.g. waste, obsolete machines and management of scraps). One of the most cited examples of EIP is Kalundborg in Denmark which operates as an IS system. Using a social networking approach, Tian et.al [108] investigated resilience (the ability of the system to absorb disruption while maintaining its structure and functionality) and they found that Kalundborg has increased its resilience over time. Another EIP is the Kymenlaakso in Finland, it was studied by Simboli et.al and Chopra et.al [109, 110]. They developed a historical analysis in the 1890-2005 period, noting increased sustainability through increased consumption of renewable resources, recycling and waste utilization [110]. The study by Simboli et.al [109] using LCA analyzes the use of fuels and energy, findind that the Kymenlaakso park is not carbon neutral, since most emissions come from outside the system. In Belgium Pakarinen et.al [111] analyzes an experimental EIP composed of 92 SMEs, which have a sharing energy production system. Performance analysis of 17 EIPs in the period (2005-2009 / 2007-2011) was done in China. It was found that economic and environmental performances were improved [106]. All 17 EIPs had improvements in resource consumption and energy intensity. Although there is the possibility of improvements in the water use and wastes (liquid solids). Although the energy intensity has improved, the total amount of energy consumption increased from 13.62 million tces (tons of coal equivalent) to 16.39 million.

Another studied concept involving more than one company is the embodied energy in the products/services (EPE). A model for assessing the impact of global manufacturing on embodied energy in the product life cycle is presented by Sokka et.al [112]. The IOA method was used to model the embodied energy in each manufacturing supply chain. The factors that affect the embodied energy are: (i) Weight of the raw material; (ii) Used energy to extract and process the raw material; (iii) Distance from the extraction site to the manufacture; and (iv) Mode of transport used.

The works of Maes et.al and Kara et.al [113, 114] develop a model to represent the total energy required to manufacture one product unit. It uses a simulation model to make decisions about energy consumption in the product life cycle. A distinction that these authors make is in relation to direct energy (energy used by the various processes to manufacture a product) and indirect energy (energy consumed by the activities to keep the production environment functional, e.g. ventilation systems, lighting, among others). The authors acknowledge that the model does not really show how much energy is required to manufacture a unit of the product, but aids in the analysis by identifying energy consumption reduction factors.

Another concept used is Direct Secondary Reuse (DSR). The DSR is defined as the reuse of an product at the end of its life cycle without destroying the basic structure of the product [115]. The authors conclude that for Germany's automotive industry the energy savings with DSR practice would be approximately 3% to 6%.

A mathematical method for the balance of energy and resources was developed by Seow et.al [116], based on a systematic detection system of materials and energy flows. Mckenna et.al [117] present an energy planning scheme for the life cycle of the plant, of the equipment and the value chain. The Goschel et.al [118] developed a simulation model for the manufacturing system that includes the energy flow and its subsystems. With a sectorial approach, Weinert et.al [119] combined the EIO-LCA approach with the DEA to analyze the sustainable performance of the US manufacturing industry, creating an eco-efficiency indicator.

A contextual socio-technical view is offered by Herrmann et.al [120], where energy efficiency does not only depend on specific technological or practice issues, but also on discussions, negotiations and agreements developed in a network.

5 Discussion

This paper presented the results of an SRL in the field of industrial energy efficiency through the application of a process model developed in Perroni et. al [15], which is based on content analysis [16]. According to Tranfield [12], the objective of a Systematic Review is to present answers to several ex-ante questions that will guide future researches: Who are the most cited authors? Which research institutes and departments are the authors from? What are the identified key themes and keywords? What methods and techniques are used in the studies? Session 3 of the paper presented answers employing a graphical analysis and session 4 shows the main contributions and the results of each categorical group.

The first issue to be discussed is: Does industrial energy efficiency really represent a field of research? Graph 1 shows a network of citations where the density of the network is 34%, meaning that the connections are one third of the maximum possible among the 100 most cited authors. If the density of the network were close to zero, doubts would be raised if industrial energy efficiency could be a field of research. Apart from being a field of research, analyzing Graph 1, Graph 3 and Graph 4 it is possible to affirm that the interest can be divided into three categorical segments: Energy Efficiency/Management, Quantitative Performance and Sustainable Inter-Firm Relations. Each of these categories are developed with particular concepts and techniques, according to the network of themes in Graph 3. Graph 3 makes it easy to visualize the most central themes of each group: Energy Efficiency/Management (EEMs and Energy Management), Quantitative Performance (DEA, Energy Performance) and Sustainable Inter-Firm Relations (Sustanability, LCA, Industrial Symbiosis, EIO).

Since industrial energy efficiency represents a field of research, which area of study does it belongs? Graph 7 reveals a multiplicity of research approaches and techniques. Graph 8 shows that the number of institutions that authors and co-authors declare to belong is greater than the number of articles in the corpus, 107 against 104. Graph 9 reveals that the 104 articles come from 83 different departments, the most central being from Engineering, Management and Sustainability. Based on Graph 7, Graph 8 and Graph 9, although the existence of some central areas such as Mechanical Engineering and Management, one can understand that the field of industrial energy efficiency it is by its own nature multidisciplinary.

Section 4 presented the contributions and results of the 104 identified in the SRL. Through an ex-post analysis, it was possible to establish a series of questions considered in the identified categories and subcategories (Fig. 2, Fig. 3 and Fig. 4).

The energy efficiency and management category was grouped in five sub-categories, as can be seen in the Figure 2. The Graph 2 summarizes the answers of the proposed questions to represent this category.

EPQ1	• ***Why study energy efficiency?*** Scarcity of nonrenewable resources, environmental impacts, best practices implementation versus reality, constraints, drivers [**22, 23, 36]**.
EPQ2	• ***What are the main factors or constraints of energy efficiency?*** Technological innovation, access to capital, energy price, project cost, hidden costs, cost of obtaining information, payback, conservation projects, government support, energy audit, housekeeping, energy flow monitoring, bechmarking, subsidies, support of top management, training, subjective perceptions, self-motivation, lack of training, risk of production stoppage, lack of submeters, incentive division, unprofitable intervention, business continuity, long-term strategy, real ambition **[24, 25, 26, 27, 32, 37, 39, 41, 51]**.
EPQ3	***Which measures can be taken?*** Energy Efficiency Measures (EETs / EEMs) and Energy Policy **[1, 46, 47].**
EPQ4	• ***What is energy management?*** There is no precise definition of energy management. Energy management can be easily integrated with other management systems. Associated with procedures for saving energy. It is a multidisciplinary field which involves the engineering and management areas where its goal is to maximize energy efficiency to support continuous improvements. It is a continuous improvement system, which uses periodically reviewed planned procedures. It is related to control, monitoring and improving energy efficiency activities. It is a context specific, depending on local factors such as product design, process choice, national energy matrix, among other factors **[9, 53, 54, 55, 56, 57, 58, 59, 60].**
EPQ5	• ***What types of energy management practices are being investigated?*** Consumption monitoring, payback criteria, energy audit, role of energy manager, energy strategy, quantitative goals for energy management, control by cost centers, corporate energy policy, objective concerns about the implementation of energy savings projects, energy efficient purchase, allocation of responsibilities, employee training **[55, 56, 61, 62,63]**.
	What are the difficulties? 3% and 14% of industrial companies practice energy management, and 76% are motivated by costs. Energy management is not a major activity, even for energy-intensive companies, the energy management is not thought at a strategic level. There is a lack of a formal energy policy **[55, 56, 62, 63]**.
EPQ6	• ***What kind of frameworks have been proposed for energy management?*** Existing frameworks are scarce. Accounting systems to reveal the costs and benefits of saving. Frameworks based on analytical techniques such as game theory and data mining. Process framework for continuous improvement **[9, 57, 58, 59, 65, 66]**.
EPQ7	• ***What types of policies can be adopted by governments?*** Prescriptive (equipment efficiency regulation, process configuration and efficiency regulation, energy management regulations, negotiated agreements); Economics (Energy tax, tax for direct reduction of energy consumption, direct financial incentives, cap and trade schemes, energy price discrimination), and Suportive (identification of energy efficiency opportunities, cooperative measures, training and capacity building) **[69]**.
EPQ8	**Did the energy policy actions give the expected result?** In the Netherlands, between one-quarter and one-half of energy savings are attributed to long-term agreements. The Highland program had a 40% adoption in Sweden. Adoption of approximately 50% in the DOE-IAC program. Many energy policy gaps can be found as in compressed air systems, Combined Heat and Power, energy audit, among others **[28, 45 70, 71,72, 74]**.

Chart 2. Ex-post questions - energy efficiency and management group.

In accordance with the described methodology section, the aim is not to give static answers to these questions, but to offer a boundary situation. Analyzing the sub-categories it can be stated that the main reasons to study energy efficiency are environmental factors (Graph 6). Due to the energy efficiency gap [22] and the energy paradox [23] a series of empirical studies were conducted to assess the factors and constraints of energy efficiency. In short, the main identified factors are cost metrics (payback, cost, energy price, subsidies and support from the managers) [27, 28, 32]. The relationship between environmental factors and the energy performance usually are positive, although the relationship between energy efficiency and economic performance is doubtful Pons et al.; Zhang e Wang [34, 35]. The latter can be seen in the work of Eccles and Serafeim [126], which doesn't belong to this SRL but it shows deviations between economic performance and sustainability.

The authors of various articles that studied the limitations of energy efficiency could not have reached different conclusions, identifying that the main barriers are (cost and risk of production stoppage, lack of time, other priorities, cost to obtain information about the energy consumption of the purchased equipment, other priorities for capital investment, lack of sub-meters, incentive division with ESCOs [37, 38, 39]. Three factors are emphasized: lack of interest in energy efficiency, risk, and the need for support from top management [3, 38, 40, 41].

Some determinants (drivers) are also identified through the case studies, which agree with the results found by means of surveys: Energy price, need of personnel with real ambition, support of top managers, subsidies, among others [38, 39, 43].

Regarding the EEM, the work to be highlighted is Abdelaziz et. al [46], which indicates that the EEMs can occur in three different forms: technologies, energy management and energy policy. The first two forms (technology and management) can be influenced by the company, where the energy police can not.

With regard to the energy management sub-category, it was sought to establish a management concept of the efficiency and energy management category. Different authors have different concepts. An aggregate concept that in essence does not contradicts this systematic review can be used: Energy management is naturally multidisciplinary and involves engineering and management areas, where its specific role is to control, monitor and promote energy efficiency improvements [9, 58, 60].

The authors of articles that sought to empirically investigate energy management, even with a narrow scope of what will become energy management, as well as the category of energy efficiency found results below what was expected, i.d. a low number of energy management companies [55, 56, 62].

In the literature review of Bunse et.al [9] the found energy management frameworks were scarce. In relation to our systematic literature review, we can confirm this result and add that the proposed frameworks are based on the PDCA [57, 58, 59]. A relevant question is that at some point of the PDCA, the energy audit is introduced. Energy audit is a technique recognized by several authors [9, 57, 58, 59]. An open question is: Considering that the energy audit is recognized by many cited authors, which are responsible for identifying the EEMs, why there is a scarce amount of work on how to proceed to perform an energy audit? An assumed hypothesis is that energy management is context specific, therefore energy audit procedures would be more useful for specific cases.

Although energy policy is not part of an isolated company's decision, it is the third way to save energy according to Abdelaziz et al. [46].One of the main proponents of energy policies and the most cited and co-cited authors of Chart 1 and Chart 2 are the works of Tanaka [68], which identifies the facilitators and forms of specific segment incentives in macro and micro policies. Some articles appear to disseminate the results of some energy policy actions as in Rietbergen et.al [70], which report that between one-quarter and one-half of energy savings are attributed to long-term agreements in the Netherlands. The Highland program in Sweden has a 40% adoption rate for SMEs. Although allocated to the category of energy efficiency, the work of Anderson and Newell et.al [27], also reached approximately 50% of adoption to the DOE-IAC program in the United States. The work of Price et al, Shen et al, Brow et al and Thollander et al [72, 73, 74, 75] identified energy policy gaps in China, USA and Sweden, i.e. energy policies can be greatly improved.

In the quantitative performance measurement category, the aim was to clarify the concept of energy efficiency, energy performance, energy intensity and specific energy consumption. The ex-post questions for this category can be seen in Chart 3. The energy efficiency indicators studied by IEA, Patterson and Phylipsen et.al [1, 86, 87] are seen in the efficiency literature as Key performance Indicators (KPI) [95].

Some studies in the energy performance category seek to develop more sophisticated models for measuring energy performance beyond KPI measurement. Two sophisticated techniques used in the literature are SFA [89] and DEA. It is important to note that the DEA data envelopment analysis is used and integrated with other techniques in several studies [5, 91, 93]. Graph 2, Graph 4,Graph 5 and Graph 6 reveal that the preference for DEA to measure energy efficiency or performance is not by chance since the word DEA appears among the most important, and one of its proponents, Olanrewaju et.al [92], is among the most cited authors in Graph 2.

EPQ9	• ***What is energy efficiency?*** There is no quantitative way of measuring energy efficiency without assuming some kind of assumption. Greater energy efficiency is associated with less energy consumption to produce the same quantity of good or service and can be measured by the ratio (*useful output of process/energy input into a process*)**[86]**.
EPQ10	• ***What is energy performance?*** In energy performance, the energy efficiency indicator is not the only variable to be controlled, it may be necessary to measure the performance of so-called use of associated resources such as water, use of energy-intensive materials, pollutant emissions, as well as many others **[60]**.
EPQ1	• ***How is energy performance being measured?*** *Energy Intensity (EI), Specific Energy Consumption (SEC), Stochastic Frontier Analysis (SFA), Data Envelopment Analysis (DEA). Logaritmic Mean Divisa índex (LMDI). More applied techniques at the national or sector level* **[1, 87, 88, 89, 93]**.

Chart 3. Ex-post questions of the quantitative performance group.

Another factor to be considered in the measurement of energy performance is the development of IDA techniques such as the LMDI algorithm (developed by Ang [88], which has expressive citations and co-citations in Chart 1 and Chart 2). The LMDI was developed to separate the structure, content and activity effects, being applied at a sectoral or multisectorial level, similar to the technique presented in Phylipsen et.al [87] to compare energy efficiency between countries.

Briefly, for the energy performance category, almost all studies apply or develop techniques to use aggregated data at sectoral or national levels. Only the work of Onut and Soner and Boyd [5, 89] applied energy performance analysis in a disaggregated way, nevertheless, one of the main limitations identified by Onut and Soner [5] was in the data collection, where they had to elaborate a Questionnaire to collect it.

A crucial issue is that energy is not used in isolation by a factory or plant. Some studies were categorized as belonging to the sustainable inter-firm relations, where the ex-post questions can be seen in Chart 4. What differentiates this category is the development or use of concepts and techniques involving more than one actor (company). The idea behind this categorical group is that, having common interests, the synergy produced by the interrelation of the parties brings a better benefit or performance than in a condition of individuality.

EPQ12	***• Which concepts and techniques have been used to study energy efficiency when more than one actor (inter-relationship between companies) is involved?*** *Industrial Symbiosis (IS), Life Cycle Analysis (LCA), Eco-Industrial Parks (EIP), input-output analysis (IOA) Embodied Energy of Products (EEP); Direct Secondary Reuse (DSR)* **[106, 107, 112, 114, 117]**.
EPQ13	***• Has the relationship between companies been successful in energy efficiency?*** *Without the development of Industrial Symbiosis, inefficiencies in (waste, obsolete machines and management of scraps) would be present. Increased resilience over time, increasing sustainability through increased consumption of renewable resources, recycling and waste utilization. Improvement of economic and environmental performance* **[108, 109,110, 111 117]**.

Chart 4. Ex-post questions of the sustainable inter-firm relations group.

The main concepts involving a set of actors are the Industrial Symbiosis and the EIPs [108, 111, 112]; the concept of energy embodied in EEP products [114, 115, 116]; and the DSR concept. The results of the studies that analyze SIs and PIDs confirm energy savings beyond other resources, but with potential to be developed. Another issue raised is that the mainly energy-related studies of PIDs appear to be limited to a few cases such as Kakundborg and Kymenlaakso with the exception of

China's cases identified by [108]. The DSR concept was considered viable since it was possible to reduce energy consumption in Germany by Tian et.al [117].

Basically, two techniques can be highlighted as the main ones for the energy performance analysis integrated in this category. The EIO [106, 119] and the LCA [106, 112],which can be integrated [117].

5.1 Meta-Analytic framework for measuring integrated energy performance

It can be summarized that the three categorical groups identified in the industrial energy efficiency literature have distinct concerns that can be integrated into a framework of meta-analytical processes. According to the definitions of Shehabuddeen [57] "*The framework supports understanding and communication of structure and relationship within a system for a defined purpose*". According to Shehabuddeen [57],"A process is an approach to achieving a managerial objective, through the transformation of inputs into outputs". Based on the work of Patterson [86] a performance indicator comes from the ratio (useful output of process / energy input into a process). From the definitions, one question that can be asked is: How to integrate the three groups found in the literature in the form of a process framework to represent energy performance?

It can be summarized that the categorical group of energy efficiency and management (Fig. 2) has concerns about the dynamics of the energy performance of processes, studying how energy performance can be affected by different internal and external factors (technologies, policies, management decisions, behavioral factors, among others) to the organizations' process (dynamics). The quantitative performance group (Fig. 3) looks for ways to objectively measure energy efficiency or savings (performance). The sustainable inter-firm relations group (Fig. 4) seeks to demonstrate the advantages of saving or energy efficiency when different processes (companies) are aggregated (structure). Fig. 5 presents the meta-analytical process framework for measuring integrated energy performance.

It can be perceived that the proposed framework is meta-analytical, since it does not directly integrate the articles, but rather integrate the contributions of the groups of articles identified in terms of the relationship (dynamic-structure-performance).

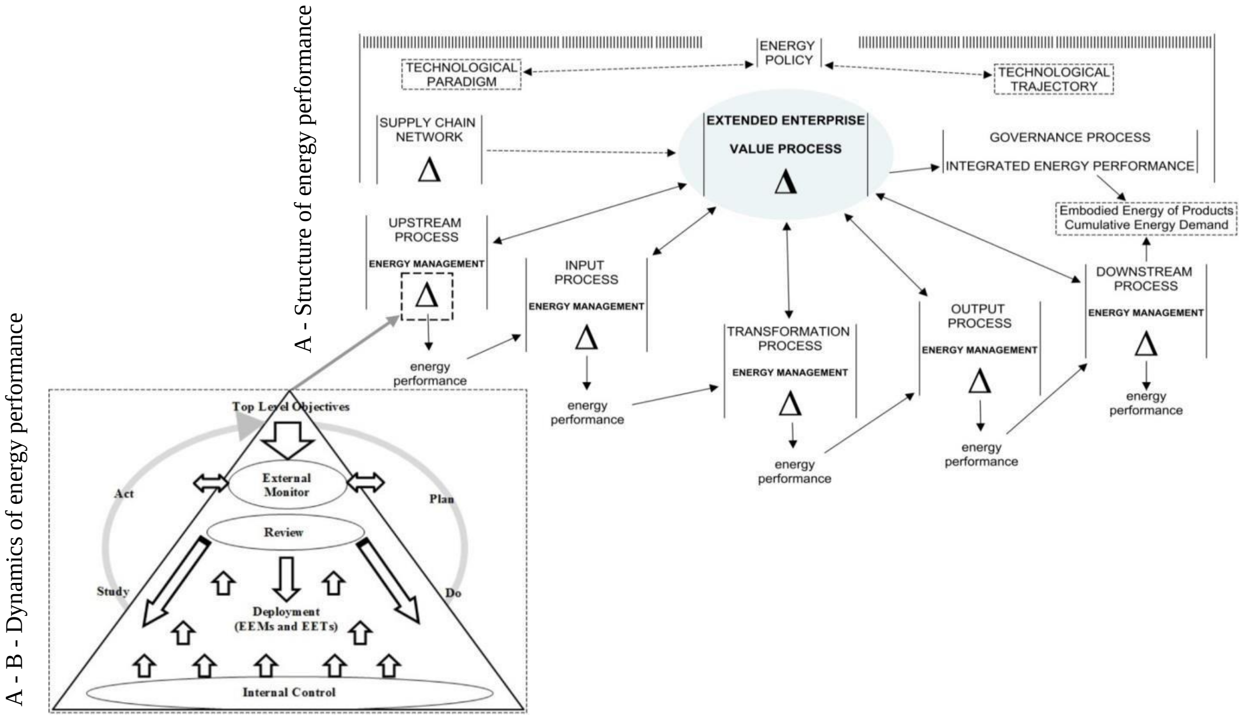


Fig. 5. - Meta-Analytic framework for measuring integrated energy performance
Source: Modified from Bititci et al. (2000) and Perroni et al. (2014) .

The framework is assembled in two blocks, the first one (Fig. 5a) describes the structure of energy performance and the second one (Fig. 5b) describes the dynamics of energy performance. In this framework, performance is determined by the relationship of the dynamics with the structure. Based on the sustainable inter-firm relations group (authors of Fig. 4 and Chart 4), the energy performance in its integrated form occurs in the process network, or otherwise in the Extended Enterprise (EE). The EE concept was first presented by O'Neill and Sackett [125], creating a new governance structure. Some concepts and techniques are identified by the sustainable inter-firm relations group to study energy performance in EE processes, such as Industrial Symbiosis (IS), Life Cycle Analysis (LCA), Eco-Industrial Parks (EIP), input-output analysis IOA) Embodied Energy of Products (EEP); Direct Secondary Reuse (DSR) [107, 106, 111, 117, 120]. Each EE process in Fig. 5a has a specific energy performance that can be calculated in several ways according to the performance group: Energy Intensity (EI), Specific Energy Consumption (SEC), Stochastic Frontier Analysis (SFA), Data Envelopment Analysis, Logarithmic Mean Currency Index (LMDI) [1,87, 89, 93, 102, 120].

The dynamics of the energy performance of each EE process in Fig. 5b is represented by the performance dynamics of Bititci et. al [6] where a performance measurement system has to have: (i) strategy aligned objectives; (ii) external monitoring; (iii) review; (iv) implementation; (v) internal control; and (vi) continuous improvement. The dimensions of energy performance dynamics can be found based in the management and energy efficiency group, but specific articles can be mentioned: recognition of the role of top management [30, 32], factors identification [36], identification of EEMs and TSEs that can actually be implemented [121,122], recognition of continuous improvement system and perception of energy audit as a system [57, 59].

Energy policy [123] and technologies [78] through technological paradigms and trajectories [124] can be considered the most important external variables to be analyzed since they can directly impact the performance.

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APÊNDICE J

APÊNDICE J: ARTIGO 5 - PROPOSAL OF A MODEL FOR EVALUATION OF INDUSTRIAL ENERGY PERFORMANCE: FROM ENERGY EFFICIENCY TO EFFECTIVENESS

CONGRESSO – 7th INTERNATIONAL CONFERENCE ON PRODUCTION RESEARCH, AMERICAN REGION, LIMA, 2014.

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Abstract

This paper aims to answer the way the Energy Performance can be measured in an efficient and effective manner through manufacturing processes, presenting and modeling the structure and the Learning Process of the Energy Performance, based on the integration of the literature review of Economic Approach to Performance, Performance Measurement Systems and Industrial Energy Performance. It was assumed that the most efficient way to measure the energy performance of processes is along the Extended Firm EF, taking as reference the energy consumption of end products and services. Energy Effectiveness was attributed to the level of maturity of the processes of energy management Extended Firm.

Keywords: Energy Performance, Performance Measurement Systems, Extended Firm

1 INTRODUCTION

By thermodynamic principles energy cannot be created or destroyed, but transformed, it is possible to transform one form of energy into another, for example, both solar radiation, wind force and the potential energy of water can be transformed into electricity. The bottom line is that this transformation has a cost, be it economic, social or environmental cost. Given the growing need for energy and the fact that the main sources are nonrenewable, exacerbated by energy price crises in the 70s, managing energy consumption is becoming an issue of sustainability [1, 2, 3, 4].

The manufacturing area has recently been the subject of interest in research, given both its demand for energy and the environmental impact of its use, is the energy-intensive sectors or not [5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. The energy performance of manufacturing output in terms of energy efficiency have to be considered simultaneously alongside other performance criteria such as cost, quality, flexibility and innovation [12].

Energy for this work can be classified as those used directly in production processes or to support this, usually referring to secondary sources classified in the National Energy Balances as: Diesel Oil, Fuel Oil, Gasoline, Gas, Kerosene, Coal Coke, Electricity, Coal Plant, Alcohol, among others [15]. Although the central concern of the work is the energy performance of manufacturing production, given the interrelationship of manufacturing with the supply chain [16], the potential for energy savings is on integration of this relationship.

The fundamental question this article raises is: How does the energy performance can be measured, taking into account both efficiency and effectiveness in managing a manufacturing? Leaving the methodology lifecycle of research in Performance Measurement area [18], seeks to integrate the three seemingly distinct areas, but with noticeable connection points: Economic Performance, Performance Measurement Systems and Performance in Energy Approach.

Tackling the issue of research are presenting and modeling the structure and the Learning Process of the Energy Performance, based on the integration of the literature review of Performance Measurement Systems, Economic Approach to performance and Industrial Energy Performance, not just a single link be energy-efficient, therefore, a product or service may be considered energetically effective, if at all phases of its transformation process occurs at energy efficiency management.

The next session will discuss the methodology, following literature reviews proposals in the areas of Economic Performance, Performance Measurement Systems and Energy Performance. In the fourth part are developed the structure model and the process of the energy performance and finally the concluding remarks.

2 METHODOLOGICAL CONSIDERATIONS

In an update of the work [17], exactly a decade later [18], seeking to investigate the professionalization of the field of Performance Measurement, Neely [18] develops the evolutionary cycle of research in performance measurement, show in Figure 1.

In Figure 1, a natural starting point is early identification of the problem, given the consolidated problem for the proposition frameworks, these frameworks are tested in a practical way, the applications have brought new problems which in turn generate new theories and the cycle resumes. This model naturally emerges with a methodological model for the proposed frameworks. The intention is to propose a framework, because there is a problem where the interrelationships are not well delineated.

A problem that arises in the area of energy is the energy performance of manufacturing firms: How to measure the energy performance taking into account the efficiency and effectiveness of action? The fundamental issue is that the energy performance is not just linked to the individual manufacturing efficiency.

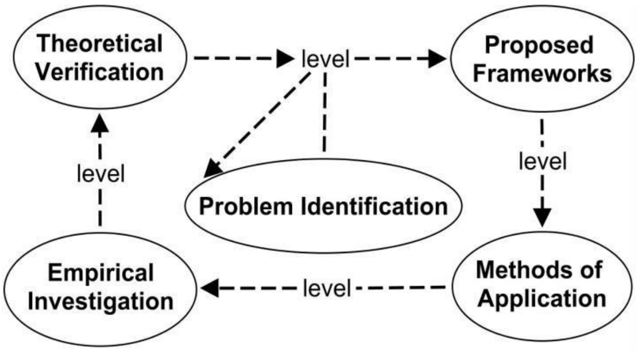

Figure 1: Methodological Approach

3 LITERATURE REVIEW

Three areas are the basis for the construction of the Framework for the energy performance of manufacturing: (a) Economic Approach of the Performance; (b) Performance Measurement Systems; (c) Energy Performance.

3.1 Economic approach to performance

The performance in the economic approach is seen in the theory of the firm, which had its developments in Industrial Organization from neoclassical propositions [19]. Basic Model of Industrial Organization, Paradigm Structure-Conduct-Performance (SCP) was developed by Mason [20], and resubmitted by Scherer and Ross [21]. Except Paradigm SCP, economic approach to performance is not an explicit approach. There is a need to analyze the Integrated Modern Theory of the Firm shown in Figure 2.

In Figure 2 the system is evolving. In stage 1 the Firm A strategically acts at a given moment in time, in a specific technological trajectory of the technological paradigm, through its resources/capabilities (based on the strategy), establishing the relationship with the market (Firm B) in a process of governance, choose the resources that will produce and the resources that will acquire the market. Firm does with full knowledge, considering the influence of bounded rationality. This process is path dependent, which means that decisions taken in the past are influencing the performance of present or future. Decisions can cause perpetuate of performance as a process of increasing returns imprisoning the market or not (Lock-in Effect). Stage 2 is a break from the stage 1, with a lapse of time usually larger and more unpredictable.

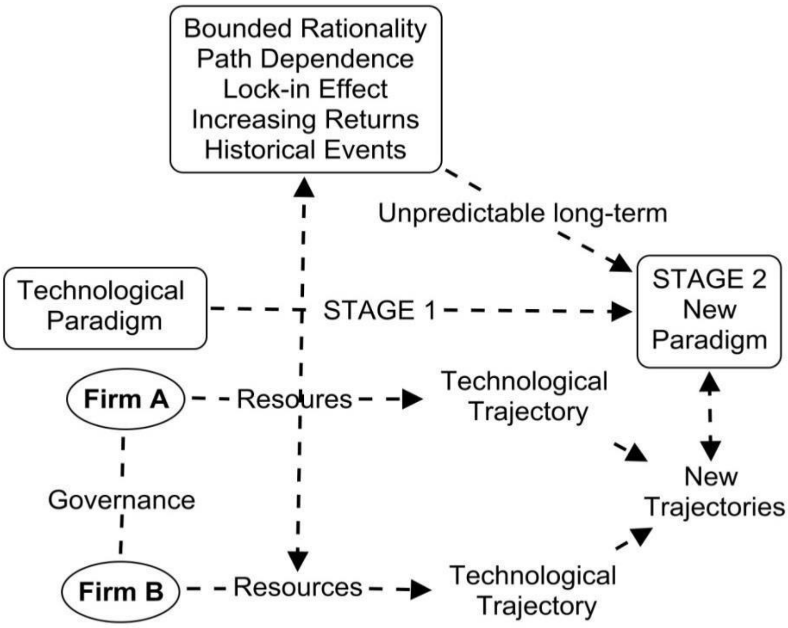

Figure 2: Modern Theory of the Firm

The transition to a new technological paradigm incurs significant reductions in both cost of production and transaction, which allows, in turn, the expansion of markets and the growth of firms, but in turn, the cost reduction does not come free because a new technological paradigm, there is usually more complex and requires different skills to manage a greater amount of information. This is a simplifying framework, since in practice there are overlaps between paradigms, trajectories and resources [22, 23, 24, 25, 26, 27].

Unlike traditional neoclassical theory, in the view of Figure 2 the performance of the firm is not only a corollary of the market structure, but the firm itself is responsive for its own decisions.

3.2 Performance measurement systems

By definition "a system of performance measurement can be defined as a set of metrics used to quantify both the efficiency and the effectiveness of action" [17]. A PMS can be seen both by the Process [28], and by its Structure [29].

In view of the process as Figure 3 [28], a PMS design [Step 1] involves identifying key objectives and measures which must be aligned with the strategy. The implementation phase [Step2] is related to the flow of information and data, which is necessary to process the data, and generate non-existent data. The use phase [Step3, Step4] is subdivided into two stages: In the first phase there is a review of the strategy in the second phase test of the validity of the strategy. Stages are not rigid and may in practice be an overlap, especially in the phases of design and implementation [28]. Another issue to be considered is that the process of developing a PMS is not linear, there is a process of revision or update separately in four mechanisms, when using, in fact the system: Review of goals, developing measures, review of measures and test strategy [28].

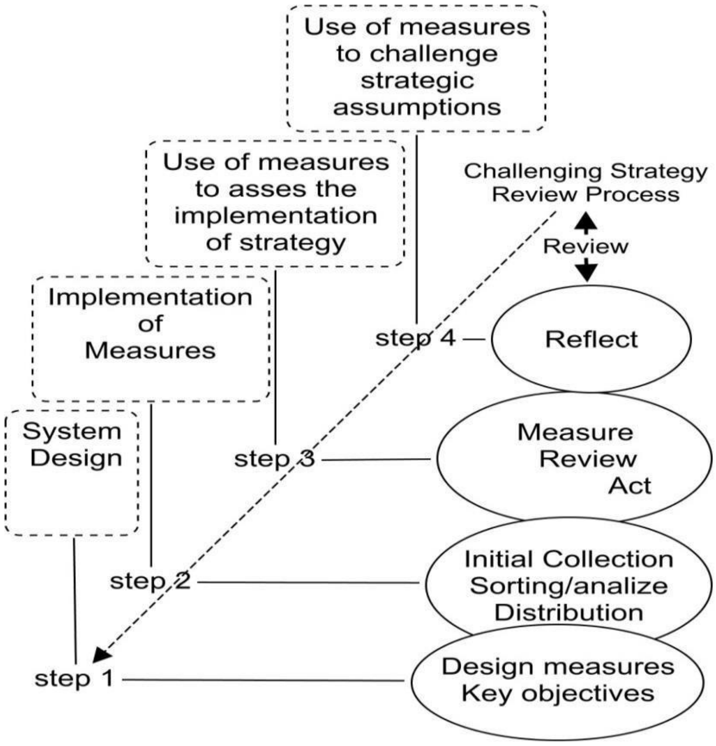

Figure 3: Performance Measurement System Process

Based on the view of structure [29], an integrated model was developed, indicating the contents of a system for measuring dynamic performance, which can be seen in Figure 4.

According Figure 4 end [29] a dynamic PMS should have:

- External Monitoring System [monitoring the evolution and external changes];
- Internal Monitoring System [monitoring the evolution and internal changes];
- Review System [use of internal and external information to review the objectives and priorities];
- System Implementation [implement the revised objectives and priorities];

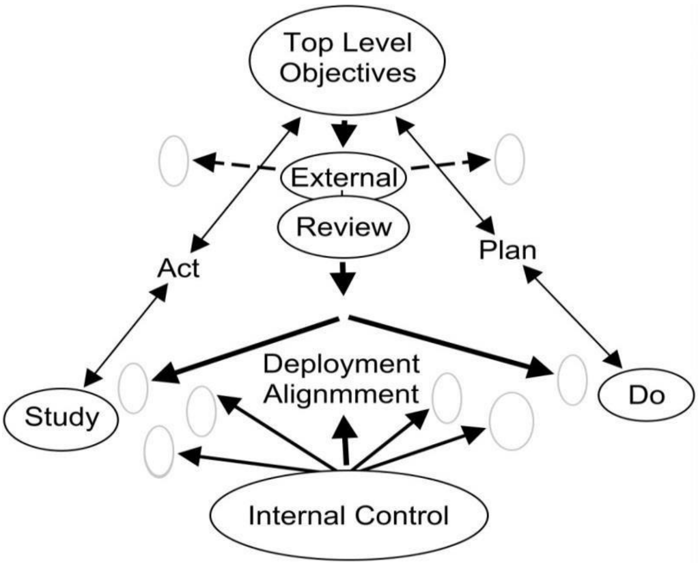

Figure 4: Performance Measurement System Structure

The framework developed by [29], is repeated throughout the organizational structure, processes and business units. Seen in this way, a change in any part of the organization is felt and passed on to other parties, the system is connected. The structure connects the planning [Plan] at the top decision makers to implementation based on [Do], based on this implementation the results are studied [Study] for further action [Act].

Once defined the process and structure of a PMS, a natural think is about how to manage the results. The performance management can be understood as a consequence of measurement and evaluation in subsequent periods, given the strategic objectives [30]. Performance management in its complete form takes the concept of Extended Enterprise or Extended Firm (EF) [31].

The result is not a consequence of an isolated firm, but a network of firms (Extended Firm) [31].

3.3 Performance in energy

The energy performance hereof, refers to the use of energy in the manufacturing production process, which brings the concern of much of the literature on energy efficiency [12].

Energy Efficiency can be defined as the quantity of services (lighting, heating, transport, etc.) provided by energy unit used. Thus the energy is related to the quality of a system or equipment. The performance here is related to the measurement of this quality [14].

In many cases an indicator of energy efficiency can be used as approximated factor measurement of this efficiency. This indicator is represented by a numerator and denominator (measuring activity versus measurement of energy consumption). Two general indicators of energy efficiency are: The economic (Energy Intensity) and physical (Specific Energy Consumption) [14].

The economic indicators are more applicable at an aggregate level and physical in disaggregated level. The energy efficiency indicators can be prioritized according to Figure 5. The closer the plant level, more data are needed to evaluate the efficiency.

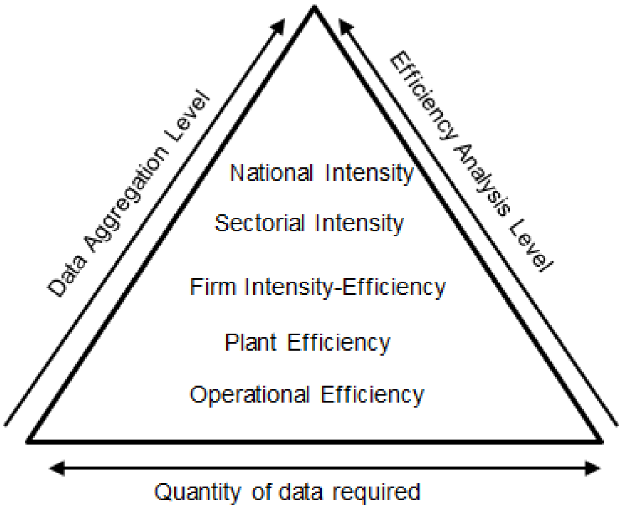

Figure 5: Energy Efficiency Indicator

Several works have been proposed to manage the energy performance of industrial processes.

A methodology for correcting structural effects, when industries in different countries are compared [14]. Conceptual Framework, for management end monitoring of energy [5,8]. Evolutionary Framework (Energy and Utility Management Maturity Model-EUMMM) based on CMMI (Capacity Maturity Model Integration) [9].

Guidelines for implementing an Energy Management System [13]. Guidelines for sustainable manufacturing in view of the flow of materials and energy [10]. Links the energy performance of the supply chain view of the consumer [6]. Simulation approach to quantify energy use throughout the supply chain [7].

Other model is IOPM (Input Output Process Model) [32], which can be used for evaluate the Energy Intensity. The model was used for understand energy efficiency in the manufacture of coke [33].

What connects these works is the concern with energy performance in terms of energy efficiency management. A new concept is the Energy Management Matrix (EMM). The idea of EMM is that there are several areas of decisions that can evolve over time, this development means that at each stage a new level of energy performance is achieved. Assuming a firm as a process, not necessarily the areas of decisions will be at the same level, or otherwise at the same stage of maturity as set forth in Frame 1 [9]. Energy Management, can be at different levels of maturity (Maturity Level). To move to the next phase, a maturation process is required (Maturation Fhase), and the last phase of maturity as a process of continuous improvement [9,13].

Frame 1: Matrix of different maturity levels - Characteristics, Process Area and Maturation Phase

Maturit yLevel	**Characteristics**	**Process Area**	**Maturatio nPhase**
1 Initial	✓ Organizations do not have energy management practice in place ✓ The energy management performance of organization depends on the competence and self-discipline of organizational members, not on implementation of management practices	✓ Not applicable	**Not applicabl e**
2 Managed	✓ Energy management requirements and manufacturing process requirements are managed, controlled, and measured ✓ Results of energy management practices are visible to management at certain points ✓ Commitment to sustainable manufacturing process is established among relevant stakeholders and is renewed when necessary	✓ Management of energy consumption ✓ Project planning should accommodate both basic product requirements and energy requirements ✓ Project monitoring and control of energy management practices in the manufacturing process ✓ Measuring and analysis should include a matrix for measuring energy management performance	**1 Energy management practice establishment**
3 Defined	✓ Organizations establish standard energy management process and procedures to achieve sustainably in the manufacturing practices ✓ Energy managements practices are consistently and proactively implemented and managed across the organization	✓ Energy consumption requirements are developed ✓ Technical solutions to problems on energy consumption ✓ Verification of the extent to which the manufacturing process satisfies energy consumption requirements ✓ Organizational process improvement bases on strengths and weaknesses of current organizational energy management ✓ Organizational process definition development to ensure consistency in the implementation of energy management practices across the organization ✓ Organizational training to maintain sufficient capability of organizational participants in implementing energy management practices or process improvement effectively and efficiently ✓ Decision analysis and resolution acting as a formal process to evaluate alternative solutions and satisfy energy consumption requirements	**2 Energy management practice standardization**
4 Quantitatively	✓ Organizations go through the energy management process efficiently and accurately, with standard quality and performance measurement controls ✓ Energy management performance data are collected, quantitatively analyzed, and evaluated against both internal and external benchmark data to identify causes of process variation	✓ Organizational energy utilization performance management	**3 Strategic environmenta lperformance management**
5 Optimized	✓ Quantitative environmental performance improvement objectives are set to address the causes of process variation, and processes area changed to improve energy management performance ✓ Continually improve energy management performance through both incremental and innovative technological improvements	✓ Organizational and innovation deployment to improve energy management performance ✓ Causal analysis and resolution for defects that negatively influence energy management performance	**4 Continuous improvement of energy management practices**

3.4 Summary of literature review

Figure 6 presents a summary of the literature review. The literature review is seen within a dimensional modular approach.

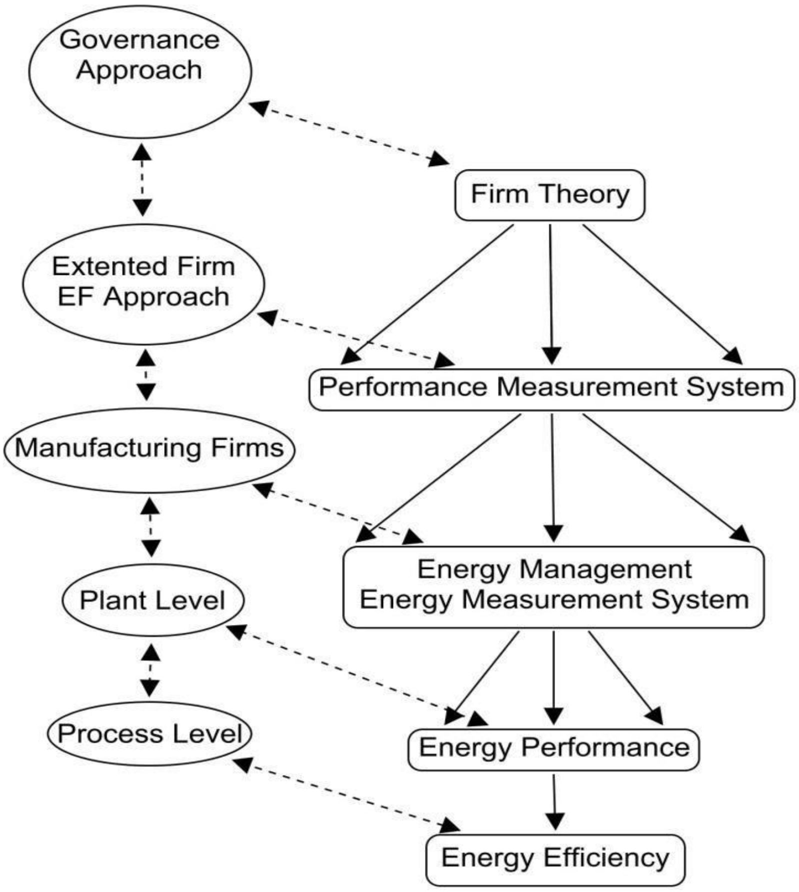

Figure 6: Literature Review

Figure 6 shows the scope of the literature review, Energy Efficiency is an indicator of energy performance as part of a Performance Measurement System that is in turn under the umbrella of the Theory of the Firm.

The fundamental question of the literature review is that these theories and models evolve, and when evolve generally have regarded an extension of the natural scope of the analysis. There is a trend of expanding the scope of performance measurement for social, learning and networking [4]. The very theory of the firm, which began with the production function [19], was broadening its scope over the twentieth century.

4 STRUCTURE AND LEARNING OF ENERGY PERFORMANCE

The proposal is made at this stage, there is a perception that the scope of analysis of energy efficiency, has to be expanded, incorporating the processing chain network, supported by the methodologies of Figures 1 and 6. Firstly are presented the model structure and subsequently the learning process of energy performance.

4.1 Structural model

The structural model of the energy performance can be seen in Figure 7. The model uses as a theory of the general contour, the paradigm (SCP) of Industrial Organization [20, 21], but does not carry all your relational properties. The view here is that the structural properties of the model are given by Structural of Performance Measurement Systems [29].

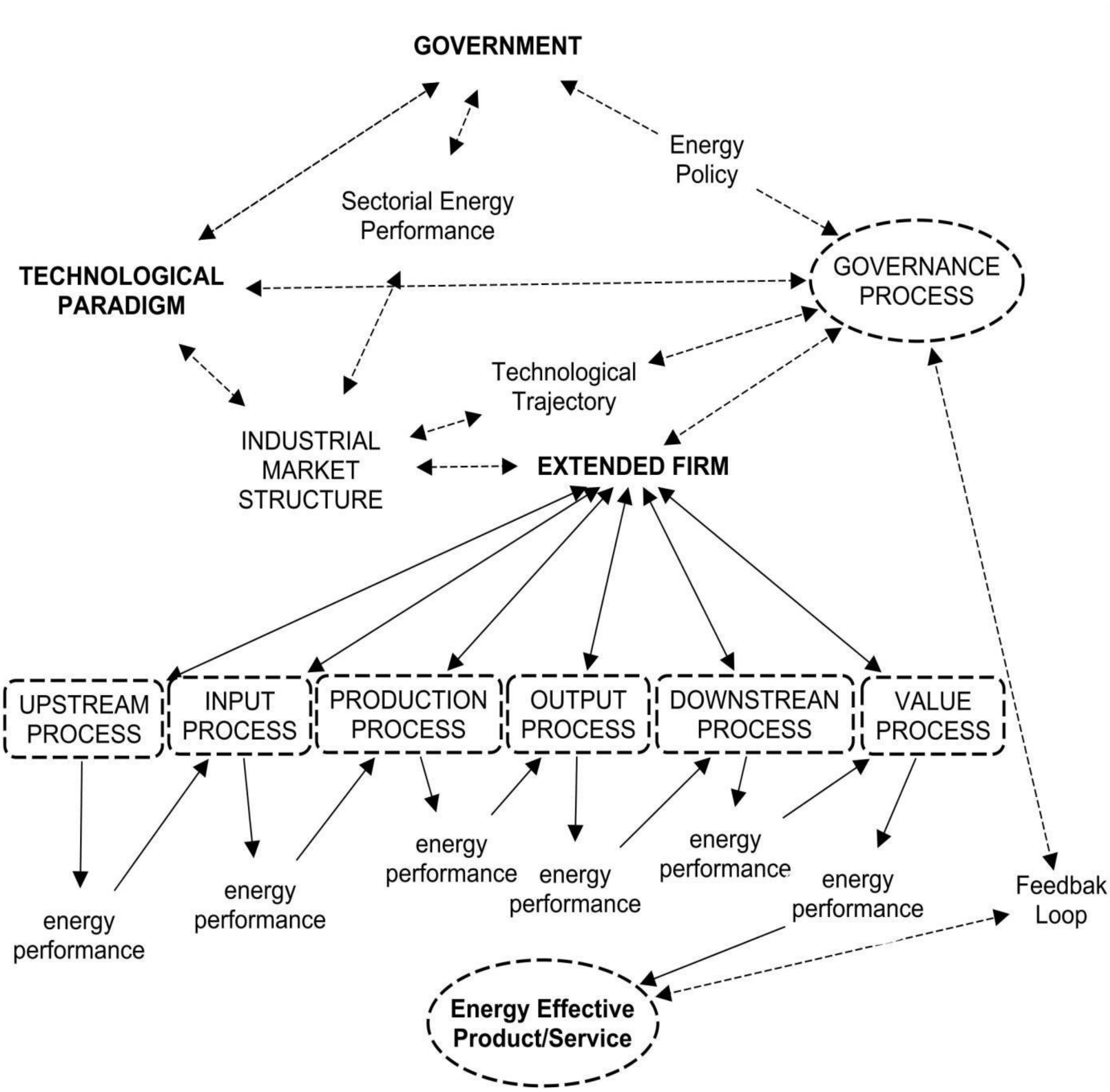

Figure 7: Structural Model of Energy Performance

In the model discussed here three main relationships are identified:

- Extended Firm;
- Technology ;
- Government Structure;

The energy consumption occurs in the Extended Firm (EF) through their processes, and the consumers of this energy flow are the end products and services.

The energy flow moves through the macro process (EF), from the upstream to downstream, creating value for stakeholders. Insofar as the flow advances it carries a particular energy performance. If the energy performance is represented by energy efficiency, each process of (EF) has a level of energy efficiency.

The management of the EF macro process is taken as an activity of the Stakeholders Governance. Governance has to take into account the strategy of each process (Manufacturing Strategy), the system performance must always be aligned with the strategy [28, 29].

Energy efficiency is not the sole responsibility of the (EF), and this in turn influenced by government policies [11]. Together government and (EF) are influenced by paradigms and technological trajectories [23, 25].

A question to be answered is: Who manages the energy performance of the Extended Firm?

The evidence suggests there is a gap in the system. The government acts on the top of the energy efficiency and firms on the factory floor. There is a need for integration and this integration can be done based on (EF) [31], end integration of the supply chain network [16].

If the processes are mobilized an (EF) for the production of a specific product or service, how to say that the product or service has energy efficiency if it went through several process of the Extended Firm?

The main point is that the energy performance represented by energy efficiency indicators of a specific process is not sufficient to say that the product or service was produced with energy efficiency. To say that the product or service is efficient, it is necessary to evaluate the energy efficiency (Energy Performance) of the process in (EF), from the upstream to the value for the stakeholders. Just by following this rule may reach the conclusion that the product or service has or not energetic effectiveness.

This work proposes a new concept that is energy effectiveness. Energy effectiveness is related to the efficiency of the network as a whole.

- Energy Efficiency - efficiency in the process at the firm level
- Energy Effectiveness – efficiency in the process at the Extended Firm level.

4.2 Learning model

Based on the literature review, the Figure 8 represents states and stages of change in energy performance, characterized as a learning process.

Each step (Performance Stage) fulfilled in the external circle requires a full turn of the internal cycle (Performance States), which means that at some point in time the system will perform as immature (Random), and systematic process (Systematic) later becoming inadequate (Bureaucratic), requiring new construction. This evolutionary process is according to the stages of development of an Performance Measurement Systems [28], can see in the form of continuous improvement [34] and the stages of evolution of energy maturity[9].

Five stages are proposed:

- Default - Absence of energy management [no monitoring and control]
- Managed - Management practices established [unstructured monitoring and control]
- Oriented - Standardization of management practices through a Performance Measurement System [standardization of monitoring and control]
- Quantitatively Managed - Energy Performance Management [monitoring, controlling and improving structured]
- Prime -. Continuous performance improvement [monitoring, control end continuous improvement]

Additional subsidies were presented to answer the question: How saying that the product or service is energetically effective?

Interpretation is made here: The product or service is energetically effective if are Quantitatively Managed. Energy effectiveness can be attributed to the level of maturity of the processes of energy management in Extended Firm.

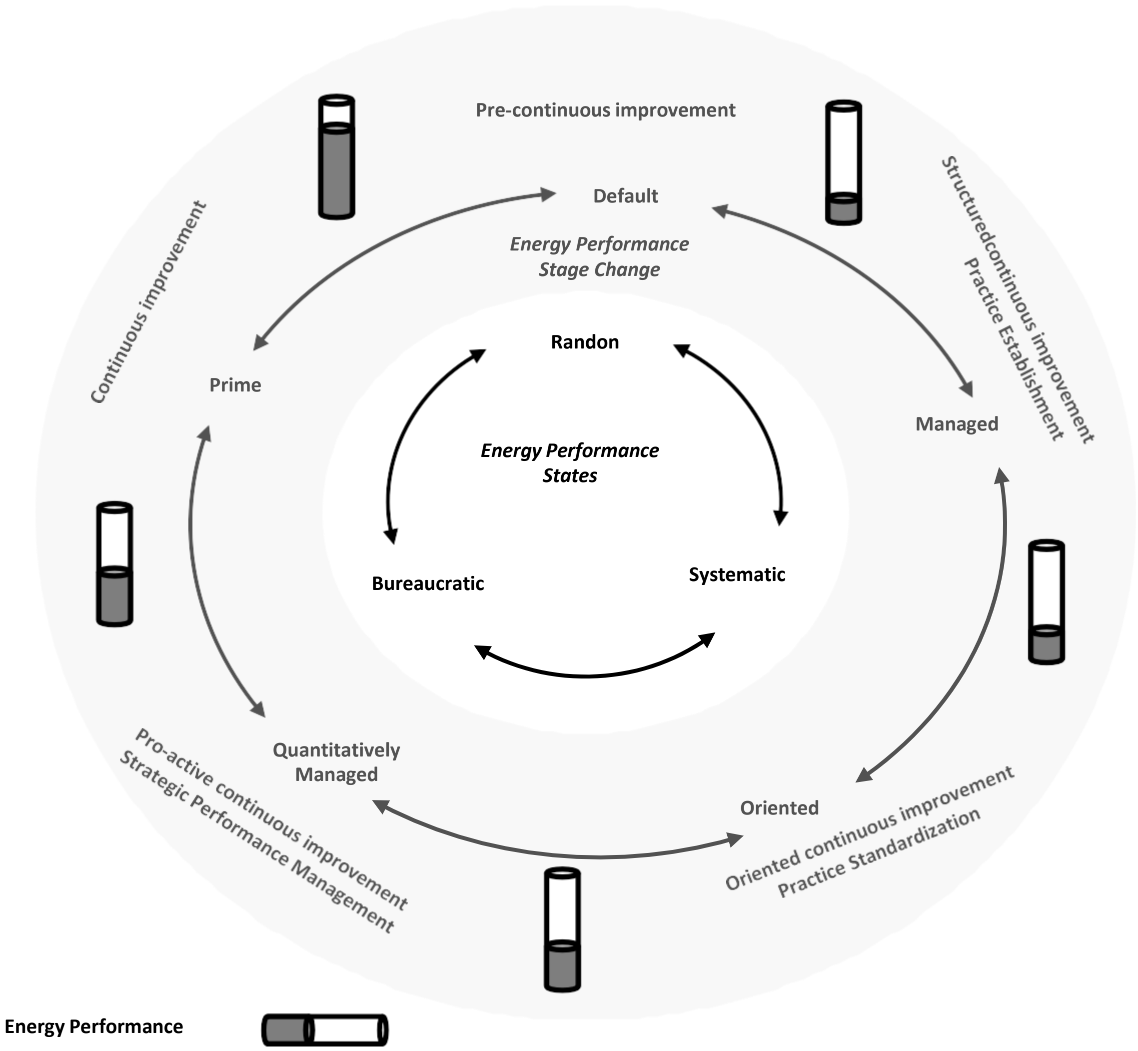

Figure 8 – Learning Process of Energy Performance – States end Stages

5 CONCLUSION

The work in order to answer the research question: How does the energy performance can be measured, taking into account both efficiency how the effectiveness in managing manufacturing? Was modeled the structure and the learning process of energy performance, it was found that the problem is more extensive involving the Extended Firm.

Regarding the structure, as shown in Figure 7, three factors were considered key to the energy performance: The government, the technological structure and conduct of the Extended Firm. The structure by itself does not generate appropriate performance. The interaction of structural elements can be a source of performance, and finished products and services responsible for energy consumption. The Structural Model serves as a support for evaluation and measurement of the energy consumed in macro process (EF).

Energy efficiency was perceived as the quality of the use energy in the processes, measured by indicators of efficiency. The effectiveness was linked to products and services. Energy effectiveness was attributed to the level of maturity of the processes of energy management in Extended Firm. In a narrower sense the energy effectiveness is linked to developments of Performance Measurement System in Energy at the Extended Firm.

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APÊNDICE K

APÊNDICE K: ARTIGO 6 - THE RELATIONSHIP BETWEEN ENTERPRISE EFFICIENCY IN RESOURCE USE AND ENERGY EFFICIENCY PRACTICES ADOPTION

CONGRESSO – *THE 23rd INTERNATIONAL CONFERENCE ON PRODUCTION, JULY 31 – AUG -6, 2016 - MANILA, PHILIPPINES*

Investigation of the Relationship between Enterprise Efficiency and Energy Efficiency Adoption for the Cases of Industrial Assessment Centers in the US

REVISTA – *INTERNATIONAL JOURNAL OF PRODUCTION ECONOMICS, IN PRESS, CORRECTED PROOF,*

The relationship between enterprise efficiency in resource use and energy efficiency practices adoption

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Abstract

The purpose of this paper is to investigate the relationship between enterprise efficiency in resource use and the adoption of energy efficiency practices recommended by the US Department of Energy (DOE) through the Industrial Assessment Center (IAC). Using non-parametric techniques such as Data Envelopment Analysis (DEA) and parametric techniques like Stochastic Frontier Analysis (SFA) and Corrected Ordinary Least Square (COLS) to measure the efficiency. The Regression Quantile (RQ) is carried out to test the hypothesis that the most efficient companies have adopted a higher level of practice. The main conclusion is that when the enterprise operates at increasing Returns-to-Scale (RTS) the impact of efficiency on adoption increases positively, inversely when the enterprise operates at decreasing (RTS) the impact of efficiency on adoption increases negatively.

Keywords: *Industrial energy efficiency, Energy efficient adoption, Enterprise efficiency*

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1. Introduction

The study of energy efficiency is not a new area; it is the focus of the studies that has changed, it went from energy conservation (Motamen and McGee, 1986; Fawkes and Jacques, 1987) to energy efficiency (Phylipsen, et al., 1997; Worrell et al., 2003), to the impact of energy use on sustainability (Gutowski et al., 2005; DelRio and Burguillo, 2008) and energy management (Bunse et al., 2011; Backlund et al., 2012; Ngai et al., 2013). The studies have identified various benefits of energy efficiency management in companies: Increased productivity, reduced pollution, reduced noise, low cost of maintenance, savings in water, reduced waste, among other benefits (Worrell et al., 2003; Trianni et al., 2014). On the other hand, the studies have also identified what is known in the literature as the *Energy Efficiency Gap*, the paradox of the existence of this gap is explained by a series of barriers that prevent greater efficiency (Jaffe and Stavins, 1994; DeCanio, 1997; Cagno, et al., 2013). This gap exists as a result of not implementing energy efficiency or energy conservation measures even though their cost effectiveness has been evaluated by techniques like *payback*, internal return rate (IRR) or net present value (NPV) (Jaffe and Stavins, 1994; DeCanio, 1997).

In the analysis of three bibliometric studies: Yaoyang and Boeing (2013), Du et al. (2013), and Du et al. (2014) comparing more robustly the total number of publications and citations in the periods 1993-2001 to 2002-2010, results show a growing interest in some specific areas in the field of energy. In the area of biofuels, as showed by Yaoyang and Boeing (2013), there was a 1310% increase in publications and 1946% in the number of citations, in the area of energy efficiency, according to Du et al. (2013), a 278% and 396% increase, and finally in solar energy, as showed by Du et al. (2014), an increase of 103% and 187% for the same indicators. Based on these studies there is a greater relative interest in researching energy efficiency over solar energy.

Data sources for energy efficiency research are scarce. One study opportunity comes from the Department of Energy of the United States (DOE), through the energy efficiency audit program for small and medium enterprises (*SMEs*), sponsored by the American government (US DOE-IAC, 2011). Participating in the study are 24 *Industrial Assessment Centers* (IAC) together with 32 American universities.

Many studies have used the information provided by the DOE-IAC for investigating impacts such as cost, price of energy, time of return on investment and other factors, on the implementation of energy management and energy efficiency practices (Tonn and Martin, 2000; Anderson and Newell, 2004; Abadie et al., 2012; Therkelsen and McKane, 2013; Blass et al., 2014). The main contribution of our work is to look at how prior enterprise efficiency has had an influence on the adoption of practices, in other words: What is the relationship between enterprise efficiency and the adoption of energy efficiency practices? The efficiency is measured by three different techniques: Data Envelopment Analysis (DEA), Stochastic Frontier Analysis (SFA) and Corrected Ordinary Least Square (COLS). DEA, SFA and COLS provide methods for estimating the best practice production frontiers and evaluating the relative efficiency of different entities (enterprise). The efficiency is measured by the distance between the enterprises that are on the frontier and below it (Bogetoft and Otto, 2010). The Regression Quantile (RQ) is carried out to test the hypothesis that the most efficient companies, measured by DEA, SFA and COLS, have adopted a higher level of practice. A second question is raised: Considering the practices, is there a difference in efficiency among the enterprises that adopted certain practices and those that did not?

The idea behind the first question is to generate evidence demonstrating that the most efficient companies are also those more concerned with environmental issues, since the use of less energy results in fewer harmful gas emissions into the environment (CO_2, CH_4, N_20). The second question seeks to determine whether or not more efficient companies have a preference for any particular practices.

This study uses the model proposed in Perroni et al. (2015), including the year 2013 in the model. A specific set of objectives was used to deal with the large body of information, approximately 17,000 cases and 130,000 recommendations, broken down into the following sections: literature review of the determinants of energy efficiency; research design, which describes the treatment of data, construction of models for calculating the efficiency, model to examine the research question, and application and test methodology; calculations of efficiency and the model which investigated the relationship between the enterprise efficiency and the adoption of energy efficiency practices; and at the last two sections discussion and conclusion are presented.

2. Literature review of the determinants of energy efficiency

Enterprise efficiency can be analyzed in various ways, the most widely known are technical efficiency and allocative efficiency. Technical efficiency is related to the use of adequate or optimal procedures and allocative efficiency takes into consideration the costs of these procedures for optimal allocation (Farrel 1957; Bogetoft and Otto, 2010).

According to Patterson (1996) efficiency in the context of energy is a generic term, where there is no single measure. Efficiency is related to the use of less input (energy), maintaining a constant output. For Patterson (1996) the energy efficiency indicator comes from the output/input ratio, classified in four groups: *Thermodynamic, Physical-thermodynamic, Economic-thermodynamic, Economic*.

The link between the concept of energy efficiency and energy management can be interpreted according to the definition put forth by Bunse et al. (2011, p. 668) "*In our research we define 'energy management in production' as including control, monitoring, and improvement activities for energy efficiency*". Based on the research of Backlund et al. (2012) both the policy documents and the academic literature recognize the existence of the so-called *energy efficiency gap*, which is related to the non-implementation of measures for energy management and energy efficiency, despite their cost effectiveness.

Studies evaluating the extent to which energy management has been adopted by industrial companies have revealed a low rate of adoption. For 304 industrial companies in Denmark, Christoffersen et al. (2006) concluded that between 3% and 14% of the companies practiced energy management. In analyzing intensive Swiss industries like paper and foundry Thollander and Otosson (2010) found that 40% and 25% respectively, practiced energy management. Studies in Italy found that in small and medium-sized companies the *energy efficiency gap* can be explained by a series of barriers such as: *High investment costs, hidden costs, intervention not sufficiently profitable, information issues on energy contracts, information not clear by technology suppliers and lack of information on costs and benefits* (Trianni and Cagno, 2012; Trianni et al., 2013).

Concerns over barriers to implementing *Energy Efficiency Measures (EEMs)* culminated in the development of a model for identifying the barriers proposed by Cagno, et al. (2013). This model proposes a taxonomy for the study of barriers, separating them into external factors (market, government, technology, suppliers of technology and financing system) and factors internal to the company (economic, behavioral, organizational, competence and awareness).

Various studies have looked at the relationship between energy efficiency variables and internal and external variables, the main results have been summarized in Table 1.

Table 1 – Relationship between energy efficiency and variables internal and external to the company.

Origin	**Authors/Acronyms**	**Energy variables**	**Internal and external variables**	**Effect**
Greece	Kounetas and Tsekouras (2010)	EETs	Productive performance	+
	EETs - Energy Efficient Technologies	EETs	Productive performance (deterministic model)	-
		EETs	Size of firms	+
		EETs	Intensive firms	+
		EETs	Not intensive firms	-
Korea	Suk et al. (2013)	ESA	Regulation, competitors and association	≠
	ESA - Energy Saving Activities	ESA	Top management, training and economic incentives	+
		ESA	Large firms	+
China	Liu et al. (2013)	CBP	Energy price	-
	CBP - Carbon Price Polices	CPB	Energy management strategies	+
		CPB	Subjective perception and self-motivation	+
Spain	Pons et al. (2013)	EST	Economic performance	≠
	EST - Energy saving technologies	EST	Environmental performance	+
USA	Eccles and Serafeim (2013)	SUS	Financial Performance	-
	SUS - Sustainability INO- Innovation	SUS-INO	Financial Performance	+
China	Zhang and Wang (2014)	IS-CER	Environmental regulations	-
	IS-CER Industrial Symbiosis Carbon Emission Reduction	IS- CER	Economic performance	+
USA-IAC	Tonn and Martin (2000)	A-EEMs	Energy efficiency decision making	+
	A-EEMs - Adoption of Energy Efficiency Measures			
USA-IAC	Anderson and Newell (2004)	A-EEMs	Payback and project cost	-
		A-EEMs	Annual savings and price of energy	+
		A-EEMs	Energy prices squared	-
USA-IAC	Abadie et al. (2012)	A-EEMs	Payback time	-
		A-EEMs	Natural gas	-
		A-EEMs	Higher emissions	+
		A-EEMs	Higher gross domestic product (GDP)	+
USA-IAC	Therkelsen and McKane (2013)	A-EEMs	Payback and Implementation cost	-
USA-IAC	Blass et al. (2014)	A-EEMs	Top operations management	+
		A-EEMs	Top general management	±

Legend: + positive; - negative; ≠ no effect; ± weak effect.

Note: Energy variables: adoption of energy efficient technologies, energy saving, pollution reduction measures or adoption of measures to increase energy efficiency.

The work of Kounetas and Tsekouras (2010) used the *Stochastic Frontier Analysis* (SFA) for manufacturers in Greece where they found a positive relationship between energy efficient technologies and the productive performance of manufacturers, but they found a negative relationship when the deterministic part of the frontier was analyzed. For productive performance, energy efficient technologies have a different effect when considering industrial sectors and company size. When the industries are intensive users of energy, the adoption of *Energy Efficient Technologies* (EETs) has a positive impact on performance, but the opposite occurs when the industries are not intensive users of energy.

In the survey by Suk et al. (2013), in energy intensive Korean companies, using a factorial analysis and logistic regression, no relationship was found between the external factors (regulation, competitors and associations) and energy savings. The energy saving practices are determined by upper management as well as training and economic incentives. Medium and large-sized companies adopt the best practices in EETs. Liu et al. (2013) in a survey in China using econometric techniques (multiple regression) a negative relationship was found between the price of energy and the acceptance of carbon tax costs and a positive relationship between energy management strategies and these same costs. The acceptance of higher carbon taxes by industries are determined by subjective perceptions as well as self-motivation, likely due to the lack of training of internal management.

In another study in Spain and Slovenia using data from the (*European Manufacturing Survey*) through linear and ordinal regression, Pons et al. (2013) found no relationship between economic performance and energy efficiency, instead they found a positive relationship between environmental performance and energy efficiency. Also for Chinese companies Zhang and Wang (2014) using multiple, logistic and ordinal linear regression demonstrated that collaboration for reducing carbon emissions (*Industrial Symbiosis*) has a positive relationship with economic performance. These authors found that for this study in China environmental regulations have no effect on the reduction of carbon emissions.

In a broad study Eccles and Serafeim (2013) conducted an econometric analysis with over 3,000 companies to examine the effect of sustainable practices on the financial performance of these companies. The result showed a negative correlation between financial performance and combined improvements in social and environmental factors, when innovation is not present.

According to Kannan and Boie, (2003) the objective of the energy audit is to scan the areas in order to find the gaps in energy efficiency. The aim of the DOE-IAC program is to find these gaps for small and medium-sized enterprises (SMEs), proposing the recommendations to be adopted. The result of whether or not they are adopted is recorded in a public database[40], revealing a source of valuable information, according to the perceptions of the various researchers listed in Table 1.

Studies that have used the information in the DOE-IAC database are listed in the lower part of Table 1. Tonn and Martin (2000) collected data on before and after the companies participated in the DOE-IAC program, they found through descriptive statistics that the benefits of the IAC are positively associated with later energy efficiency decisions. In one of the most cited studies in the literature, Anderson and Newell (2004), in the period from 1981 to 2000, found that only half of the recommended energy efficiency projects were implemented. Using logistic regression panel data they found that the rate of adoption is higher for projects with smaller paybacks, lower cost, higher savings/conservation of energy and prices. The companies are more motivated by the implementation costs than energy savings.

A more recent study by Abadie et al. (2012) also using logistic regression for the period from 1984 to 2009, confirmed the results of Anderson and Newell (2004), adding that the recommendation for natural gas has a lower probability of implementation. Companies located in states with higher Greenhouse Gas (GHG) emissions have a greater probability of adoption. Companies located in states with a higher Gross Domestic Product (GDP) have a lower probability of adoption. Therkelsen and McKane (2013) focus on the industrial vapor systems using 1,165 cases, finding that the implementation is primarily determined by cost metrics. The main reasons for non-adoption are (%): Economic 41; Facility/Production 25; Behavioral 19; Other 8; Organizational 7. The work of Blass et al. (2014) using logistic regression techniques, investigated the role of upper management in adopting energy efficiency practices, finding that when upper management is involved in operations there is a significant improvement in the adoption rate. For management in general the impact on adoption is low.

3. Research Design

The methodological approach is presented in four subsections according to the objectives of our study: Selection and gathering of data, models for estimation of enterprise efficiency, model for testing the relationship between the adoption or implementation of energy efficiency practices and estimated enterprise efficiency, finally a brief subsection describing the application methodology. There was a need to include the subsection selection and gathering of data due to the complexity of the database, which called for delimitations and further clarification. In the subsection estimated efficiency, both parametric and non-parametric models were used under varying conditions of return to scale aiming to test the influence of efficiency on the level of implementation of practices in

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[40] https://iac.university/download

different ways. For the test approach the quantile regression model was used for modeling all of the conditional distribution of the dependent variable (level of implementation).

3.1. Selection and gathering of data

The DOE-IAC project has 24 IAC centers together with 31 American universities. There are some rules in place for the companies to qualify for the program: sales lower than 100 million; cost of energy between 100 thousand and 2.5 million; up to 500 employees and the firm cannot have a dedicated energy management specialist (US DOE-IAC, 2011). The database covers the period from 1981-2015, containing a table with the data from the 16,859 companies evaluated and a second table with the 127,479 recommendations made, generating an average of seven recommendations per company (case). The recommendations are classified under three larger categories, according to the table *Assessment Recommendation Code* (ARC): *Energy Management, Waste Minimization/Pollution Prevention and Direct Productivity Enhancement* (US DOE-IAC_ARC, 2007).

This study is an update of the model developed by Perroni et al. (2015) for the period 1990-2012. This updated work for the period 1990-2013 applies the same rules, but adds the year 2013 to the analysis. The beginning of the period was chosen due to a certain stability in the price of energy, 2014-2015 was excluded as the evaluations are conducted for a period of up to two years and many of the evaluations are still pending. For the period of analysis 13,796 assessments were carried out, but for a variety of reasons approximately 30% of the data were omitted, which is similar to the rate of 25% found in the work of Anderson and Newell (2004) for similar reasons such as: the exclusion of questionable data, incomplete data, status of implementation pending or excluded, did not include at least two sources of energy (*Electrical*, *Natural Gas*). Companies with 10 or more employees and sales over U$10,000 were selected as cases. After refining the data 10,448 companies remained, with 62,263 recommendations. Table 2 describes the twenty (20) most recommended practices of the 10,448 selected cases and 62,263 recommendations.

Table 2 – Energy efficiency practices more recommended

Status	Recommended	Implemented			Not Implemented		
(ARC) Energy efficiency practices more recommended	%Q	%QI	%cost	%save	%NQI	%cost	%save
27142 Utilize higher efficiency lamps and/or ballasts	11.7	6.4	4.3	2.6	5.3	4.1	2.2
24236 Eliminate leaks in inert gas and compressed air lines/ valves	7.8	6.3	0.5	2.6	1.5	0.2	0.6
24221 Install compressor air intakes in coolest locations	5.6	2.5	0.1	0.3	3.1	0.1	0.4
24133 Use most efficient type of electric motors	5.3	3.4	2.0	1.1	1.8	1.1	0.5
27135 Install occupancy sensors	4.6	1.7	0.2	0.3	2.9	0.3	0.4
22511 Insulate bare equipment	3.5	1.6	0.3	1.0	1.8	0.4	1.0
27143 Use more efficient light source	3.3	1.7	1.2	0.7	1.6	0.9	0.6
24231 Reduce the pressure of compressed air to the minimum	3.0	1.5	0.1	0.3	1.5	0.2	0.4
24111 Utilize energy-efficient belts and other improved	2.7	1.4	0.2	0.3	1.3	0.3	0.3
24141 Use multiple speed motors or afd for variable pump	2.0	0.6	0.8	0.7	1.4	1.8	1.6
22434 Recover heat from air compressor	1.9	0.6	0.1	0.2	1.3	0.2	0.5
21233 Analyze flue gas for proper air/fuel ratio	1.8	1.2	0.2	0.9	0.6	0.2	0.6
27261 Install timers and/or thermostats	1.5	0.8	0.1	0.3	0.8	0.1	0.2
27111 Reduce illumination to minimum necessary levels	1.5	0.8	0.1	0.3	0.8	0.1	0.2
24232 Eliminate or reduce compressed air used for cooling	1.4	0.6	0.1	0.3	0.8	0.2	0.4
22131 Insulate steam/hot water lines	1.3	0.8	0.1	0.3	0.5	0.1	0.2
21311 Replace electrically-operated equipment with fossil fuel	1.2	0.3	0.8	0.6	0.9	2.1	1.8
22411 Use waste heat from hot flue gases to preheat combusti	1.2	0.2	0.3	0.4	1.0	2.2	3.2
27134 Use photocell controls	0.9	0.4	0.0	0.1	0.5	0.1	0.1
26218 Turn off equipment when not in use	0.8	0.4	0.1	0.3	0.4	0.2	0.2
Total partial	62.9	33.1	11.6	13.8	29.8	14.9	15.7

Source: (US DOE-IAC_ARC, 2007; US DOE-IAC, 2011)

Note: This table shows only the 20 most recommended practices in a total of 504, calculated by Excel® pivot table. a) %: (percentage of 62,263 recommendation aggregate by 504 ARC code in 10,448 companies audited); b) (%Q= %QI+%NQI) where %Q (% of quantity); %QI (% of quantity Implemented); %NQI (% of quantity not implemented), c) %cost: (% of sum of client reported implementation cost in dollars); d) %save: (% of sum for primary resource's dollar savings for recommendation).

Considering that the ARC table contains 676 possible practices for the recommendation, 504 practices (ARC) were recommended to the selected data that cover 10,448 cases. The most recommended practice was (*Utilize higher efficiency lamps and/or ballasts*) meaning 11.7% of the recommendations, 8.5% of the cost and 4.8% of savings, where, 6.4% were implemented and 5.3% were not implemented.

The twenty recommendations in Table 2 represent 62.9% (33.1% + 29.8%) of the recommendations, 26.5% (11.6% + 14.9%) for cost and 29.5% (13.8% + 15.7%) for savings, in other words, 4% (20/504) of practices is responsible for 63% of recommendations, 30% of cost and 16% of savings.

Different from the work of Anderson and Newell (2004) and Abadie et al. (2012) that used the table of recommendations, our work uses the table with the data from the companies (cases), adding the recommendation information (i to j). The data on recommendation of cost of implementation (*impcost*) was added to the variable IC, resources saved (*psaved*) was added to the variable PS and resource conservation (*pconserved*) generated the variable PC as demonstrated in Equations 1 to 3. An IL variable was created (*implementation level*), which is the proportion of recommendations implemented, varying from 0 to 100%, the IL is the sum of recommendations implemented by the companies QI divided by the total recommendations (implemented QI plus not implemented NQI), as shown in Equation 4.

$$IC_k = \sum_{i=1}^{j} IMPCOST_{ARC_i} \tag{1}$$

$$PS_k = \sum_{i=1}^{j} PSAVAD_{ARC_i} \tag{2}$$

$$PC_k = \sum_{i=1}^{j} PCONSERVD_{ARC_i} \tag{3}$$

$$IL_k = \sum_{i=1}^{j} QI_{ARC_i} / (\sum_{i=1}^{j} QI_{ARC_i} + \sum_{i=1}^{j} NQI_{ARC_i}) \tag{4}$$

The added recommendations were handled in two ways, first by including all of the categories in the table: *Assessment Recommendation Code (ARC)* (*Energy Management*, *Waste Minimization/Pollution Prevention and Direct Productivity Enhancement*) and second by only including the category *Energy Management* of ARC (US DOE-IAC_ARC, 2007). This distinction was made to verify whether there was a difference between the impact of enterprise efficiency on adoption if only energy management actions are considered. Two points to be highlighted are that the ARC *Energy Management* represents almost 90% of the recommendations and there is also the synergy factor among the recommendations, for example the use of waste (wood) to generate energy.

3.2. *Models for estimating enterprise efficiency*

In the Benchmarking area, the classification of Patterson (1996) can be seen as a *Key Performance Indicator* (*KPI*) of the company, or the measuring of productivity. Based on Bogetoft and Otto (2010) efficiency, inefficiency and enterprise effectiveness can be represented as:

$$InEfficiency = (Actual\ Peformance - Minimal\ Performance)/Actual\ Performance \tag{5}$$

$$Efficiency = Minimal\ Performance/Actual\ Performance = 1 - InEfficiency \tag{6}$$

$$\begin{aligned} Effectiveness &= Actual\ Performance/Ideal\ Performance = U(A)/\{max_{y \in T} U(y)\} \\ &= U(A)/U(ideal) \end{aligned} \tag{7}$$

The problem with effectiveness is that it depends on utility function U (.) which is not always known a priori. One way of overcoming this problem has been through the application of the concept of efficiency called Farrel efficiency (1957), moving the focus from effectiveness to relative efficiency.

Three different techniques have been applied to the literature to estimate relative efficiency: *Corrected Ordinary Least Squares* (COLS) (Azadeh et al. 2009), *Stochastic Frontier Analysis* (SFA) (Boyd et al., 2008, Boyd 2014) and *Data Envelopment Analysis* (DEA) (Olanrewaju et al., 2013; Olanrewaju and Jimoh, 2014). The origin of the first two methods is from the econometric approach and the latter from mathematical programming and management science (Bogetoft and Otto, 2010). In a bibliometric study Lampe and Hilgers (2015) confirm a growing number of publications, both DEA and SFA for measuring performance, finding that DEA is more widely used in operations while SFA is used in the area of finance. In another literature review Zhou et al. (2008) found that there has been an emphasis on the area of energy efficiency in the use of DEA.

Equation 8 shows the COLS and the Equation 9 the SFA, where (x) is a n dimensional input vector, (y) is the m =1 dimensional output and β are unknown vector of parameters. COLS (Equation 8) is attributed to Aigner and Chu (1968), classified as parametric-deterministic, it can be estimated by the traditional method of *ordinary least squares* (OLS). COLS is deterministic because it takes into consideration the error term (u) fully as inefficiency (the deviation from frontier is always inefficiency). The N_+ denotes a half-normal distribution $N_+(0,\ \sigma^2)$ of the (u) in the interval [0, ∞[. SFA (Equation 9) is attributed to Aigner et al. (1977), considered a parametric-stochastic method, assuming that errors are divided into noise (v), normally distributed $N(0,\ \sigma^2)$ and inefficiency (u), half-normal distributed $N_+(0,\ \sigma^2)$ (the deviation from frontier not only reflects inefficiencies, but noise as well), and can be estimated by the *maximum likelihood* principle, estimating the parameters $(\beta,\ \sigma^2,\ \lambda)$[41] (Bogetoft and Otto, 2010).

$$\begin{aligned} y^k &= f(x^k,\beta) - u^k, \quad u^k \sim N_+(0,\sigma^2) \quad k =, \dots, K \\ u^k &= f(x^k,\beta) - y^k \end{aligned} \tag{8}$$

$$\begin{aligned} y^k &= f(x^k,\beta) + v^k - u^k, \qquad v^k \sim N(0,\sigma^2), \quad u^k \sim N_+(0,\sigma^2) \quad k =, \dots, K \\ u^k &= f(x^k,\beta) - y^k + v^k \end{aligned} \tag{9}$$

The DEA approach can be attributed to Charnes et al. (1978), it is a non-parametric deterministic method that uses mathematical programming to estimate the frontier of best practices. DEA can be represented in different return systems, like CRS (*constant returns to scale*), VRS (*variable returns to scale*), DRS (*decreasing returns to scale*) and IRS (*increasing returns to scale*) as shown in Equation 10, where θ is the measure of efficiency, x_{ij} and y_{rj} are the *i*th input and *r*th output of the problem, x_{io} and y_{ro} are the *i*th input and *r*th output under evaluation and λ_j are the weights to be determined by the solution (Zhu, 2008). Based on Bogetoft and Otto (2010) DEA is more flexible in terms of the economic properties of production, while SFA is more flexible in terms of the quality of data.

After preliminary studies the multiplicative model (Equations 11 and 12) was adopted for calculating the parametric efficiency. Equation 11 represents COLS and equation 12 SFA, where Y(annual sales); L(employees); PH(annual production hours); UE(annual use of electricity); UN(annual use of natural gas); CE(annual cost of electricity); CN(annual cost of natural gas); e^{vk} (error); e^{-uk} (estimation of the efficiency). The variables cost of gas and cost of electricity act as control variables.

$$\begin{aligned} &\theta^* = \min \theta \\ &subject\ to \\ CRS\ &\left| \begin{array}{ll} \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{i0} & {\scriptstyle i=1,2,\dots,m;} \\ \sum_{j=1}^{n} \lambda_j y_{rj} \leq y_{r0} & {\scriptstyle r=1,2,\dots,s;} \end{array} \right| \quad VRS - \sum_{j=1}^{n} \lambda_j = 1 \,|\, IRS - \sum_{j=1}^{n} \lambda_j \leq 1 \,|\, DRS - \sum_{j=1}^{n} \lambda_j \geq 1 \\ &\lambda_j \geq 0 \end{aligned} \tag{10}$$

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[41] The log-likelihood function can be written: $l(\beta,\sigma^2,\ \lambda) = -\frac{1}{2}K\ log\left(\frac{\pi}{2}\right) - \frac{1}{2}K\ log\ \sigma^2 + \sum_{k=1}^{K} log\ \Phi\left(-\frac{\lambda(y^k - f(x^k;\beta))}{\sqrt{\sigma^2}}\right) - \frac{1}{2\sigma^2}\sum_{k=1}^{K} (y^k - f(x^k;\beta))^2$ where $\sigma^2 = \sigma_v^2 + \sigma_u^2$, and $\sigma_v^2 = \frac{1}{1+\lambda^2}\sigma^2$; $\sigma_u^2 = \frac{\lambda}{1+\lambda^2}\sigma^2$ (implemented in R package Benchmarking, Bogetoft and Otto, 2010, p.197-231).

$$Y_k = \beta_1 L_{2K}^{\beta_2} PH_{3k}^{\beta_3} UE_{4k}^{\beta_4} UN_{5k}^{\beta_5} CE_{6k}^{\beta_6} CN_{7k}^{\beta_7} e^{-u_k} \qquad (11)$$

$$Y_k = \beta_1 L_{2K}^{\beta_2} PH_{3k}^{\beta_3} UE_{4k}^{\beta_4} UN_{5k}^{\beta_5} CE_{6k}^{\beta_6} CN_{7k}^{\beta_7} e^{v_k} e^{-u_k} \qquad (12)$$

DEA modeling does not require a functional form, using Equation 10 as a basis, the X_j are the inputs and the Y_j are the output, the variables L, PH, UE, UN, CE, CN and Y are the same as in equations 10 and 11, but in logarithm form.

$$X_j = \{\ln(L_i), \ln(PH_i) \ln(UE_i), \ln(UN_i), \ln(CE_i), \ln(CN_i)\} ; Y_j = \{\ln(Y_r)\} \qquad (13)$$

3.3. *Test model: Implementations verses enterprise efficiency*

To reach our main objective, which is to investigate the relationship between enterprise efficiency and the adoption of energy efficiency practices, a quantile regression model is proposed. Quantile regression was developed by Koenker and Bassett (1978), having the advantage of modeling the complete conditional distribution of the independent variable, instead of just the average as in OLS, thus generating more robust results. Represented as a linear program, the quantile regression can be estimated at 14, where θ is the quantile in the interval $0 < \theta < 1$, the term $'y_t - x_t\beta'$ is an error term in the linear regression $'u_t = y_t - x_t\beta'$.

$$\min_{\beta g \mathbb{R}^K} \Big[\sum_{tg\{t: y_t \geq x_t\beta\}} \theta|y_t - x_t\beta| + \sum_{tg\{t: y_t < x_t\beta\}} (1-\theta)|y_t - x_t\beta|\Big] \qquad (14)$$

The values $b\theta$ can modify as they advance in the quantiles. The proposed quantile regression is 15.

$$(IL)_k = b_{0\emptyset} + b_{1\theta} u_k^{Eff} + b_{2\theta} \ln\left(\frac{IC}{PS}\right)_k + b_{3\theta} \ln\left(\frac{PS}{PC}\right)_k + b_{4\theta} \ln\left(\frac{UE}{Y}\right)_k + b_{5\theta} \ln\left(\frac{UN}{Y}\right)_k + u_k \qquad (15)$$

Where IL and the proportion of implemented projects; u_k^{Eff} represents the estimated efficiency of the parametric and non-parametric models presented previously; IC/PS cost of project implementation ratio by the potential for energy savings, since the two values are monetary this variable can be interpreted as a simple payback; PS/PC as the potential ratio for savings and potential for conservation. Energy savings is in a monetary value and conservation in Kilowatt-hour (KWh) or British Thermal Unit (BTU), making this variable the average price of energy for each project. The variables payback and average price of energy were computed in a similar manner in the work of Anderson and Newell (2004). UE/Y energy intensity of electricity; UN/Y energy intensity of natural gas.

3.4 Application methodology

The application is designed to attend the proposed research objective, which is to investigate the relationship between enterprise efficiency and the adoption of energy efficiency practices, using the data treated in subsection 3.1 (selection and gathering of data). In the first stage (subsection 4.1) it was calculated the efficiency using the regression method SFA and COLS, as shown in Equations 11 and 12 respectively, then the efficiency was calculated using the approach of mathematical programming, data envelopment analysis (DEA), assuming the hypothesis of four different systems of return to scale: decreasing (DRS), constant (CRS), increasing (IRS) and variable (VRS). In the second stage (subsection 4.2) the quantile regression model of Equation 15 was used to test the relationship between the level of energy efficiency adoption (dependent variable) and the efficiency calculated by the regression and mathematical models (independent variable).

4. Application of models

Based on the description of the application methodology, this section is divided into two subsections: The subsection 4.1 presents the estimation of enterprise efficiency using SFA, COLS and DEA (Equations 8 to 13). The calculation of efficiency and the implementation level (Equation 4) are aggregated based on the industrial sectors that enterprises belong to check the concordance between the efficiency estimation, and the level of implementations by sectors. The Pearson correlation matrix also shows the calculated efficiencies and the level of implementation. The subsection 4.2 shows the relationship between enterprise efficiency and the adoption of energy efficiency practices (Equation 15). Efficiency of recommendation equivalent to 10,448 enterprise efficiency was aggregate by 504 ARC code to verify the difference in efficiency between the enterprises that adopted certain practices and those that did not. To investigate the relationship between enterprise efficiency and the adoption of energy efficiency practices, 120 models of quantile regression (15 quantile *versus* 8 efficiency calculations) are proposed, changing the quantile and the variable of efficiency.

4.1. Estimation of enterprise efficiency for the DOE-IAC cases

For estimating the efficiency, the methodological model developed in Equations 8 to 13 was used. Table 3 presents the SFA (estimated by R package Benchmarking and tested in R package Frontier) and COLS coefficient (estimated in R), where the dependent and independent variables were defined Equations 11 and 12 (Coelli and Henningsen, 2013; Bogetoft and Otto, 2014). The interpretation of SFA parameters is made easier, since it is a logarithmic model, therefore, 1% of variation in annual sales (dependent variable, Y) results in an increase of 0.14% in the annual use of electricity (UE) or curiously, a reduction of 0.12% in the annual use of natural gas (UN). The interpretation of COLS parameters is similar. From Table 3 it is possible to note that all of the SFA and COLS estimations are significant at 1%. The t_value ratio in SFA and COLS indicates that the parameters are statistically different from zero, since the t_value belong to critical region (Student's t-distribution), the null hypothesis that the parameters are in fact zero are rejected (see footnote 2). Considering the SFA lambda value ($\lambda = 1.54$) informs that the percentage variation in inefficiency is 70%, therefore 30% is random variation (see footnote 2 and 3). An important observation is about the return to scale, both in the SFA and COLS estimations, the returns to scale are decreasing, as the sum of the coefficients is lower than 1. but closer to the unit with 0.98 for SFA and 0.99 for COLS.

Table 3 - Parameters of SFA and COLS - (dependent variable: annual sales)

Independent variables		**(Intercept)**	**L**	**PH**	**UE**	**UN**	**CE**	**CN**
SFA	**Parameters**	9.694*	0.565*	0.078*	0.141*	-0.126*	0.114*	0.205*
	Std. Error	0.199	0.014	0.028	0.018	0.020	0.019	0.022
	t_value	48.513	39.923	2.809	7.864	-6.373	5.897	9.421
COLS	**Parameters**	8.965*	0.587*	0.106*	0.160*	-0.102*	0.070*	0.170*
	Std. Error	0.174	0.013	0.023	0.019	0.018	0.019	0.019
	t_value	51.456	45.215	4.568	8.352	-5.766	3.644	8.777

Note: a)* significant at 1%; b) SFA ($\lambda = 1.54$; σ^2=1.48; σ_v^2 =0.44; σ_u^2 = 1.04; log likelihood =-13623.22)[42]

c) COLS (Adjusted R-squared = 0.41); d) t_value ratio= (Parameters/Std. Error)[43].

Table 4 presents a summary (class of efficiency) of the calculation for the DEA, with input oriented efficiency, estimated by R package Benchmarking and tested in Excel® OpenSolver (Zhu,

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[42] The parameters are calculated by the maximum likelihood estimation method in software R (Coelli and Henningsen, 2013, Bogetoft and Otto, 2014) where $\sigma^2 = \sigma_v^2 + \sigma_u^2$ *and* $\lambda = \sqrt{\sigma_u^2 / \sigma_v^2}$, when $\sigma_u^2 = 0$ and $\lambda = 0$ we have the ordinary regression. The percentage of total error variance due to inefficiency can be found from $\frac{\lambda^2}{\lambda^2+1} = \frac{1.54^2}{1.54^2+1}$=0.70, 70% of the total variation is due to inefficiency and 30% is random variation.

[43] The hypothesis test:($|\text{t\_value}| > t_{(N-K)\alpha/2}$), where $(N-K)$ is the degree of freedom and α is the significance level. For the L variable in Table 3 we have: ($|39.923| > t_{(10448-7)0.05/2}$)

2008; Bogetoft and Otto, 2014). The input and output variables are the same as defined for regression models (Table 3) using the same data set (10, 448 enterprise) treated in subsection 3.1

Table 4 – Class of efficiency of DEA models

Efficiency class		0.00-0.59	0.60-0.79	0.80-0.99	1	Total
DRS	Number of enterprises	86	8735	1611	16	10448
	%	0.82	83.60	15.42	0.15	100
CRS	Number of enterprises	86	8735	1611	16	10448
	%	0.82	83.60	15.42	0.15	100
IRS	Number of enterprises	0	51	10324	73	10448
	%	0.00	0.49	98.81	0.70	100
VRS	Number of enterprises	0	51	10324	73	10448
	%	0.00	0.49	98.81	0.70	100

Note: Average efficiency (CRS=DRS=0.75; IRS=VRS=0.88)

The efficiency estimation using DEA is done assuming the hypothesis of four systems of return to scale: decreasing (DRS), constant (CRS), increasing (IRS) and variable (VRS), as shown in Equation 10**.** Considering constant or decreasing returns the efficiency average was 0.75 with 16 enterprises considered efficient respectively. For the hypothesis of variable or increasing return the efficiency average was 0.88 with 73 enterprises considered efficient. The estimation of constant and decreasing returns are very similar, the same occurring with variable and increasing returns. Regarding the distribution of efficiency, 83% of the enterprises belong to efficiency class (0.60-0.79) assuming returns DRS and CRS, and 98% for efficiency class (0.80-0.99), assuming IRS and VRS.

Table 5 shows the average value of enterprise efficiency (aggregated by industrial sectors) for examine the concordance between the efficiency estimation, and between the efficiency estimation and level of implementations by the 20 industrial sectors of the *Standard Industrial Code* (SIC), the darker brown color is associated with lower efficiency and white with greater efficiency.

Table 5 – Aggregation of efficiency and implementation level by industrial sectors

SIC - Industrial Sectors	SFA	DRS	CRS	COLS	GMD	IRS	VRS	GMI	IL
29 Petroleum and Coal Products	0.615	0.781	0.781	0.004	0.716	0.885	0.886	0.885	0.517
21 Tobacco Products	0.608	0.831	0.828	0.011	0.739	0.904	0.908	0.906	0.433
28 Chemicals and Allied Products	0.584	0.759	0.759	0.003	0.689	0.872	0.872	0.872	0.458
20 Food and Kindred Products	0.567	0.754	0.754	0.003	0.679	0.874	0.874	0.874	0.486
26 Paper and Allied Products	0.555	0.736	0.736	0.002	0.667	0.859	0.859	0.859	0.463
38 Instruments and Related Products	0.554	0.777	0.777	0.002	0.686	0.899	0.899	0.899	0.469
37 Transportation Equipment	0.547	0.762	0.762	0.002	0.676	0.885	0.885	0.885	0.485
35 Industrial Machinery and Equipment	0.546	0.759	0.759	0.002	0.675	0.891	0.891	0.891	0.492
24 Lumber and Wood Products	0.537	0.769	0.769	0.002	0.678	0.898	0.898	0.898	0.480
39 Miscellaneous Manufacturing Industries	0.533	0.761	0.761	0.002	0.671	0.901	0.901	0.901	0.446
25 Furniture and Fixtures	0.532	0.775	0.775	0.002	0.681	0.916	0.916	0.916	0.477
36 Electronic & Other Electric Equipment	0.526	0.761	0.761	0.002	0.668	0.887	0.887	0.887	0.473
31 Leather and Leather Products	0.511	0.775	0.775	0.001	0.671	0.920	0.920	0.920	0.506
34 Fabricated Metal Products	0.502	0.742	0.742	0.002	0.646	0.883	0.883	0.883	0.486
27 Printing and Publishing	0.500	0.743	0.743	0.001	0.646	0.871	0.871	0.871	0.456
30 Rubber and Miscellaneous Plastics Products	0.486	0.734	0.734	0.001	0.635	0.861	0.861	0.861	0.465
32 Stone, Clay, And Glass Products	0.481	0.738	0.738	0.001	0.635	0.866	0.866	0.866	0.492
33 Primary Metal Industries	0.479	0.734	0.734	0.002	0.630	0.865	0.865	0.865	0.443
23 Apparel and Other Textile Products	0.475	0.764	0.764	0.001	0.644	0.916	0.916	0.916	0.517
22 Textile Mill Products	0.468	0.725	0.725	0.001	0.621	0.856	0.856	0.856	0.477
Mean	0.526	0.750	0.750	0.002	0.661	0.879	0.879	0.879	0.476

Note: a) Aggregation of the 10,448 enterprise efficiency estimated by the models of the equation 10,11 and12 and the IL variable of the equation 4, taking into account the sector in which each of the enterprise belong: (*sum* of *efficiency or IL of the enterprises belonging to the sector/number of enterprise in the sector*), (classified by SFA). b) Darker color (Percentile 30% less efficient); Lighter color (Percentile 70% more efficient).

In Table 5 the classification is made in relation to SFA, which means that the position of the other efficiency calculations is relative to SFA. Three other variables appear in Table 5: Implementation level of recommendations IL (Equation 4), GMI and GMD. The GMI variable is the geometric average of (SFA, CRS and DRS) and the GMD variable is the geometric average of (VRS, IRS). According to Azadeh et al. (2009) the geometric average is an approach used to consolidate the average efficiency from different perspectives. The choice to separate these variables for calculating the geometric average was not by chance, it is possible to note in Table 5 that even when efficiency is added by sectors, the colors of SFA, CRS and DRS which have constant or decreasing returns are in agreement, on the other hand, efficiency when considering variable or increasing returns (VRS, IRS) have agreeing colors, making the GMD representative of the constant and decreasing returns and the GMI a representation of the increasing and variable returns. Regarding the variable (IL), from the sectoral analysis it was not possible to extract information based on the gradient of colors.

Sector 29, *Petroleum and Coal Products* were classified with the best efficiency average using SFA with no significant discrepancy in relation to other methods. In sector 26 *Paper and Allied Products*, there is a clear divergence between the parametric and non-parametric methods. In sector 22 *Textile Mill Products* there is an agreement of less efficiency for all methods. From a general perspective there is an agreement of methods for estimation of enterprise efficiency, given that the lower part of Table 5 is almost all dark brown. Regarding the variable (IL), as an addition or through a sectoral analysis it is not possible to extract information based on the color gradient, as the implementation level of the practices, speaking in terms of sectors, seems not to have a clear relationship with the calculated enterprise efficiency.

Table 6 shows the coefficients of the Pearson correlation between the calculated efficiencies and the level of implementation, confirming the strongest correlations between (SFA, CRS, DRS) and (VRS, IRS).

Table 6 – Matrix of Pearson correlation of efficiency and implementation level

	SFA	DRS	CRS	COLS	GMD	IRS	VRS	GMI	IL
SFA	-	**0.697***	**0.697***	0.145*	**0.956***	0.216*	0.217*	0.217*	0.000
DRS	-	-	**1.000***	0.148*	**0.852***	**0.663***	**0.664***	**0.664***	0.016
CRS	-	-	-	0.148*	**0.852***	**0.664***	**0.665***	**0.664***	0.016
COLS	-	-	-	-	0.143*	0.067*	0.068*	0.067*	-0.015
GMD	-	-	-	-	-	0.376*	0.377*	0.376*	0.011
IRS	-	-	-	-	-	-	**1.000***	**1.000***	0.036*
VRS	-	-	-	-	-	-	-	**1.000***	0.036*
GMI	-	-	-	-	-	-	-	-	0.036*

Note: * significant at 1%. Calculation: (correlation matrix between efficiency estimated by the models of the equation 10,11 and12 and the IL variable of the equation 4).

Based on the correlation coefficients of Table 6, it can be affirmed that the degree of linear association between the estimations of efficiency and the adoption of energy efficiency practices is low (less than 3%), requiring an alternative approach for modeling the entire distribution of the dependent variable (quantile regression).

4.2. Relationship between enterprise efficiency and the adoption of energy efficiency practices

Table 7 shows the aggregated enterprise efficiency by 20 most recommended practices. The efficiency of practices is equivalent to the efficiency of enterprise that did and did not adopt the recommended practices in Table 2, remembering that the 39,150 recommendations represent 62.9% of the total practices where 20,599 were implemented and 18,551 not implemented (see Table 2 in %).

The calculated efficiency values of the companies that adopted and did not adopt the practices are very close in all of the 20 practices. Also coinciding with the percentile of 40% greater efficiency values. The testing for differences in the efficiency averages also was not significant. These data show that there is no preference for practices by more efficient companies, when the most recommended practices are analyzed.

Table 7 – Aggregation of efficiency by ARC practice implemented and not implemented

Status	Recommendad	Implemented		Not Implemented	
(ARC) Energy efficiency practices more recommended	Q	Eff	QI	Eff	NQI
27142 Utilize higher efficiency lamps and/or ballasts	7,284	0.7386	4,010	0.7359	3,274
24236 Eliminate leaks in inert gas and compressed air lines/ valves	4,883	0.7425	3,942	0.7391	9,41
24221 Install compressor air intakes in coolest locations	3,465	0.7336	1,558	0.7362	1,907
24133 Use most efficient type of electric motors	3,273	0.7356	2,126	0.7305	1,147
27135 Install occupancy sensors	2,865	0.7413	1,052	0.7395	1,813
22511 Insulate bare equipment	2,149	0.7278	1,027	0.7271	1,122
27143 Use more efficient light source	2,053	0.7425	1,069	0.7386	984
24231 Reduce the pressure of compressed air to the minimum required	1,856	0.7420	913	0.7479	943
24111 Utilize energy-efficient belts and other improved mechanisms	1,680	0.7319	854	0.7295	826
24141 Use multiple speed motors or afd for variable pump, blower	1,225	0.7285	347	0.7325	878
22434 Recover heat from air compressor	1,184	0.7451	379	0.7413	805
21233 Analyze flue gas for proper air/fuel ratio	1,105	0.7349	725	0.7243	380
27261 Install timers and/or thermostats	961	0.7472	492	0.7351	469
27111 Reduce illumination to minimum necessary levels	949	0.7419	478	0.7359	471
24232 Eliminate or reduce compressed air used for cooling	859	0.7379	365	0.7391	494
22131 Insulate steam/hot water lines	805	0.7293	473	0.7316	332
21311 Replace electrically-operated equipment with fossil fuel equipment	777	0.7318	195	0.7315	582
22411 Use waste heat from hot flue gases to preheat combustion air	725	0.7246	115	0.7213	610
27134 Use photocell controls	547	0.7434	222	0.7459	325
26218 Turn off equipment when not in use	505	0.7297	257	0.7399	248
Total Implementations	39,150	-	20,599	-	18,551
Mean of Efficiency		0.7365	-	0.7351	-
t-test - Eff Implemented *versus* Eff Not Implemented			p-value = 0.5236		

Source: (US DOE-IAC_ARC, 2007; US DOE-IAC, 2011)

Note: This table shows only the 20 most recommended practices in a total of 504, calculated by Excel® pivot table. a) (Q= QI+NQI) where Q:(62,263 efficiency of recommendation equivalent to 10,448 enterprise efficiency aggregate by 504 ARC code); QI (quantity Implemented); NQI (quantity not Implemented) c) Eff = geometric mean (SFA. CRS. DRS. VRS. IRS); d) Shaded area (percentile 40% more efficient); e) t-test presuming equivalent variances.

To investigate the level of efficiency of the audited companies and the adoption of energy efficiency practices the quantile regression model (Equation 15)[44] was developed. Based on Equation 15 the dependent variable is the implementation level (IL). The main independent variable is the value of enterprise efficiency u_k^{Eff}estimated by the various methods (SFA. COLS. CRS. DRS. VRS. IRS. GMD and GMI). The auxiliary independent variables are: Energy Intensity of electricity (UEY); Energy Intensity of gas (UNY); Simple Payback (ICPS); Average energy price of the project (PSPC). Table 8 presents the estimations made considering the different efficiency measurements in 15 different quantiles (0.20 to 0.90) of the (IL) variable generating a total of 120 regression models (the coefficients of the GMI and GMD variable regressions are not presented in Table 8).

The supposition of these models in quantile regression is that the level of implementation of the practices depends on the efficiency present in the company, which is different in the various quantiles. Therefore, payback, average price of energy and energy intensity are control variables. Analyzing it another way, once the price of the project, payback and energy intensity are controlled, what is the relationship between enterprise efficiency and the level of implementation of the practices?

Table 8 can be analyzed in two ways: (a) Taking the type of return to scale into consideration for estimating efficiency; (b) Considering the quantile of the dependent variable implementation level (IL). Firstly, when analyzing the returns to scale what stands out is that in all of the quantiles, the sign of the coefficients of the models in constant or decreasing returns (SFA, COLS, CRS, DRS) are negative and the signs of the models in variable or increasing returns (VRS, DRS) are positive. Another factor to be considered is the magnitude of these coefficients, as the measure of the higher

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[44] Estimated by pacote R quantreg (Koenker, 2015) and tested in Gretl (Gnu Regression, Econometrics and Time-series Library - gretl.sourceforge.net) . The (Std. Error and t_value) was omitted for reasons of space.

quantiles are achieved the strength of the relationship increases, either positively or negatively. This factor means that the companies that have higher rates of implementation in energy efficiency are more tuned in to their previous level of efficiency. Taking as an example the quantile 0.90 of SFA, the coefficients can be interpreted in the following manner: An increase of one percentage point (1.0%) in enterprise efficiency lowers implementation to (0.28%). Considering (IRS and VRS) also in quantile 0.90 the interpretation is the inverse: An increase of one percentage point (1.0%) in enterprise efficiency increases the implementation of practices by (0.43%).

Table 8 – Parameters of quantile regression (dependent variable: implementation level)

Quantile θ	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**
SFA	**-0.027**	**-0.077**	**-0.104**	**-0.088**	**-0.083**	**-0.098**	**-0.071**	**-0.118**	**-0.139**	**-0.168**	**-0.190**	**-0.153**	**-0.167**	**-0.217**	**-0.280**
UEY	-0.016	-0.023	-0.02	-0.02	-0.019	-0.022	-0.01	-0.019	-0.022	-0.024	-0.026	-0.022	-0.02	-0.031	-0.036
UNY	0.003	0.004	0.003	0.003	0.003	0.004	0.001	0.000	0.001	0.001	-0.001	-0.001	-0.001	-0.004	-0.002
ICPS	-0.034	-0.033	-0.02	-0.02	-0.027	-0.030	-0.02	-0.032	-0.030	-0.028	-0.028	-0.025	-0.02	-0.022	-0.024
PSPC	-0.005	-0.006	-0.005	-0.00	-0.008	-0.009	-0.00	-0.011	-0.012	-0.012	-0.013	-0.011	-0.01	-0.014	-0.016
COLS	**-0.262**	**-0.348**	**-0.40**	**-0.44**	**-0.467**	**-0.512**	**-0.53**	**-0.559**	**-0.600**	**-0.637**	**-0.284**	**-0.328**	**-0.38**	**-0.474**	**-0.505**
UEY	-0.015	-0.018	-0.01	-0.01	-0.013	-0.015	-0.01	-0.009	-0.011	-0.012	-0.011	-0.011	-0.01	-0.014	-0.010
UNY	0.003	0.005	0.004	0.003	0.004	0.005	0.001	0.001	0.002	0.003	0.001	0.000	-0.001	-0.002	-0.002
ICPS	-0.034	-0.032	-0.03	-0.02	-0.026	-0.031	-0.02	-0.032	-0.029	-0.028	-0.028	-0.025	-0.02	-0.023	-0.023
PSPC	-0.005	-0.005	-0.005	-0.00	-0.008	-0.009	-0.00	-0.010	-0.012	-0.011	-0.012	-0.010	-0.01	-0.013	-0.014
CRS	**-0.047**	**-0.107**	**-0.111**	**-0.081**	**0.004**	**-0.007**	**-0.030**	**0.003**	**-0.051**	**-0.003**	**0.015**	**-0.002**	**-0.108**	**-0.005**	**-0.107**
UEY	-0.015	-0.019	-0.01	-0.01	-0.012	-0.015	-0.01	-0.009	-0.011	-0.011	-0.009	-0.011	-0.01	-0.013	-0.013
UNY	0.003	0.004	0.003	0.003	0.004	0.005	0.001	0.001	0.002	0.003	0.001	0.001	-0.001	-0.003	-0.002
ICPS	-0.034	-0.032	-0.03	-0.02	-0.026	-0.031	-0.02	-0.032	-0.028	-0.028	-0.028	-0.025	-0.02	-0.023	-0.023
PSPC	-0.005	-0.004	-0.006	-0.00	-0.008	-0.009	-0.00	-0.010	-0.012	-0.011	-0.012	-0.010	-0.01	-0.013	-0.013
DRS	**-0.047**	**-0.112**	**-0.111**	**-0.087**	**0.003**	**-0.007**	**-0.030**	**0.002**	**-0.052**	**-0.003**	**0.015**	**-0.004**	**-0.108**	**-0.006**	**-0.107**
UEY	-0.015	-0.019	-0.01	-0.01	-0.012	-0.015	-0.01	-0.009	-0.011	-0.011	-0.009	-0.011	-0.01	-0.013	-0.013
UNY	0.003	0.004	0.003	0.003	0.004	0.005	0.001	0.001	0.002	0.003	0.001	0.001	-0.001	-0.003	-0.002
ICPS	-0.034	-0.032	-0.03	-0.02	-0.026	-0.031	-0.02	-0.032	-0.028	-0.028	-0.028	-0.025	-0.02	-0.023	-0.023
PSPC	-0.005	-0.004	-0.006	-0.00	-0.008	-0.009	-0.00	-0.010	-0.012	-0.011	-0.012	-0.010	-0.01	-0.013	-0.013
VRS	**0.037**	**0.059**	**0.090**	**0.118**	**0.130**	**0.177**	**0.177**	**0.247**	**0.326**	**0.373**	**0.354**	**0.283**	**0.399**	**0.370**	**0.428**
UEY	-0.013	-0.015	-0.01	-0.01	-0.010	-0.012	-0.006	-0.005	-0.004	-0.004	-0.005	-0.005	-0.006	-0.007	-0.002
UNY	0.003	0.004	0.004	0.003	0.004	0.005	0.002	0.002	0.003	0.003	0.003	0.002	0.000	0.000	0.001
ICPS	-0.034	-0.032	-0.02	-0.02	-0.028	-0.030	-0.02	-0.032	-0.030	-0.031	-0.029	-0.025	-0.02	-0.023	-0.025
PSPC	-0.005	-0.005	-0.005	-0.00	-0.008	-0.009	-0.00	-0.011	-0.012	-0.013	-0.014	-0.011	-0.01	-0.014	-0.016
IRS	**0.041**	**0.065**	**0.091**	**0.121**	**0.135**	**0.180**	**0.177**	**0.247**	**0.326**	**0.373**	**0.357**	**0.283**	**0.400**	**0.370**	**0.428**
UEY	-0.013	-0.015	-0.01	-0.01	-0.010	-0.012	-0.006	-0.005	-0.004	-0.004	-0.005	-0.005	-0.006	-0.007	-0.002
UNY	0.003	0.004	0.004	0.004	0.004	0.005	0.002	0.002	0.003	0.003	0.003	0.002	0.000	0.000	0.001
ICPS	-0.033	-0.032	-0.03	-0.02	-0.028	-0.030	-0.02	-0.032	-0.030	-0.031	-0.029	-0.025	-0.02	-0.023	-0.025
PSPC	-0.005	-0.005	-0.005	-0.00	-0.008	-0.009	-0.00	-0.011	-0.012	-0.013	-0.014	-0.011	-0.01	-0.014	-0.016

Note: a) Independent variables are defined in quantile regression model of equation 15: ($SFA, COLS, CRS, DRS, VRS, IRS = u_k^{Eff}$; $UEY = \frac{UE}{Y}$; UNY = $\frac{UN}{Y}$; ICPS = $\frac{IC}{PS}$; PSPC = $\frac{PS}{PC}$). b) Shaded area (Coefficients statistically significant by at least 5%).

One issue to be resolved, related to the main objective of this work is interpreting the sign, using the models under different hypotheses of return to scale. When the sign is positive it means that a more efficient company adopts more energy management practices and the opposite is true when the sign is negative. Figure 1 shows the graph of the estimated coefficients of Table 8 (underlined values significant at 5% for SFA and IRS), which consider the practices in all of the recommended categories, (*Energy Management. Waste Minimization/Pollution Prevention and Direct Productivity*

Enhancement) and Figure 2 only the recommendations of energy management which represent 88% of the recommendations.[45]

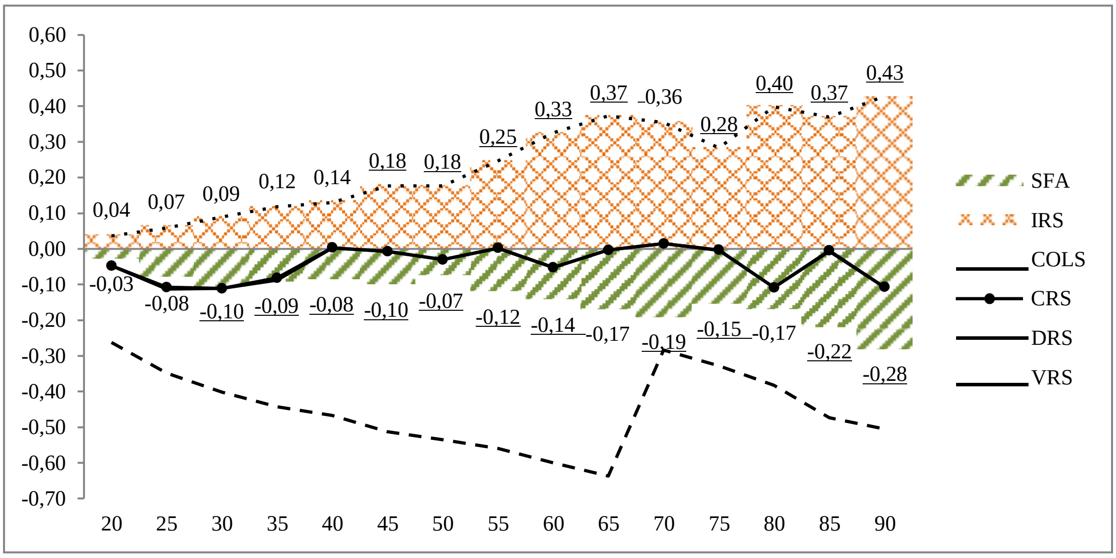

Fig. 1. Quantile coefficients (all three categories of recommendations)

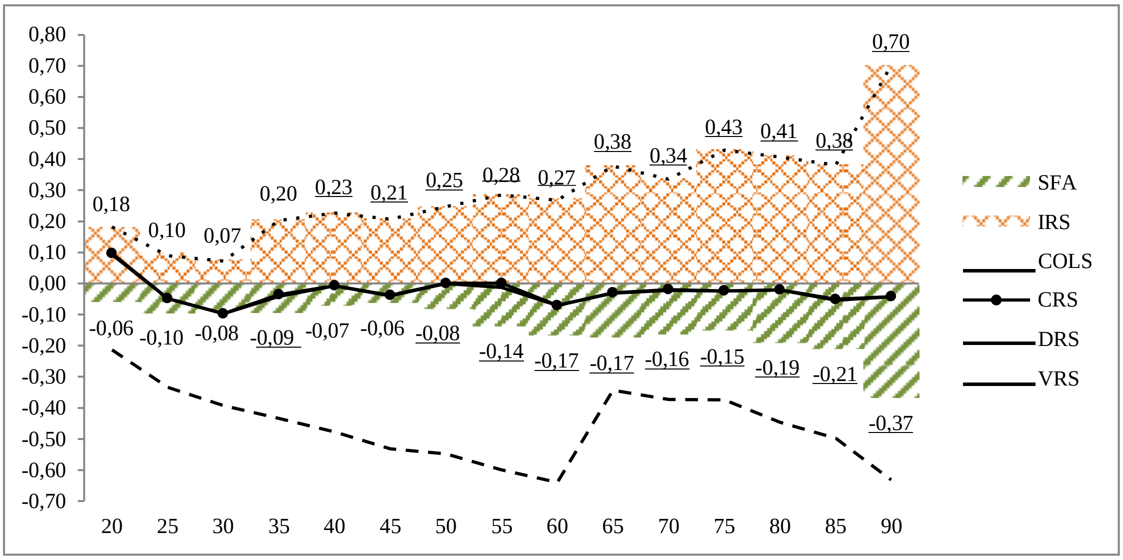

Fig. 2. Quantile coefficients (energy management recommendations)

Figure 2 was included to demonstrate that even if only the energy management category is considered, the behavior or tendency of the graph does not change, possibly because the majority of the recommendations (88%) are for energy management practices or in synergy with other categories such as: waste minimization/pollution prevention and direct productivity enhancements.

According to Figures 1 and 2 the implementation of energy efficiency practices depends on two factors related to enterprise efficiency: The returns to scale of the company and the actual level of implementation of practices. Considering a situation of increased returns to scale, controlling factors such as price, payback and energy intensity, the companies will tend to implement a greater number of practices (IRS area of the graphs in Figures 1 and 2). On the other hand, if there are decreased returns, fewer practices will be implemented (SFA area in the graphs Figures 1 and 2). The degree of

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[45] The ARC table (Assessment Recommendation Code - https://iac.university/technicalDocuments) has 357 recommendations of 5 digits recorded for energy management, 243 for waste minimization/pollution prevention and 76 for direct productivity enhancements. The majority of the recommendations (88%) in the sample used for this work (10.448 cases) are for energy management.

advancement, whether positive or negative depends on the number of implementations executed, otherwise, if the number of implementations increases (higher quantile), when the company operates on increasing returns, the efficiency has a greater positive impact on implementations, on the other hand when the company operates on decreasing returns, the efficiency has a greater negative impact on implementations.

Figure 3 uses the estimated efficiency values on increasing or variable returns (GMI) and constant or decreasing returns (GMD). The behavior of the graph in Figure 3a is similar to the IRS coefficients in Figures 1 and 2, in turn, the graph for Figure 3b is similar to the SFA coefficients for the same figures, generating proof of the existence of dominant behavior of increasing and decreasing returns.

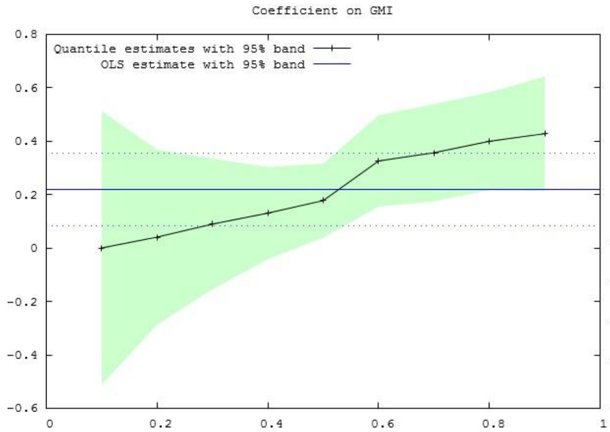

Fig. 3a – Coefficients GMI *versus* OLS

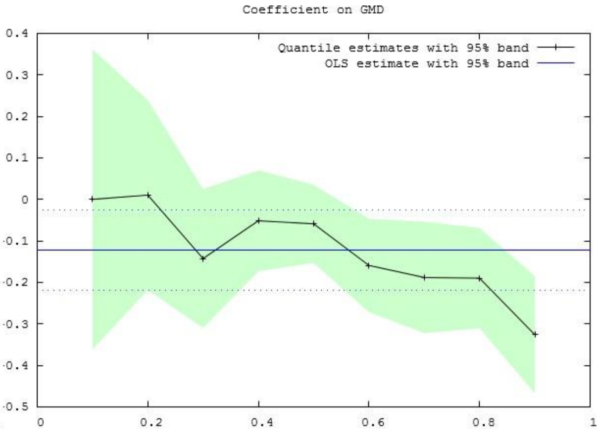

Fig. 3b – Coefficients GMD *versus* OLS

5. Discussion

Table 1 presents the main results found in the literature review regarding the implementation of technologies for energy efficiency/savings. These works can be classified into two different groups. Those that want to know the determinants for more effective energy efficiency, considering energy efficiency as an effect (Christoffersen et al. 2006; Thollander and Otosson, 2010; Suk et al. 2013; Liu et al. 2013; Zhang and Wang, 2014; Tonn and Martin, 2000; Anderson and Newell, 2004; Abadie et al. 2012; Therkelsen and McKane, 2013; Blass et al., 2014) and the articles that want to measure the impact of efficiency on the company's performance, considering energy efficiency as a cause (Kounetas and Tsekouras, 2010; Pons et al., 2013; Eccles and Serafeim, 2013). The objective of our work more closely resembles that of the first group. In other words, it sought mainly to find out if prior efficiency in the companies is a determinant for the implementation of energy efficiency measures or technologies.

Table 2 reveals that among the most recommended energy efficiency practices, the proportion of implementations (33.15%) is almost equal to the non-implementations (29.8%). Even more simple practices like (Utilizing higher efficiency lamps and/or ballasts; Turning off equipment when not in use) are not fully adopted. The 20 most recommended practices have a rate of adoption similar to that found in Anderson and Newell (2004) and is in agreement with the results of Christoffersen et al. (2006) and Thollander and Otosson (2010) as the energy management practices still are not a priority for the majority of industrial enterprises. The data in Table 7 indicates that there is no preference for practices by more efficient companies when considering the practices most recommended in audits, as the average individual values are very close and the general average shows no significant difference.

In terms of sectors, Table 5 shows a certain level of agreement for estimated enterprise efficiency, considering the different models, although there are differences, especially among the models under different conditions of return to scale for sectors such as Chemicals and Allied Products, Food and Kindred Products and Paper and Allied Products. A correspondence can be found in the literature for the results in Table 5, as the petroleum sector was also considered more efficient in the work of Azadeh et al. (2007) and the literature identifies resource efficiency problems in the Textile sector, which was found to be the least efficient sector (Negai et al. 2012; Moon et al. 2013; Alkaya and Demirer, 2014). According to the correlation matrix of Pearson in Table 6 it was not possible to draw conclusions regarding the main problems of the research (relationship between enterprise efficiency and the adoption of practices), which calls for a more sophisticated approach such as quantile regression.

The application of the quantile regression model in Equation 15 was more satisfactory, as summarized in Table 8 and in Figures (1, 2 and 3), revealing that there is both a positive and negative relationship between enterprise efficiency and the adoption of energy efficiency practices. The energy intensity of electricity (UEY) had a negative relationship, in other words, more intensive companies implemented fewer practices possibly due to the fact that these companies have already adopted simpler practices, as only the number of recommendations was considered in the (IL) variable. The energy intensity variable for natural gas (UNY) in the majority of estimations showed a positive relationship to implementation, but without significance. In the work of Abadie et al. (2012) the implementations related to natural gas had a lower probability of implementation. The ICPS variable or simple payback obtained statistical significance in all of the models and shows a negative relationship, confirming the results of Anderson and Newell (2004) and Abadie et al. (2012) that the greater the payback the fewer practices will be implemented. The variable average price of energy of the project (PSPC) shows a negative relationship with implementation. The price of energy in the work of Anderson and Newell (2004) has a positive relationship with implementation but when the variation was increased raising the price to the square the relationship was also negative, similar to the findings in our work.

Regarding the various models of enterprise efficiency, it was found that the sign of relationship depends on the return to scale of the companies, negative for decreasing and positive for increasing. Clearly Figures (1, 2 and 3) reveal that the strength of the relationship depends on the quantile of implementations. This result shows that in addition to cost, the payback of the project and price of energy found by Anderson and Newell (2004) and Abadie et al. (2012) and also in our work, the implementations also depend both on prior efficiency and returns to scale of the company and the strength of the relationship depends on whether the company has already adopted many or few of the practices. Figure 4 summarizes the behavior of the companies translated in Figures 1, 2 and 3 into four categories: Low rate of adoption, high rate of adoption, low rate of rejection, high rate of rejection. The interpretation of the categories indicates that the same variation in efficiency can stimulate behaviors that depend both on returns to scale of the company (low or high return on investments) as well as whether the company adopts many or few practices (being more conscious or less conscious).

			Level of Implementation	
			Low **Less Conscious**	High **More Conscious**
Returns to Scale	Increasing	**High Return on investment**	**α** LOW RATE OF ADOPTION	**β** HIGH RATE OF ADOPTION
	Decreasing	**Low return on investment**	**λ** LOW RATE OF REJECTION	**Θ** HIGH RATE OF REJECTION

Fig. 4. Quadrant of the categories of adoption of energy efficiency practices

The practical interpretation of the quadrant adoption of energy efficiency practices in Figure 4 is that for a certain level of efficiency the adoption will be higher if the company has a higher return on investments and is still initiating the adoption process (β). The policymakers can take this into consideration since in the other three cases of Figure 4 (α. λ and θ) the result is going to be lower than desired. Also the literature review in Table 1 informs that other factors are determinants for the implementation of energy efficiency practices like: Energy management strategies, self-motivation, support of upper management, trainings, economic incentives, innovation strategies, industrial symbiosis, involvement of operations manager. The quadrant in Figure 4 does not negate these other determinants in the literature, but raises the hypothesis that these factors can be happening in companies with a greater return on investment that are already started on the process of adopting practices.

6. Conclusion

The literature identifies various barriers to industrial energy efficiency and energy management, an understanding of these barriers is needed to make the necessary corrections, both for internal company issues and external policies. Our work sought to answer the following question: What is the relationship between enterprise efficiency and the adoption of energy efficiency practices? To answer the question, we proposed models for the estimation of efficiency as well as a model to test the question. These models were idealized to use the cases from energy efficiency audits for small and medium-sized DOE-IAC companies. The main result found in our work was that projects do not depend only on cost and payback, they also depend on the current level of efficiency of the company and whether or not the company has already started some energy efficiency projects. This dependence occurs in two ways, if the company operates with increasing returns, it will probably incorporate more energy management and energy efficiency projects, on the other hand, if the returns are decreasing, more projects will be put aside. This result generates evidence that it is not necessarily the most efficient companies that are concerned with environmental issues. Since according to our study if a company is more efficient, but is operating with decreasing returns to scale, it will adopt a lower number of practices for energy savings.

A second issue raised was if there is a difference in efficiency between the companies that adopted certain practices and those that didn’t? When the efficiency was added to more recommended practices we did not find significant evidence that there is a preference for practices by the more efficient companies. Our work suggests that policies for stimulating sustainable behaviors in the area of energy efficiency can have unintended results. This fact can be seen in the quadrant of categories for adopting energy efficiency practices, since, for example, a more conscious company can have a high level of rejection if it operates with decreasing returns.

The main limitation of our work is related to the creation of the dependent variable in the test model, implementation level (IL), since this variable measures the number of recommendations adopted and not the quality of the recommendations related to the energy savings potential. Another limitation is that the extrapolation of the results has to be analyzed with care since the sample of IAC cases is made up of small and medium-sized companies.

For future work we suggest including the quality of the recommendations as well as additional variables such as innovation, in other words, how innovation has influenced the implementations of the IAC-DOE project. Do the more innovative companies have higher rates of implementation? If it is found that the companies with higher return to scale are also more innovative, thus this work can conclude that more innovative companies also have greater rates of implementation.

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APÊNDICE L

APÊNDICE L: ARTIGO 7 - PROPOSAL A DYNAMIC VISUAL PROCESS FOR MONITORING AND CONTROL OF THE ENERGY MANAGEMENT BASED ON ENTERPRISE INPUT OUTPUT MODEL

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Abstract

This paper proposes a dynamic visual process based on enterprise input output model (EIOM) for monitoring and control of energy management of extended enterprise (EE). The logic takes place in four steps: representation of the energy performance of the EE through a framework of processes, mapping of energy efficiency indicators of processes that can be used by processes of EE, adaptation of the EIOM by adding a time dimension allowing the generation of energy performance indicators, and finally the visual representation of the indicators by graphics panels.

Keywords: energy management, enterprise input output model, visual process

Introduction

The aim of this paper is to propose a dynamic visual process for monitoring the energy management actions based on the logic of enterprise input output model (EIOM) (Lin and Polenske, 1998), where are interpreted productivity, efficiency and energy flow indicators. Our paper takes into account the hypothesis recognized by literature on industrial energy efficiency that a continuous improvement of efficiency through energy management is possible (Abdelaziz, et al. 2011; Kannan and Boie 2003; Gordic et al. 2010). The production process is a flexible unit of our representation, since it is in the process that occurs the transformation of inputs (resources) into outputs (products/services). The processes are thought as the base where the energy performance is realized, it is possible to create indicators for the processes (key performance indicators and frontier indicators) and the integration of these indicators in the chain (extended enterprise). The model was implemented in R software. A visual representation of the indicators through graphic panels is proposed.

The work was divided into four sections: Framework of processes for the integrated energy performance management, dynamic enterprise input-output model, visualization of dynamic enterprise input-output model and conclusion.

Framework of processes for the integrated energy performance management

Figure 1 show a framework of processes for managing the energy performance, using the concept of extended enterprise (EE) (Perroni et al. 2014). The concept of EE was first presented by O'Neal and Sackett (1994), creating a governance structure. The work of Beamon (1998) also assumes that performance management in its complete form occurs in the process of the extended enterprise. Traditionally the supply chain is concerned with the flow of materials and information, but gradually is being included the reverse logistics, waste recovery, reuse and remanufacturing (Beamon, 1998). Another flow that can be included is the study of energy flow (Kara et al. 2010). Figure 1 shows that each process of the extended enterprise has its energy performance derived from energy management practices, and this performance is integrated in the extended enterprise (Bititci, et al. 2000).

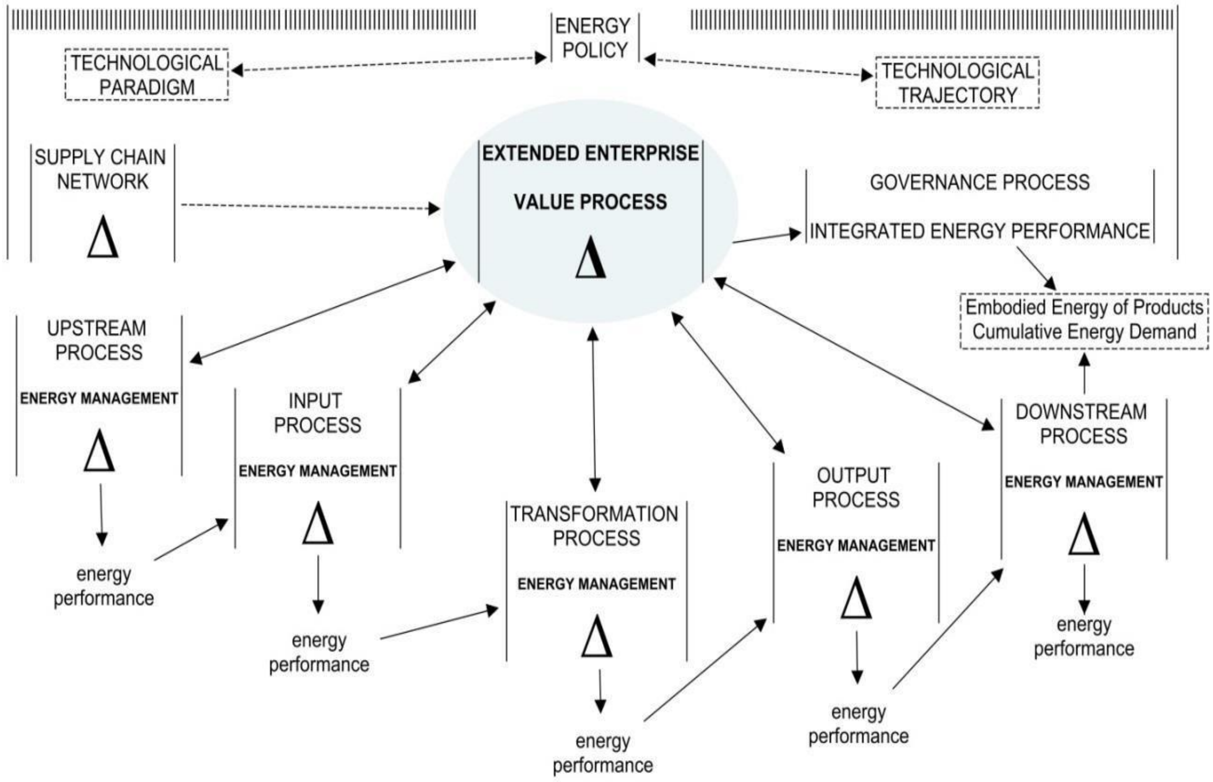

Figure 1- Framework of processes for the management of the integrated energy performance
Source: Adapted from Perroni et al. (2014)

According with Figure 1 the energy performance of extended enterprise can be evaluated by the concept embodied energy of products (Kara et al. 2010) or cumulative energy demand (Patel, 2003). The energy performance of the extended enterprise is not in an isolated environment depending on the supply chain network as well as existing technologies (paradigms and technological trajectories) in the equipment area (Worrell and Biermans 2005) or alternative sources for power generation (Wee et al. 2012). The coordination of the whole system is done by energy policies (Tanaka, 2008).

Map of indicators of energy efficiency of the processes.

Another question is regarding the measures or energy efficiency indicators to represent the energy performance of processes. Using the performance indicator defined in Patterson (1994) (useful output of the process/energy input into the process), by the analysis of the work represented by the group of performance (Perroni et al. 2015), Figure 2 shows the branching of the composition of numerator and of the denominator of the indicator, going to so-called key performance indicators (KPIs) (Phylipsesen et al. 1997; Patterson, 1994; IEA, 2014) to the parametric indicators (Azadeh et al. 2007) and nonparametric (Boyd et al. 2008).

In addition to the indicators, the dotted lines of the map in Figure 2 list some positive or negative characteristics of the indicators.

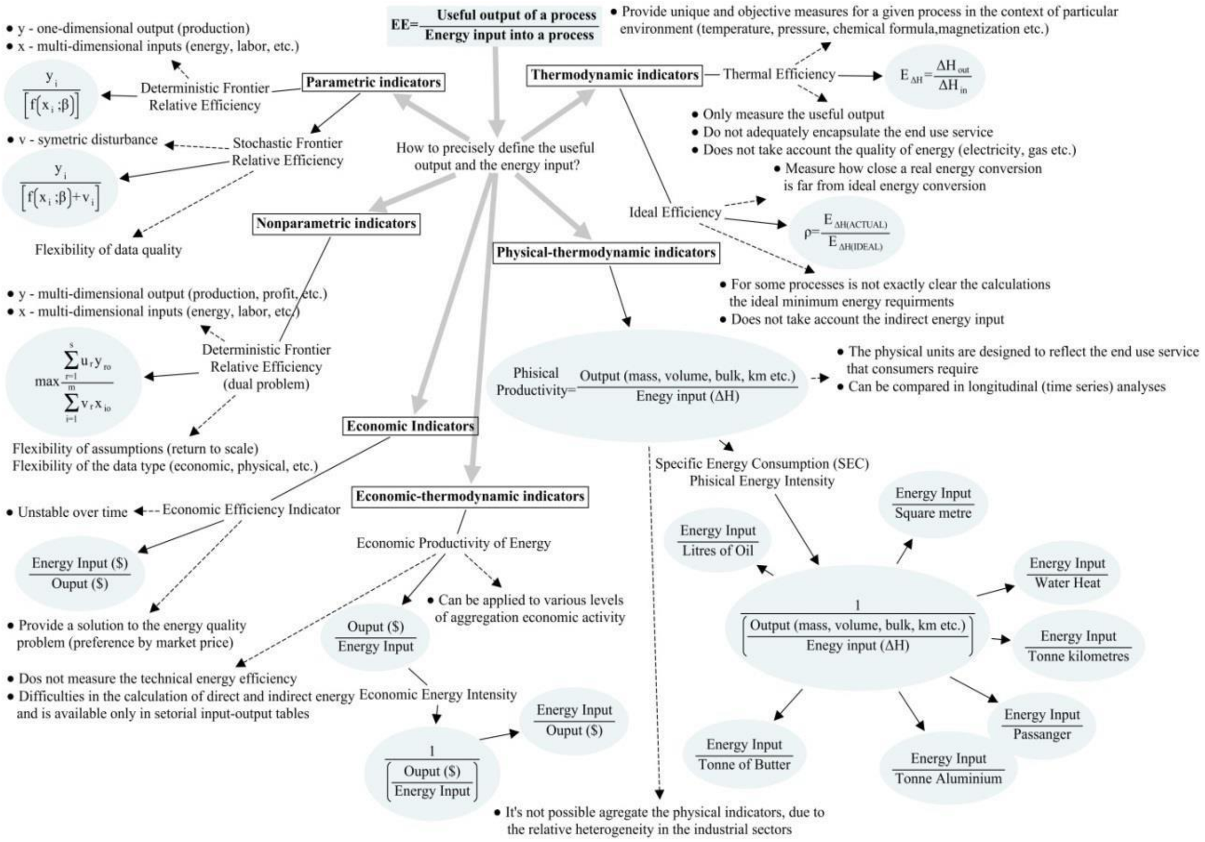

Figure 2: Map of energy efficiency indicators for production processes
Source: (Phylipsesen et al. 1997; Patterson, 1994; Boyd et al. 2008 IEA, 2014)

Dynamic enterprise input-output model

The enterprise input-output model (EIOM) has been designed and applied in the processes of an extended enterprise or part thereof, such as: processes for steelmaking (Lin and Polenske, 1998) processes for the production of coke (Polenske and McMichael 2002), processes for making upholstered (Albino et al. 2002, Albino et al. 2003, Albino et al. 2008), processes for production of tiles (Albino and Kuhtz 2004 Kuhtz et al. 2010) and processes for biodiesel of second generation (Yazan et al. 2012), therefore a natural candidate to represent the energy performance of extended enterprise of Figure 1. The model can be used as a planning/control tool: develop scenarios to see the impact of changes in inputs/outputs, study the flow of materials and energy, analyze the internal and external links of the chain, to quantify the demand for resources, monitor the generation/use of waste/pollution, understand the dematerialization process, among others (Lin and Polenske 1998; Albino et al. 2003; Kuhtz et al. 2010).

Each process of EIOM transforms inputs into outputs, where the main output of a process is the input of the next process and the final output is the product/service sold outside the system (Albino et al. 2003). Each production process requires an amount of materials and energy and that after processing in addition to the main output are generated waste and by-products (Polenske, 1998; Albino et al. 2003; Kuhtz et al. 2010). Figure 3 shows a simplified diagram of logic, adding the time variable in the model, giving the idea of divisibility of processes also in relation to time, and the analysis can be processed after the end of the production cycle. Each new production cycle (time t =1 to n in Figure 3) can produce new results (derived from energy management for example) that need to be analyzed and compared.

With regard to the hierarchy of EIOM, the main unit of analysis is the processes of production (transformation of inputs into outputs through the resource arrangement). An ordered sequence of production processes is defined as the production cycle. The production cycle belongs to a network of production processes that may be located in a local cluster or a global supply-chain (Albino et al. 2002; Kuhtz et al. 2010). Figure 3 is a production cycle, which is a more simplified manner since there is no feedback mechanism (one-way model) (Albino et al. 2003).

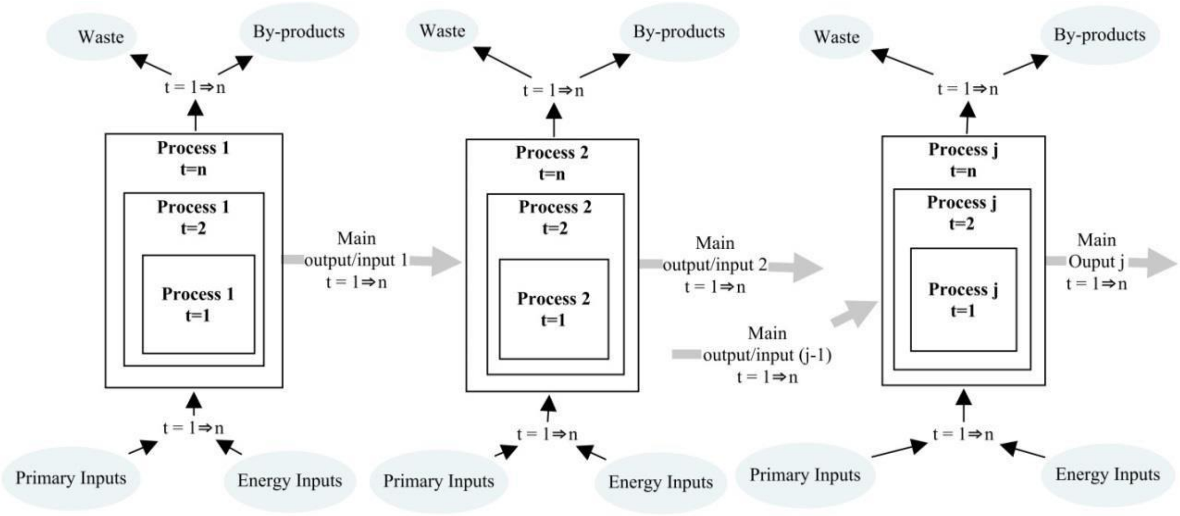

Figure 3 – Dynamic enterprise input-output model
Source: Adapted from Kuhtz et al. (2010)

The Frame 1 shows the main matrix equations of the EIOM and Table 1 is a numerical example of the matrices considering processes for the production of tiles in China. For our purpose only the matrix of the main products (Z and X) and the energy matrix (EM) will be used in the analysis.

$Direct\ coefficients$	$Matrix$	$Demand$	$Indirect\ Coeficients$
$\left\| A = a_{ij} = \frac{Z_{ij}}{X_j} = Z\hat{X}^{-1} \right\|$	$\|Z = AX\|$	$\|Y = AX^T\|$	$\|A^{-1}\|$
$\left\| E = e_{ij} = \frac{E_{ij}}{X_j} = EM\hat{X}^{-1} \right\|$	$\|EM = EX\|$	$\|ED = EX^T\|$	$\|EF = EA^{-1}\|$

Frame 1 - Equations of the enterprise input output model
Source: (Lin and Polenske 1998; Kuhtz et al. 2010)

Considering Table 1 the two matrixes of energy indicators generated by the model are the matrix of direct coefficients ($EM\hat{X}^{-1}$) and the matrix of indirect coefficients (EA^{-1}). The matrix of direct coefficients is the inverse of the indicator of factor productivity of energy (a unit of energy can produce X), or otherwise measure the energy content of the process (a production unit consumes X of energy in its process) (see map of the indicators in Figure 2).

Table 1 - Processes and energy inputs for a ceramic tiles production in China

Processes and products		**Z** – production and intermediate consumption of man products					Y – Final demand
	10^4	**M**	**N**	**O**	**P**	**Q**	**Y**
M – Clay mixture	**t**	16.300	-16.300	0	0	0	**0**
N – Dried tiles	**t**	0	15.600	-15.600	0	0	**0**
O – Cooked tiles	**t**	0	0	15.130	-15.130	0	**0**
P – Polished tiles	**t**	0	0	0	14.740	-14.740	**0**
Q – Packaged tiles	**t**	0	0	0	0	14.760	**14.760**
Types of Energy inputs	**10^4**	**EM** – energy matrix					
Electric Power Kcal	**Kcal**	1.084.129	0	955.066	1.204.588	34.416	3.278.200
Thermal Power Kcal	**Kcal**	4.387.224	1.203.847	9.780.426	0	0	15.371.497
Heavy oil	**Kcal**	4.387.224	0	0	0	0	4.387.224
Diesel oil	**Kcal**	0	0	1.848.000	0	0	1.848.000
Natural gas	**Kcal**	0	1.203.847	7.932.426	0	0	9.136.273
		X – Gross output of main products					
Gross output	**t**	16300	15600	15130	14740	14760	

Source: Fonte: Kuhtz et al. (2010)

Depending on the choice for the composition of the data in Table 1 (changing the denominator and/or the numerator as map of Figure 2), the matrix of direct coefficients of the EIOM may represent a physical-thermodynamic indicator, economic-thermodynamic or economic. The matrix of indirect coefficients is the flow of energy, measuring the energy incorporated into the final product/service (cumulative energy demand) as specified in the model of extended enterprise of Figure 1.

Performance indicator versus energy efficiency indicator

An efficiency indicator is the ratio of two performance indicators, comparing a specific indicator with the maximum that this indicator can achieve. The energy efficiency indicator can be obtained from the ratio of two energy content indicators generated by the model of Figure 3 (Bogetoft and Otto 2011; Perroni et al 2015b). Since the goal is always to reduce energy consumption an ideal indicator comes from ratio of minimum performance/current performance (Perroni et al. 2015b). Based on Figure 2 and 3 and Table 1 with the inclusion of the time variable (t) in EIOM it is possible create some indicators for measuring the energy efficiency.

The indicator (1.ideal) is only the division of the matrix of minimum energy content of the process by the current energy content matrix. The second indicator (2.Change) reflects the change in energy efficiency by dividing the matrix of current content by the matrix of the previous period. The indicator (3.global) takes into account the embodied energy in the processes being a ratio of minimum direct and indirect consumption by current consumption (results of process j of Figure 3). The indicator of relative efficiency (4.relative) takes into account the inter-temporal frontier with the possibility of aggregation of several inputs (electric, thermal, etc.) and several outputs (production, gross output, waste etc.).

$1. \mathit{Ideal}$	$2. \mathit{Change}$	$3. \mathit{Global}$	$4. \mathit{Relative}$
$\left\lvert \frac{[min\,(\frac{E^{t}_{ij}}{X^{t}_{j}})]}{(\frac{E^{t}_{ij}}{X^{t}_{j}})} \right\rvert$	$\left\lvert \frac{(\frac{E^{t}_{ij}}{X^{t}_{j}})}{(\frac{E^{t-1}_{ij}}{X^{t-1}_{j}})} - 1 \right\rvert$	$\left\lvert \frac{\min(\sum_{p=j} EA^{-1})}{\sum_{p=j} EA^{-1})} \right\rvert$	$\left\lvert max\,\frac{\sum_{r=1}^{s} u_r X_{ro}}{\sum_{i=1}^{m} v_i EM_{ro}}\ ; u_{r,}\ v_i \geq 0\ ; st\ \frac{\sum_{r=1}^{s} u_r X_{rt}}{\sum_{i=1}^{m} v_i EM_{it}} \leq 1 \right\rvert$

Frame 2- Energy efficiency indicators of processes

Through the dynamic EIOM, there is a possibility of generation of a large number of indicators, making it impossible to individualized analysis of the indicators, requiring a multidimensional graphical approach.

Visualization of dynamic enterprise input-output model

Two techniques to make multiple viewing of the EIOM are the graphics in panels (Wickham, 2009, 2011) and mosaic plots (Friendly 1994; Meyer et al. 2006).

The visualization process is important to the model for two reasons. A first as identified by Wee et al. (2012) due to a further decline of traditional energy resources such as oil, coal and natural gas, renewable sources such as biomass, geothermal, wind and solar will tend to grow in the energy matrix of the extended enterprise. A visualization system will help in identifying structural comparison in the energy matrix of EE. A second reason is that the visualization can be helpful to monitor the progress of the indicators of the processes over time.

A problem that arises is that the data in Table 1 are not sufficient to represent a dynamic EIOM containing only the time t_0. To generate the data to represent the dynamic EIOM was developed a simulation function based on the central limit theorem (CLT), so that each energy source of the matrix or the output of the EIOM receives the simulation function to decrease/increased of input/output, implemented in software R. Based on data from Table 1 a set of 12 periods were generated for the model data, was possible to mount an energy efficiency indicator panel (see Table 2). The simulation function, simulation matrix and partially panel indicators can be seen in Appendix A.

Chart 1a shows the energy matrix visualization (EM) of Table1 through mosaic graphic and Chart 1b shows the same data through the graphic tiles. The red rectangles mean an energy use below expectations in relation to energy sources, and the blue color represents the energy use larger than expected. The lack of use of the energy source in a given process is represented by a line in the chart 1a and an empty space in Chart 1b.

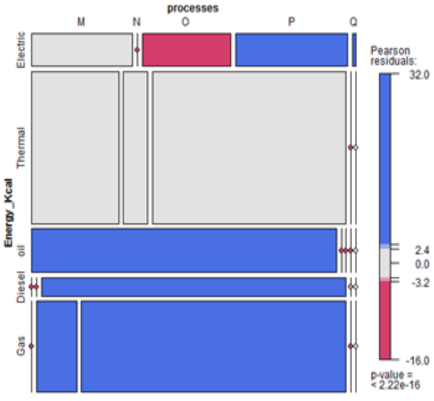

Chart 1a – Mosaic plot of energy matrix

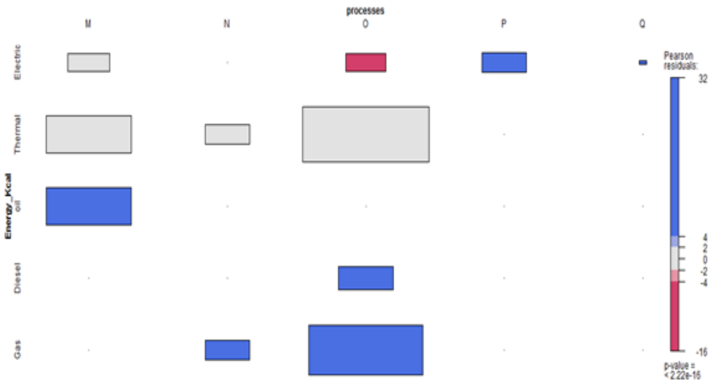

Chart 1b – Tile plot of energy matrix

The Charts 1a and 1b are only demonstrations, since it is also possible to construct visualizations of direct and indirect indicators of Table1. A second question is the comparison of the efficiency indicators of Table 2 over time, considering the energy sources and the processes. The ideal efficiency (1.Ideal) generates 132 indicators. A solution for comparison is to represent these indicators in a graphic panel as Chart 2.

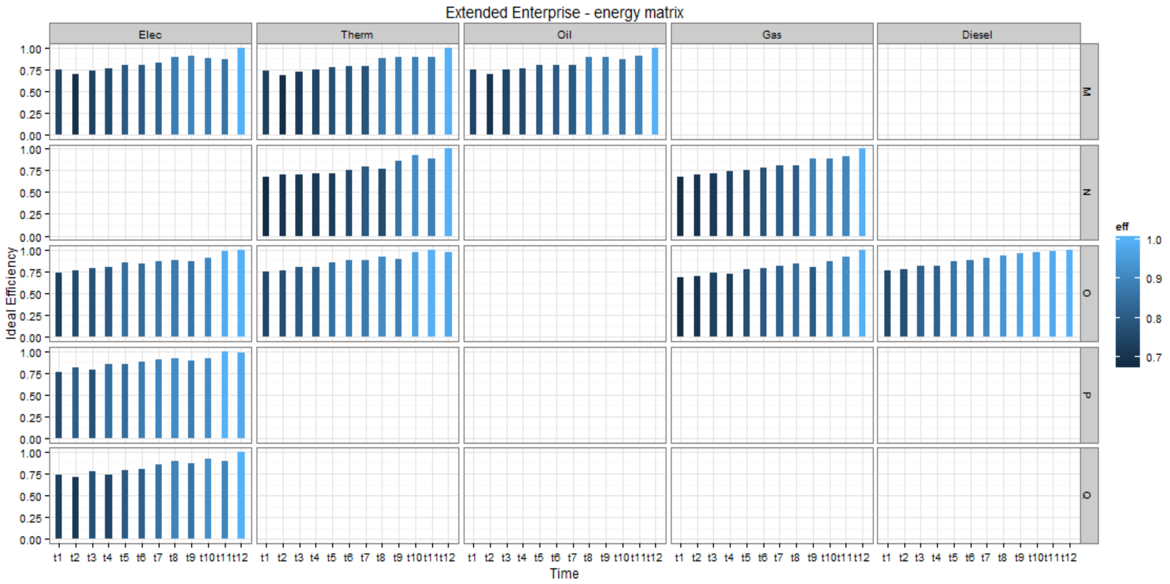

Chart 2 – Panel plot of energy efficiency indicator (1.Ideal)

The larger bars and lighter blue in Chart 2 mean greater efficiency. The structure of Chart 2 is identical to the energy matrix of Table 1, so that the empty spaces indicate that there is no consumption of energy for their specific process. Chart 3 shows the visualization panel for the change in efficiency (2. Change), it is easy to see the improvement or worsening in the simulated energy efficiency.

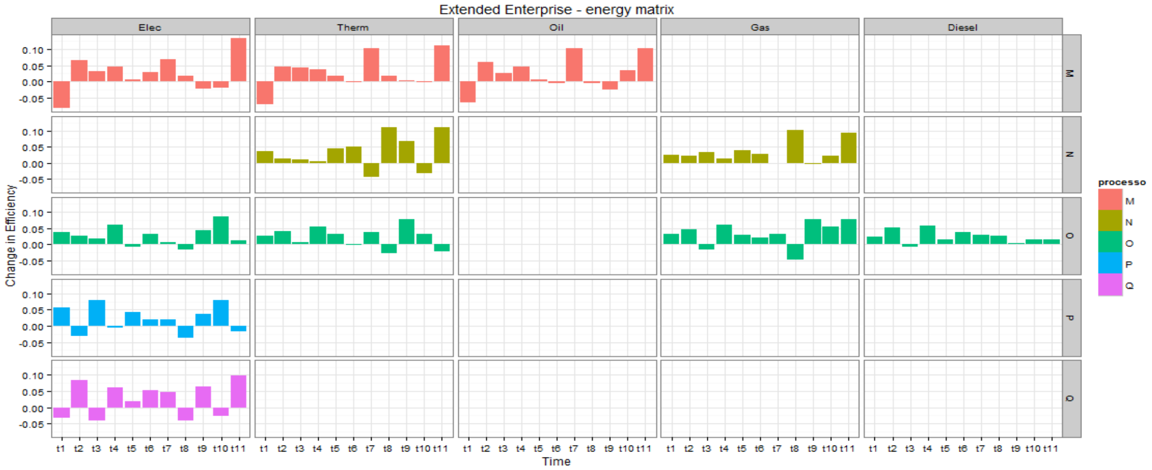

Chart 3 – Panel plot of energy efficiency indicator (2.Change)

Chart 4 shows a second alternative (staircase) to visualization change in efficiency. Any negative changes in proportion efficiency is represented by a red bar, on the other hand, the positive variations are represented by green color.

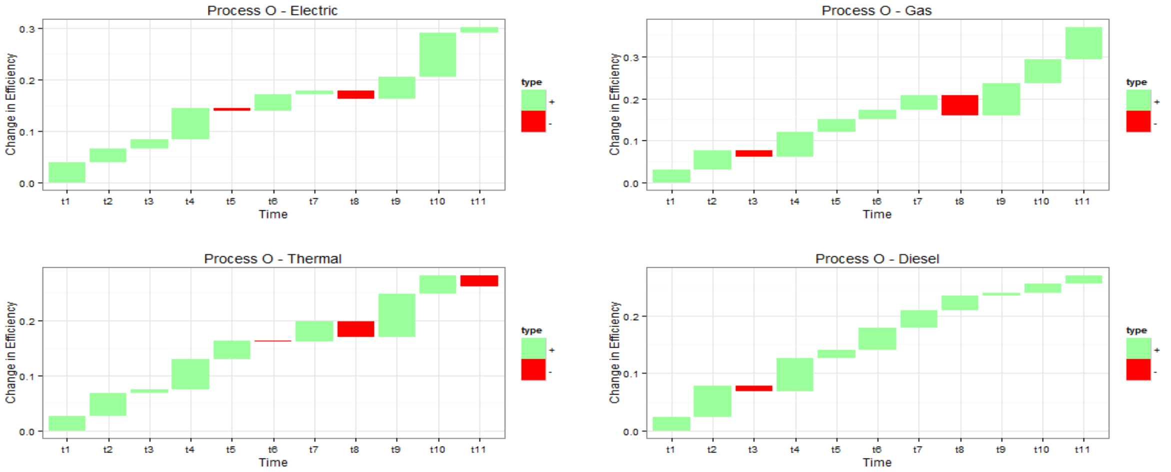

Chart 4 – Staircase Panel of energy efficiency indicator (2.Change – process O)

The indicators of relative efficiency (4.Relative) are shown in Chart 5a and the global efficiency (3.Global) in Chart 5b.

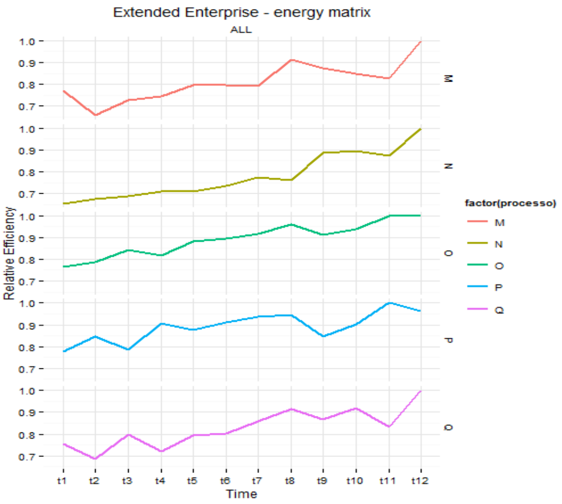

Chart 5a – Intertemporal frontier

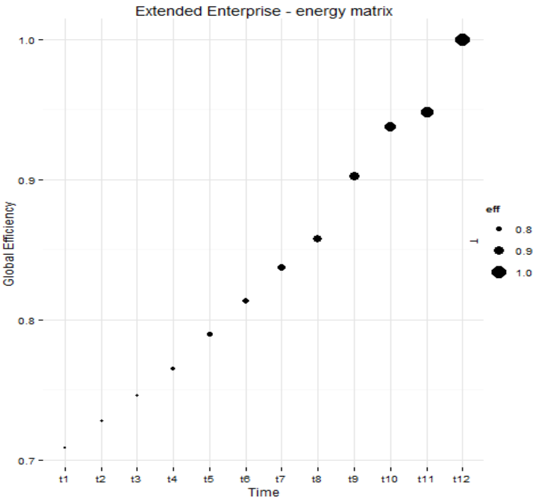

Chart 5b – Global efficiency

The relative efficiency takes into account all energy sources used in the process together (in the case of M process: Electric, Thermal and Oil). The global efficiency indicator takes into account both all energy sources like all processes, is an aggregate efficiency indicator.

Conclusion

The paper proposes a dynamic interpretation of enterprise input output model (EIOM) for measuring the performance of extended enterprise (EE). The EIOM is designed as a flexible framework to compose the processes of the extended enterprise, as well as all appropriate indicators. Was possible to develop indicators for measuring the efficiency of individual energy sources (1.Ideal), change in efficiency (2.Change) energy sources in aggregate processes (4.Relative) and energy efficiency of EE as a whole (3.Global), generating a hierarchy of indicators.

For viewing the indicators, a panel was built where the main dimensions are the energy sources, processes and time. The hierarchy of the visual representation varies according to the hierarchy of the indicators, with three dimensions for ideal and change (Chart 2, 3 and 4) two dimensions for relative efficiency (Chart 5a) and one dimension to the global efficiency (Chart 5b).

Within the framework of dynamic EIOM, new indicators can be created based on the principle of energy content, based on stochastic frontier, for example, depending on the needs of the extended enterprise under analysis and the data quality.

Three limitations can be listed. The first relates to the economic, organizational and behavioral barriers that prevent optimal adoption of measures for energy efficiency raised by Cagno et al. (2013). A second limitation of the model is that, in specific contexts, is not sufficient evaluate only the energy sources but construct indicators of generation/use of waste and related resources (water, waste generation, cogeneration, use of intensive materials energy, among others). The good news is that the flexibility of the EIOM allows extending the logic of the extended enterprise energy matrix to other matrices of resources (materials) with relative facility. A third limitation is in the representation of the EIOM in Figure 3, since processes are simple dependencies (one-way model), forming a production cycle (process sequence). The great advantage of the EIOM is to represent processes with mutual dependence (multi-way model) (Albino et al. 2003) created by a network of productions process, both locations when global.

Acknowledgments

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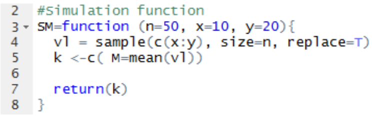
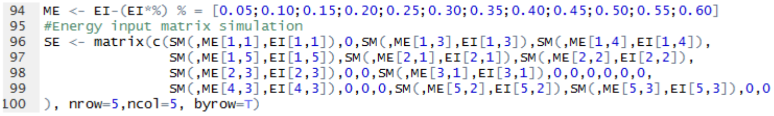
Appendix A



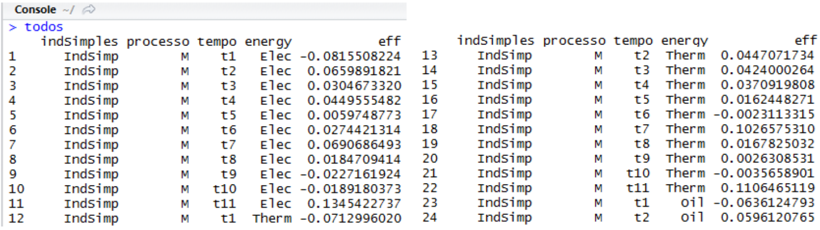
```
#Simulation function
SM=function (n=50, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))

  return(k)
}
```

Code A.1 – Simulation function



```
ME <- EI-(EI*%) % = [0.05;0.10;0.15;0.20;0.25;0.30;0.35;0.40;0.45;0.50;0.55;0.60]
#Energy input matrix simulation
SE <- matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),
               SM(,ME[1,5],EI[1,5]),SM(,ME[2,1],EI[2,1]),SM(,ME[2,2],EI[2,2]),
               SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0,0,0,
               SM(,ME[4,3],EI[4,3]),0,0,0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0
), nrow=5,ncol=5, byrow=T)
```

Code A.2 – Example of matrix simulation



```
> todos
   indSimples processo tempo energy           eff        indSimples processo tempo energy           eff
1     IndSimp        M    t1   Elec -0.0815508224   13     IndSimp        M    t2  Therm  0.0447071734
2     IndSimp        M    t2   Elec  0.0659891821   14     IndSimp        M    t3  Therm  0.0424000264
3     IndSimp        M    t3   Elec  0.0304673320   15     IndSimp        M    t4  Therm  0.0370919808
4     IndSimp        M    t4   Elec  0.0449555482   16     IndSimp        M    t5  Therm  0.0162448271
5     IndSimp        M    t5   Elec  0.0059748773   17     IndSimp        M    t6  Therm -0.0023113315
6     IndSimp        M    t6   Elec  0.0274421314   18     IndSimp        M    t7  Therm  0.1026575310
7     IndSimp        M    t7   Elec  0.0690686493   19     IndSimp        M    t8  Therm  0.0167825032
8     IndSimp        M    t8   Elec  0.0184709414   20     IndSimp        M    t9  Therm  0.0026308531
9     IndSimp        M    t9   Elec -0.0227161924   21     IndSimp        M   t10  Therm -0.0035658901
10    IndSimp        M   t10   Elec -0.0189180373   22     IndSimp        M   t11  Therm  0.1106465119
11    IndSimp        M   t11   Elec  0.1345422737   23     IndSimp        M    t1    oil -0.0636124793
12    IndSimp        M    t1  Therm -0.0712996020   24     IndSimp        M    t2    oil  0.0596120765
```

Code A.3 - Partial view of the indicators panel

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APÊNDICE M

APÊNDICE M: ARTIGO 8 - PROCESSES APPROACH FOR CONTINUOUS MEASUREMENT OF ENERGY PERFORMANCE

CONGRESSO – II EPPGEP – ENCONTRO DE PESQUISA E PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

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Abstract

The objective of this study is to develop a processes approach for continuous measurement of energy performance. The issue of energy performance is represented by a process framework, a map of energy efficiency indicators of processes, and a longitudinal input-output process model. Based on the concept of enterprise efficiency, direct and indirect energy efficiency indicators to continuously monitor energy performance are proposed. The application of the approach is implemented by real processes of tile manufacturing, with simulated data using the R analytics tool. A graphic system of panels is proposed to visualize the indicators.

Keywords: *energy performance, energy efficiency indicators, processes approach to energy*

1 Introduction

The topic of energy has been gaining attention in all sectors of society. The perception that energy is a finite resource has become increasingly clear since the oil crisis of the 1970s. The founding of the International Energy Agency (IEA) in 1974 shows that the problem is not specific to a given country, but a global concern. IEA reports illustrate that the study of energy is relevant for various reasons, such as energy security; economic and social impact of energy prices; concerns about climate change; and competitiveness of businesses (IEA, 2008; IEA, 2014a; IEA, 2014b). Based on statistical data from British Petroleum (BP), spanning 1965–2015, primary energy consumption had an average growth of 2.5% per year. Two factors that impact energy consumption are population growth and increased wealth. According to the United Nations Development Programme (UNDP), from 2016–2030, the global population will increase by about 1 billion people. The desired equalization of development in the world—with the most recent Human Development Index (HDI) ranging from 0.348 in Niger to 0.944 in Norway—would cause an increase in energy consumption that would necessitate an alternative energy solution (UNDP, 2015). Despite the growth of renewable energy, which as of 2011 reached 6.7% in Organisation for Economic Co-operation and Development (OECD countries and 2.7% in other countries, fossil fuels account for 80% of global energy use (IEA, 2014b; IEA, 2016). Fossil fuels are associated with an increased production of harmful pollutants into the environment, such as greenhouse gases (carbon dioxide (CO_2), methane, nitrous oxide). Another problem associated with non-renewable energy is its long term sustainability. The required investment in the pursuit of transitioning to clean energy has been estimated at 1% of the gross world product (US$0.8 trillion for a gross world product of US$83 trillion) (IEA, 2008).

As acknowledged by Tanaka (IEA, 2008), the ideal scenario involves multiple actions, both from the demand side and from the supply side of energy. On the supply side, efforts have been made to support renewable energy sources such as biomass, ocean waves, geothermal, wind, and solar (Wee et al., 2012). As for the demand side, it is recognized that energy efficiency can be a critical step towards a more rational and sustainable use of energy. According to the IEA, the contribution of energy efficiency to CO_2 reduction can reach 44% (IEA, 2014a). The IEA states that if it were not for energy efficiency improvement actions (Tanaka, 2011), the energy consumption in 2005 would have been 58% higher (IEA, 2008).

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Recent literature has postulated that the role of energy efficiency/management is no longer only applicable to governmental and non-governmental agencies, or even to companies and industries considered intensive users of energy, but to any entity that relies on energy (Gordic et al., 2010; Bunse et al., 2011; Negai et al., 2013). The problem is that, as acknowledged by Bunse et al. (2011), there is a lack of frameworks from which this systematic approach can be studied, as well as a lack of development and interpretation of indicators, and a shortage of models in which the logic of energy efficiency can be made operational.

The objective of this study is to develop a processes approach for continuous measurement of energy performance. The production process is the flexible unit in our representation, since the transformation of inputs into outputs occurs in processes. The processes are considered the base in which energy performance becomes a reality, making it possible to create indicators for the processes and further integrate these indicators into the production chain (extended enterprise). The energy performance relates to energy efficiency or a lower energy use to achieve a specific end (Patterson, 1996). Three *ad hoc* hypotheses are fundamental: (1) the problem of energy efficiency is part of the positive heuristic of the protective belt of the sustainability research program; (2) it is possible to identify both measures and technologies that, with their implementation, can improve the energy efficiency of the processes; (3) it is possible to split an organizational entity (company, chain) into a finite number of main processes.

The main objective is broken down into the following complementary objectives: (a) propose a processes framework for measuring energy performance; (b) create a map of indicators of energy efficiency of processes; (c) propose a longitudinal input-output process model for continuous measurement of energy performance; (d) develop hierarchical indicators for continuous measurement of energy performance based on the proposed processes approach; (e) develop a simulation approach, from a real process structure, to feed the model with data; and (f) build an approach for the multidimensional visualization of the indicators.

The following sections are organized to meet the complementary objectives. Section 2 presents the methodological discussion of how the problem can be represented and approached. Section 3 develops the energy performance representation through a framework, a map, and a model. Section 4 presents the approach for continuous measurement of energy performance, creating the indicators, as well as the approach to simulation and visualization. Sections 5 and 6 include a discussion and conclusion, respectively.

2 Research Design: Representation and Approach

The objective of proposing a processes approach for continuous measurement of energy performance is complex because it involves a multidisciplinary approach related to energy efficiency. The affinity of several areas to the theme of performance/energy efficiency can be explained in general terms by the pursuit of sustainable production and consumption of goods and services (Machado, 2015). The energy efficiency issue is related to the emerging sustainability paradigm (Kuhn, 1962). The work of Lakatos (1978) proposes that science evolves through research programs. The research program has a hard core, which is protected from falsification by a belt of auxiliary hypotheses. Scientists solve certain problems within the protective belt, identifying the problems that will be solved (positive heuristic) and the problems that will remain unaddressed (negative heuristic). Energy efficiency can be positioned within the sustainability research program. The research question from the sustainability hard core appears in the Brundtland Report of 1987 (WCED, 1987): How to meet the needs of the present without compromising the ability of future generations to meet their own needs? The sustainability research program becomes complex because it involves a number of forces or megaforces described in a KPMG report: climate change, material resource scarcity, ecosystem decline, food security, energy/fuels, population growth, urbanization, water scarcity, and deforestation (Machado, 2015; KPMG, 2012). These global forces described by KPMG form the positive heuristic of Lakatos' sustainability research program (1978).

According to Lakatos (1978), the energy efficiency hypothesis is part of the core protective belt/sustainability paradigm. A prerequisite to be sustainable is to be energy efficient; thus, the hypothesis cannot be falsified. Figure 1 shows the energy efficiency positioning in the sustainability research program. What makes the theme of energy/energy efficiency complex within the research program is the relationship that energy has with the other nine forces. There is an undeniable connection between energy and climate change, resource use, urbanization, wealth, and other factors.

The development complexity of a processes approach for continuous measurement of energy performance must be seen from a systemic perspective. Based on the manufacturing management perspective, the engineering department of the Institute for Manufacturing at the University of Cambridge presents definitions in terms of how complex problems could be represented or approached from the engineering point of view (Shehabudden et al., 1999). Figure 2 illustrates how the representation of and approach to problems can be seen.

Just like with Kuhn (1962), the starting point is the energy efficiency problem positioning within the paradigm, which was positioned within the emerging sustainability paradigm. As defined by Shehabudden et al. (1999, p. 7): "A paradigm describes the established assumptions, and conventions which underpin a particular perspective on a management issue." A paradigm thus defined is similar to the Lakatos (1978) research program.

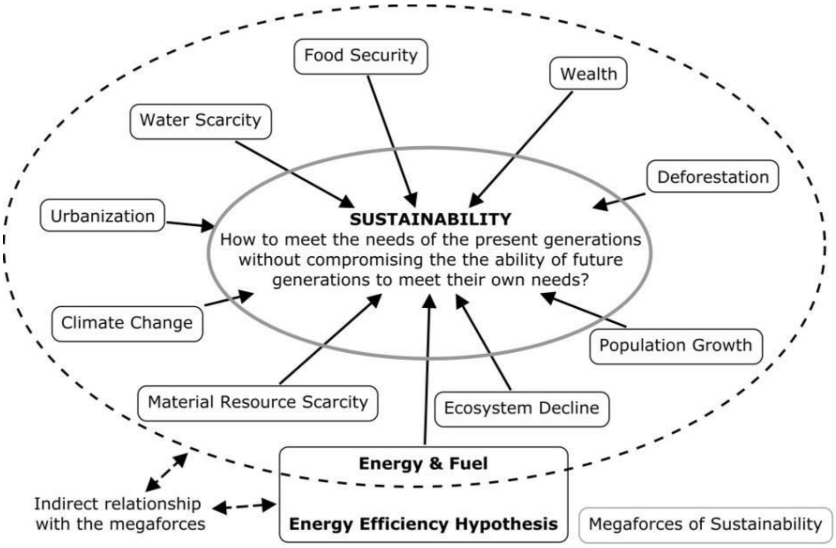


Figure 1 – Energy efficiency positioning in the sustainability research program
Source: WCED, 1987; KPMG, 2012; Machado, 2015

In Figure 2, the representations and approaches are positioned in four dimensions: conceptual, applied, static, and dynamic. The representations (framework, map, model) are ways to report problems, which are more conceptual and inductive. The approaches (process, procedure, technique, tools) are more practical ways to implement the concepts contained in the representations, which are more deductive. Another relevant dimension is the interaction of the elements composition of the problem, which looks more like a map if static and more like a model if dynamic (Shehabudden et al., 1999).

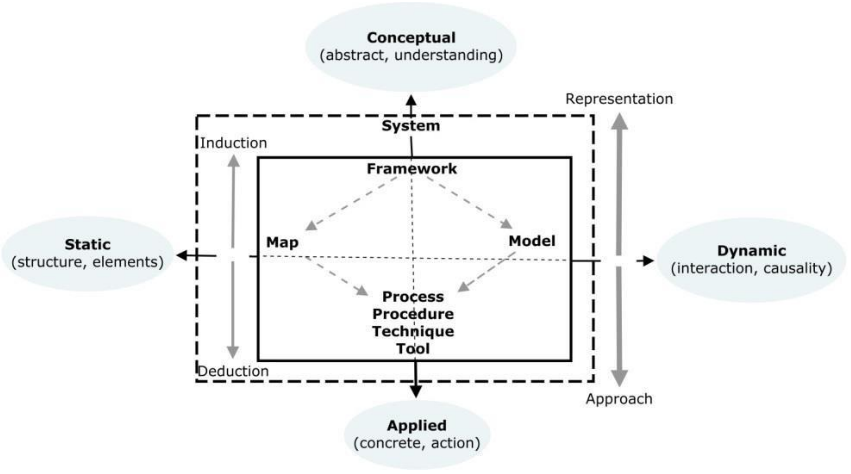


Figure 2 – Methodology of representation of and approach to research
Source: Adapted from Shehabudden et al. (1999)

In Figure 2, the approaches and representations work within a system: “A system defines a set of bounded interrelated elements with emergent properties and represents it within the context of a paradigm” (Shehabudden et al., 1999, p. 8). Delimitation is necessary to propose a processes approach for continuous measurement of energy performance. The main focus is in the manufacturing sector (Napp et al., 2014), which can be considered a boundary by which the energy efficiency of production processes can be unfolded, since manufacturing is responsible for more than 30% of direct energy consumption (Napp et al., 2014). A relevant issue is the indirect energy consumption, with the industrial sector (manufacturing) at the center of the energy flow, as it uses energy from raw material extraction to the product/service (output) consumption.

As a complementary objective, the building of a structural framework of the integrated energy performance was proposed. In Figure 2, a framework has a higher conceptual level: “A framework supports understanding and communication of structure and relationship within a system for a defined purpose” (Shehabudden et al., 1999, p. 9). The structural framework of the integrated energy performance attempts to highlight two fundamental issues: (a) that the energy performance can be improved continuously; (b) and the energy performance can be integrated into a flow or network.

Another complementary objective is to build a map of energy efficiency indicators of processes: “A map supports understanding of the static relationship between elements of a system” (Shehabudden et al., 1999, p. 11). The system elements are the range of indicators that can be created to represent the energy performance.

One of the complementary objectives in relation to Figure 2 is the proposal of a longitudinal input-output process model: “A model supports the understanding of the dynamic interaction between the elements of a system” (Shehabudden et al., 1999, p. 13). The function of the model is to describe how the system will operate if there is a change in certain variables; in other words, it captures the relation of cause and effect (Shehabudden et al., 1999).

The implementation of the processes approach for continuous measurement of energy performance is made possible by the procedures, techniques, and tools: “A process is an approach to achieving a managerial objective, through the transformation of inputs into outputs” (Shehabudden et al., 1999, p. 14). The processes are the fundamental units used to calculate and integrate the energy performance in this study, continuously measuring performance. To achieve this objective, the input-output process model was used (Lin and Polenske, 1998; Polenske and McMichael, 2002), which was adapted to work longitudinally.

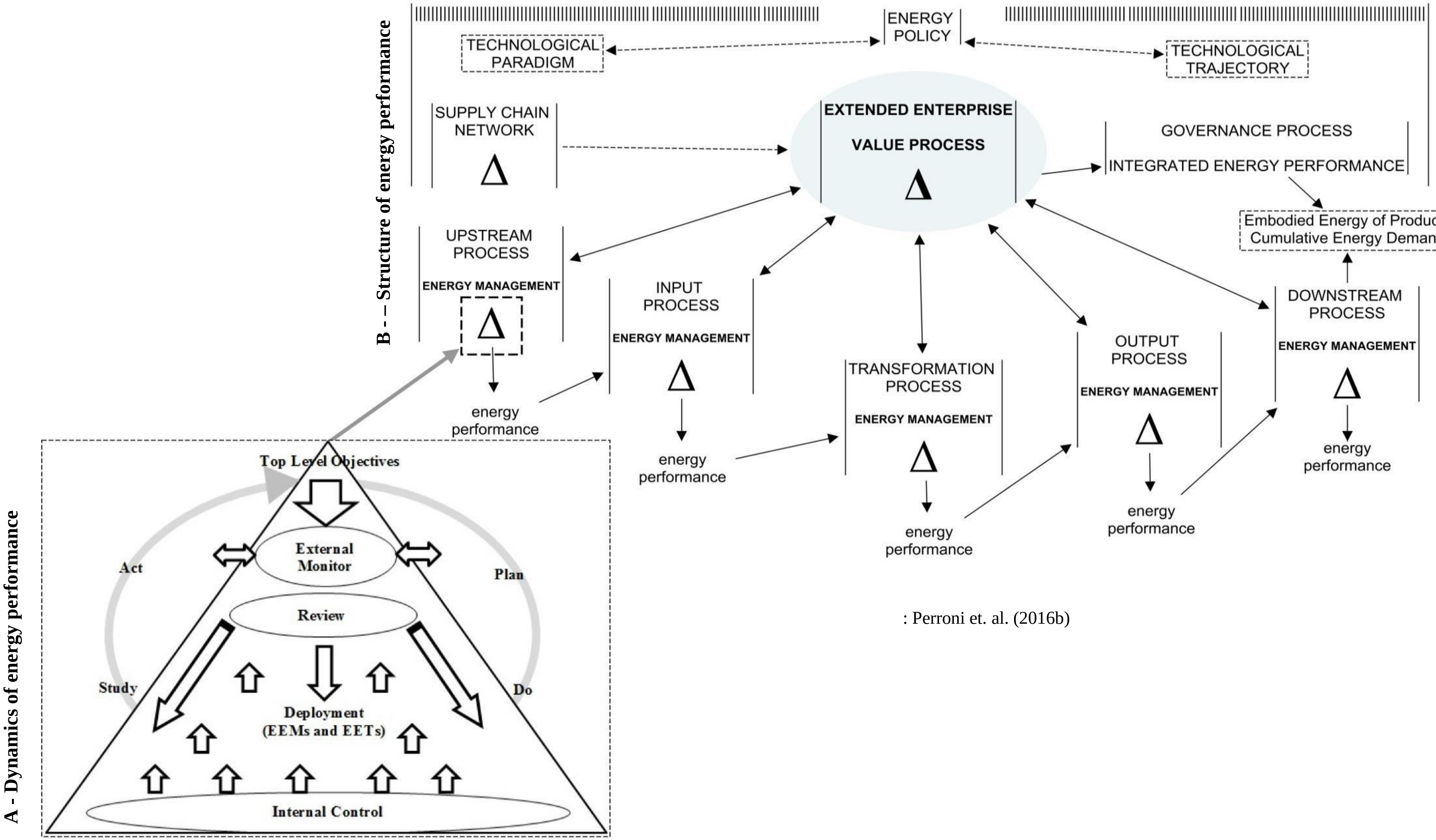
The implementation of a model requires the definition of procedures, techniques, and tools: “A procedure is a series of steps for operationalising a process,” “[a] technique is a structured way of completing part of a procedure,” and “[a] tool facilitates the practical application of a technique” (Shehabudden et al., 1999, p. 15). The procedures and techniques to operationalize the input-output process model are given by Lin and Polenske (1998), derived from the work of Leontief (1966).

3 Energy Performance Representation

Relying on the methods proposed in Figure 2, the purpose of this section is to provide a representation of energy performance from the energy management point of view, and to propose the following: (a) a processes framework for measuring integrated energy performance; (b) a map of energy efficiency indicators of processes; and (c) a longitudinal input-output process model for continuous measurement of energy performance.

3.1 Processes framework for measuring integrated energy performance

“Process” refers to production processes; the production process is the mechanism responsible for the transformation of inputs into outputs (Albino et al., 2003; Slack et al., 2007; Kuhtz et al., 2010). The process can be defined as “an approach to achieve the management objectives through the transformation of inputs into outputs” (Shehabudden et al., 1999, p. 14). Defining production processes in this way makes it easier to hierarchize the production system. The production process can be seen in different levels of aggregation, considering a company or a chain as a set of processes responsible for the transformation of inputs into outputs. The set of processes can form a network with intermediate and final products (Slack et al., 2007; Kuhtz et al., 2010).



: Perroni et. al. (2016b)

Figure 3 – Processes framework for measuring integrated energy performance

Source: Adapted from Bititci et al. (2000) and Perroni et al. (2014)

Note: EEMs = energy efficiency measures; EETs = energy efficiency technologies

A fundamental issue is that, unlike other resources, energy is used in virtually all production processes, so energy performance can be studied within these processes (Patterson, 1994). Figure 3 shows the processes framework for measuring integrated energy performance.

The framework is put together on two blocks; Figure 3a describes the energy performance dynamics and Figure 3b describes the energy performance structure. According to the methodology of Figure 2, the framework has a higher conceptual level, supporting an increased understanding, so that the evolution (Figure 3a) as well as the structure (Figure 3b) of energy performance become more clear (Shehabudden et al., 1999, p. 9).

Figure 3a is adapted from the framework of Bititci et al. (2000), in which a performance measurement system consists of four auxiliary systems: external monitoring, internal monitoring, review, and deployment. These systems interact in a continuous improvement loop, plan-do-study-act (PDCS) generating feedback between an operational base (monitoring/control) and a strategic level (main objectives through planning). According to Bititci et al. (2000), this system is not dedicated to a specific process, since when many processes are aggregated (network of processes), the same mechanism can be in operation, as in the case of Figure 3b, where the performance is integrated in what is called an extended enterprise (EE) (O’Neill and Sackett, 1994; Folan and Browne, 2005).

The EE can be understood as a composition or network of processes in which the energy performance can be integrated. Studying the energy performance in the EE entails studying the flow of energy of the network of processes. The works of Beamon (1998) and Folan and Browne (2005) also presume that performance management in its complete form is found in the processes of the EE. Traditionally, the supply chain is concerned with the flow of materials and information. Gradually, it is being included the reverse logistics chain, waste recovery, reuse, and remanufacturing (Beamon, 1998). Another flow that can be included is the study of energy flow (Kara et al., 2010; Rahimifard et al., 2010). Energy policy (Tanaka, 2011) and technologies (Worrell and Biermans, 2005), through the technological paradigms and technological trajectories (Dosi, 1982), can be considered the most important external variables to be analyzed, since these are capable of changing energy performance.

The framework of Figure 3a and 3b relates to the literature about energy efficiency/management. In a systematic review of recent literature, Perroni et al. (2015) found that the literature on recent industrial energy efficiency/management can be divided into three groups: energy efficiency/management, quantitative performance in energy, and sustainable inter-firm relations. The energy efficiency/management group generally discusses the dynamic factors that can change positively (Abdelaziz et al., 2011) or negatively (Cagno et al., 2013) the energy performance, highlighting the importance of a review and deployment system, such as an energy audit (Gordic et al., 2010), to identify ways to implement the energy efficiency measures (EEMs) and the energy efficiency technologies (EETs) (Alkaya and Demirer, 2014). The quantitative performance group shows different ways to measure and assess the energy performance through key performance indicators (KPIs) (Patterson, 1996) or frontier indicators such as stochastic frontier analysis (SFA) (Boyd et al., 2008) and data envelopment analysis (DEA) (Azadeh et al., 2007). The sustainable inter-firm relations group starts from an assumption of an energy system integration between companies, developing concepts such as the embodied energy of products (Rahimifard et al., 2010) and cumulative energy demand (Patel, 2003).

The key issue in the dynamics of energy performance is the possibility to identify both measures (EEMs) and technologies (EETs) that can improve energy performance (Abdelaziz et al., 2011). The heterogeneity of the processes makes it difficult to produce specific solutions to more general cases (Vikhorev et al., 2013), since the EEMs and EETs can differ between the processes, requiring plan-do-check-act (PDCA) continuous improvement approaches (Kannan and Boie, 2003; Gordic et al., 2010; Negai et al., 2013), like the plan-do-study-act (PDSA) of Figure 3a (Bititci et al., 2000).

3.2 Map of energy efficiency indicators of processes

Having discussed the dynamic context of energy performance and the structure in which the energy performance can be integrated, another issue relates to the measures or energy efficiency indicators to represent the energy performance of the processes of the EE of Figure 3.

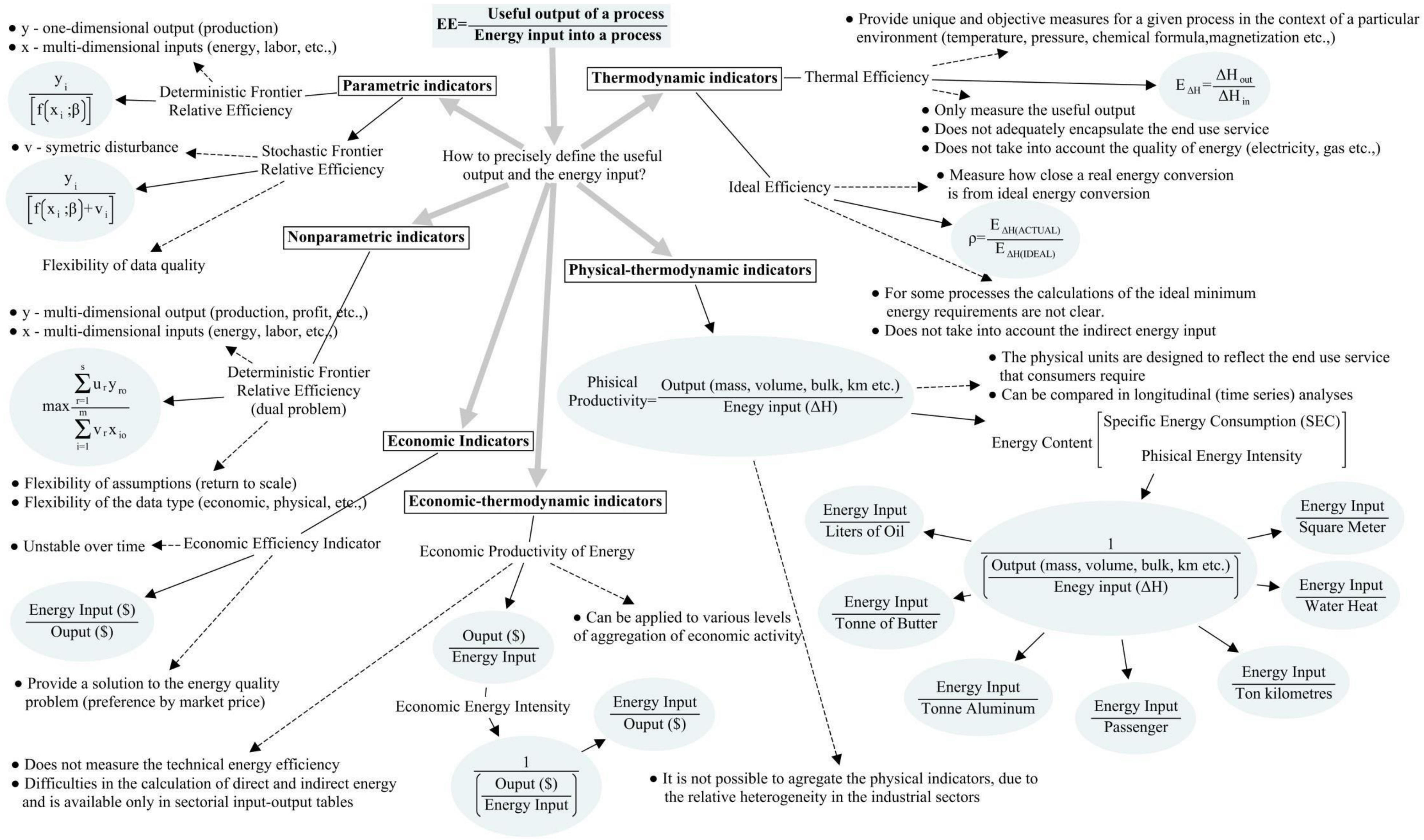


Figure 4 - Map of energy efficiency indicators of processes

Source: Perroni et al. (2016b)

A group of authors supporting a quantitative performance in energy (Perroni et al., 2015) presents several ways to measure energy performance. In this group, including within IEA reports (IEA, 2014b), there is a concern about how to measure the results achieved by energy saving actions or energy management. A number of terms to represent energy performance can be found in the literature, including: energy efficiency, energy productivity, energy content, energy intensity, specific energy consumption, and relative efficiency (Patterson, 1994; Phylipsesen et al., 1997; Boyd et al., 2008; IEA, 2014b). Figure 4 is a map of the energy efficiency indicators.

Based on Patterson (1994), there is no quantitative way to measure energy efficiency without incurring any assumptions. Using the efficiency indicator defined in Patterson (1994) (useful output of a process/energy input into a process), through analysis of the work represented in the quantitative performance group (Perroni et al., 2015), Figure 4 represents a ramification map of the numerator composition and indicator denominator, ranging from the KPIs (Phylipsesen et al., 1997; Patterson, 1994; IEA, 2014b) to the parametric (Charnes et al., 1978; Azadeh et al., 2007) and nonparametric (Aigner et al., 1977; Boyd et al., 2008) frontier indicators. It is possible to classify them into at least six categories of indicators: thermodynamic, physical-thermodynamic, economic-thermodynamic, economic, parametric frontier, and nonparametric frontier (Patterson, 1994; Perroni et al., 2016b). According to methodological discussion, a map helps to understand the static relations between many indicators that can be created, providing a reference system or positioning for the indicators (Shehabudden et al., 1999, p. 11).

In Figure 4, two thermodynamic indicators are identified: the thermal efficiency indicator and the ideal efficiency indicator. The thermal efficiency indicator is based on the law of conservation of energy of thermodynamics and measures the efficiency of the heat content of the processes inputs and outputs. The ideal efficiency indicator indicates how far the real energy conservation is from the ideal conservation, since it is the ratio of thermal efficiencies (Patterson, 1994; Perroni et al., 2016b).

The physical-thermodynamic indicators can be divided in two groups: physical productivity and energy content (energy content can also be called physical energy intensity or specific energy consumption). The productivity indicator measures the productivity of the energy factor; in other words, how much an energy unit (Btu, joules, calories) can produce in a given process. The more output generated by the energy unit, the greater the energy production.

Energy content indicators, on the other hand, measure the amount of energy contained in one physical unit of production (tons, kilometers, liters, etc.), being the inverse of the productivity indicator (Patterson, 1994; Phylipsesen et al., 1997).

Figure 4 shows the main advantages and disadvantages of the indicators. Physical-thermodynamic indicators have the advantage of reflecting the end-use of goods and services and the ease of comparison in longitudinal series. The main disadvantage of this type of indicator is the difficulty of aggregation due to the heterogeneity of the production processes. As for the indicators involving economic variables, they reflect the market allocative issues and are easy to aggregate; on the other hand, they move further away from the technical concept of energy efficiency. The indicator that best reflects the technical aspects of energy are the pure thermodynamic indicators. However, they do not encapsulate the end-use of the service, and it is difficult to estimate the ideal thermal efficiency. The frontier indicators, especially the DEA, are the most frequently used in the literature, mainly because of flexibility, the ability to aggregate multiple inputs/outputs, and dealing with the returns to scale. The KPIs indicators always take on constant returns to scale; as with the DEA, it is possible to work with decreasing, constant, and increasing returns, among other combinations (Charnes et al., 1978; Patterson, 1994; Bogetoft and Otto, 2010).

Based on Neely et al. (1995), a performance measurement system can be defined as a set of metrics that quantify the efficiency and effectiveness; as for the performance measurement, it is related to the process of this quantification. The indicators on the Figure 4 map can be understood as metrics used to quantify the efficiency and/or effectiveness of energy management actions (Neely et al., 1995).

3.3 Input-output model of longitudinal production processes

This section proposes a longitudinal input-output process model for continuous measurement of energy performance. The input-output model can be understood as an architecture capable of representing the energy performance of the EE of Figure 3b (Gordic et al., 2010; Negai et al., 2013; Perroni et al., 2014).

The input-output model was developed in the research of Nobel Prize in Economics winner Professor Leontief (1936, 1966). Based on Leontief (1966), the input-output analysis is a practical extension of the classical theory of general interdependence, which views the whole economy (business, region, country, world) as an interdependent system of transactions between companies/sectors. The central idea of the input-output analysis is that there is a fundamental relation between the output of an industry/company and the vast inputs that it absorbs. The described relation is a linear relation between the input amount and the amount of goods and services to be produced. The input-output model has specific procedures and techniques such as the preparation of input-output tables and the calculation of direct/indirect coefficients. The input-output tables describe the flow of goods and services among all sectors in a specific period of time. The direct coefficients are technical coefficients of production that show the relation between inputs and products/services. The indirect coefficients, also known as a Leontief matrix, show the direct and indirect relation between inputs and products/services. Since the data collection for the input-output tables of all transactions between companies would be virtually impossible (in the time in which Leontief was active), the solution was the aggregation of companies into sectors showing the relation between these sectors (Leontieff, 1936; Leontief, 1966[46]).

Lin and Polenske (1998) reorganized the input-output tables to work with business processes, being a processes approach of the input-output model of Leontief. The processes approach proposed by Lin and Polenske (1998) is known as an input-output process model or an enterprise input-output model (Lin and Polenske, 1998; Albino et al., 2003). The main matrices of the model are outlined in Table 1.

Table 1 – Input-output process model matrices

Matrices	*Processes*					*Demand*
		1	2	3	n	
Main Product	1	$\mathbf{Z_{11}}$	Z_{12}	Z_{13}	Z_{1n}	Y_1
	2	Z_{21}	$\mathbf{Z_{22}}$	Z_{23}	Z_{2n}	Y_2
	3	Z_{31}	Z_{32}	$\mathbf{Z_{33}}$	Z_{3n}	Y_3
	n	Z_{n1}	Z_{n2}	Z_{n3}	$\mathbf{Z_{nn}}$	Y_n
—	—	—	—	—	—	—
Energy	1	$\mathbf{E_{11}}$	$\mathbf{E_{12}}$	$\mathbf{E_{13}}$	$\mathbf{E_{1n}}$ $\mathbf{X^E}$	**1**
	2	$\boldsymbol{E_{21}}$	$\mathbf{E_{22}}$	$\mathbf{E_{23}}$	$\mathbf{E_{2n}}$ $\mathbf{X^E}$	**2**
	3	$\mathbf{E_{31}}$	$\mathbf{E_{32}}$	$\mathbf{E_{33}}$	$\mathbf{E_{3n}}$ $\mathbf{X^E}$	**3**
	n	$\mathbf{E_{n1}}$	$\mathbf{E_{n2}}$	$\mathbf{E_{n3}}$	$\mathbf{E_{nn}}$	$\mathbf{X^E_n}$
—	—	—	—	—	—	—
Primary Inputs	1	P_{11}	P_{12}	P_{13}	P_{1n} X^P	1
	2	P_{21}	P_{22}	P_{23}	P_{2n} X^P	n 2
	3	P_{31}	P_{32}	P_{33}	P_{3n} X^P	3
	n	P_{n1}	P_{n2}	P_{n3}	P_{nn} X^P	
—	—	—	—	—	—	—
Waste	1	W_{11}	W_{12}	W_{13}	W_{1n} X^w	1
	2	W_{21}	W_{22}	W_{23}	W_{2n} X^w	2
	3	W_{31}	W_{32}	W_{33}	W_{3n} X^w	3
—	—	—	—	—	—	—
Prod. Main Process		X_1 $\mathbf{Z_{11}}$	X_2 $\mathbf{Z_{22}}$	X_3 $\mathbf{Z_{33}}$	X_n $\mathbf{Z_{nn}}$	

Note: Z = Processes and main product matrix; Y = Final production of the main products matrix; E = Energy matrix; X^E = Total energy use matrix; P= Primary inputs matrix; X^P= Total primary inputs matrix; W= Waste matrix; X^W= Total waste generation matrix; B = Byproducts matrix; X^B = Total production of byproducts matrix; X^z= Gross production of the main product matrix (main diagonal of processes matrix)

Source: Lin and Polenske (1998)

In Table 1, the components of the model matrices are: processes (Z), energy (E), primary inputs (P), waste (W), and byproducts (B). Each process matrix (Z) transforms *inputs* into *outputs*,

---

[46] "The Royal Swedish Academy of Sciences has awarded the 1973 year's Prize in Economic Science in Memory of Alfred Nobel to Professor Wassily Leontief for the development of the input-output method and for its application to important economic problems. The input-output system has found extensive use especially in forecasting and planning, both in the short and in the long run. The wide usefulness of the input-output technique is indicated by the fact that it is used in forecasting and planning in quite different types of economic systems—decentralized market economies with mainly private enterprise as well as centrally-planned economies dominated by public ownership." http://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/1973/press.html (accessed Oct. 18, 2016).

where the main *output* of a process is the *input* of the following process, and the final *output* is the product/service sold outside of the system (Albino et al., 2003). Each production process requires an amount of materials and energy, and after processing, besides the main *output*, waste and byproducts are generated (Lin and Polenske, 1998; Albino et al., 2003; Kuhtz et al., 2010). Two basic hypotheses are necessary to operationalize the input-output process model (Wang and Jia, 2012):

1. Each process can only generate one main product (main diagonal of matrix Z);
2. The main product of a process cannot be consumed by itself.

The model can be used as a planning/control tool to develop scenarios to check the impact of changes in *inputs/outputs*, study the flow of materials and energy, analyze the internal and external links of the chain, quantify the demand for resources, monitor the generation/use of waste/pollution, and understand the dematerialization process, among others (Lin and Polenske, 1998; Albino et al., 2003; Kuhtz et al., 2010).

Figure 5a depicts a longitudinal input-output process model in a simplified diagram in which the time variable is added to the original model, providing for the divisibility of the processes in regards to time, considering that the analysis can be conducted after the production cycle is complete.

Each new production cycle (time (t) from 1 to k in Figure 5a) can produce new results (derived from energy management, for example) that need to be analyzed and compared.

The input-output process model has been designed and applied in the processes of an EE, or part thereof, such as steel manufacturing processes (Lin and Polenske, 1998), coke manufacturing processes (Polenske and McMichael, 2002), upholstery manufacturing processes (Albino et al., 2002; Albino et al., 2003; Albino et al., 2008), tile manufacturing processes (Albino and Kuhtz, 2004; Kuhtz et al., 2010), and processes for second generation biodiesel (Yazan et al., 2012), all of which are natural candidates to represent the energy performance of the EE in the framework of Figure 3.

As for the input-output model hierarchy, the main units of analysis are the processes of production (transformation of inputs into outputs through resource arrangement) (Shehabudden et al., 1999). An ordered sequence of manufacturing processes is defined as a production cycle. The production cycle belongs to a network of production processes, which can be located in a local cluster or a global supply chain (Albino et al., 2002; Kuhtz et al., 2010). Figure 5a shows a production cycle, which is a more simplified form, since there are no feedback mechanisms (a one-way model) (Albino et al., 2003).

Figure 5b also shows the matrix equations of the model for the matrices of the main products/processes (Z and X), energy (E), primary inputs (P), waste (W), and byproducts (B), as seen in Table 1. The focus of this study is the energy matrices, but since the method is independent of the analyzed matrix, it may be applied to other tables or matrices as well. The two matrices of the energy indicators generated by the model are the matrix of the direct coefficients ($E\hat{X}^{-1}$) and the matrix of the indirect coefficients ($EDCA^{-1}$). The matrix of direct coefficients is the inverse of the energy productivity indicator (how much a unit of energy can produce), measuring the energy content of the process (how much energy is consumed in a production unit in the respective process) (see Figure 4). Depending on the choice for the data composition (changing the numerator and/or the denominator according to the map of Figure 4), the matrix of direct coefficients of the model may represent a physical-thermodynamic, economic-thermodynamic, or economic indicator.

The matrix of indirect coefficients is the energy flow, measuring the cumulative energy demand, as specified in the EE processes model in Figure 3b.

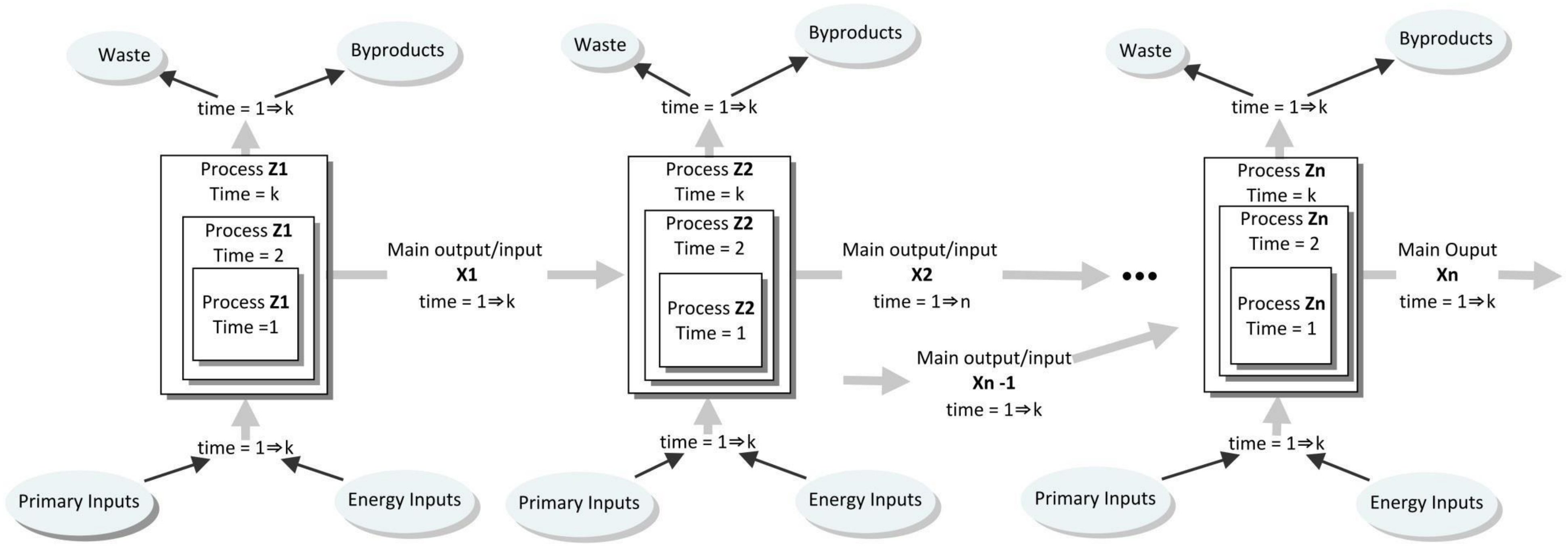


Figure 5a – Longitudinal input-output process model

$$1 - \left|\mathit{Direct\ coefficients} \rightarrow A = a_{ij} = \frac{Z_{ij}}{X_j} = Z\hat{X}^{-1}\right| \quad \left|\mathit{Process\ matrix} \rightarrow Z = A\hat{X}\right| \quad \left|\mathit{Demand} \rightarrow Y = AX^{T}\right| \quad \left|\mathit{Indirect\ Coefficients} \rightarrow A^{-1}\right|$$

$$2 - \left|\boldsymbol{\mathit{Energy\ direct\ coefficients}} \rightarrow \boldsymbol{EDC = e_{ij} = \frac{E_{ij}}{X_j} = E\hat{X}^{-1}}\right| \quad \left|\boldsymbol{\mathit{Energy\ matrix} = EDC\hat{X}}\right| \quad \left|\boldsymbol{\mathit{Energy\ demand} = EDCX^{T}}\right| \quad \left|\boldsymbol{\mathit{Energy\ indirect\ coefficients} = EDCA^{-1}}\right|$$

$$3 - \left|\mathit{Primary\ inputs\ direct\ coefficients} \rightarrow PIDC = p_{ij} = \frac{P_{ij}}{X_j} = P\hat{X}^{-1}\right| \quad \left|\mathit{Primary\ inputs\ matrix} = PIDC\hat{X}\right| \quad \left|\mathit{Primary\ inputs\ demand} = PIDCX^{T}\right| \quad \left|\mathit{Primary\ inputs\ indirect\ coefficients} = PIDCA^{-1}\right|$$

$$4 - \left|\mathit{Waste\ direct\ coefficients} \rightarrow WDC = w_{ij} = \frac{W_{ij}}{X_j} = W\hat{X}^{-1}\right| \quad \left|\mathit{Waste\ matrix} = WDC\hat{X}\right| \quad \left|\mathit{Waste\ genertion} = WDCX^{T}\right| \quad \left|\mathit{Waste\ indirect\ coefficients} = WDCA^{-1}\right|$$

$$5 - \left|\mathit{Byproducts\ direct\ coefficients} \rightarrow BDC = b_{ij} = \frac{B_{ij}}{X_j} = B\hat{X}^{-1}\right| \quad \left|\mathit{Byproducts\ matrix} = BDC\hat{X}\right| \quad \left|\mathit{Byproducts\ production} = BDCX^{T}\right| \quad \left|\mathit{Byproducts\ indirect\ coefficients} = BDCA^{-1}\right|$$

Figure 5b - Equations of input-output process model (time = 1; The circumflex over the X denotes the diagonal of the matrix)

Source: Adapted from Lin and Polenske (1998) and Kuhtz et al. (2010)

4 Approach for Continuous Measurement of Energy Performance

Based on Figure 2, making the representation operational involves processes, procedures, techniques, and tools (Shehabudden et al., 1999). The representation identifies procedures and techniques that can be used as procedures for creating the input-output table, matrix calculation techniques, and techniques for building efficiency indicators, among others. This section aims to integrate some of these techniques, as they are based on deductivism, and thereby meet the following complementary objectives: (1) based on enterprise efficiency, propose indicators to continuously monitor the energy performance; (2) from a real process structure, develop a simulation approach to feed the model; and (3) build an approach for multidimensional visualization of the indicators.

4.1 Indicators based on enterprise efficiency

An efficiency indicator is derived from the ratio of two performance indicators (Perroni et al., 2016a). According to Bogetoft and Otto (2010) and Perroni et al. (2016a), efficiency, inefficiency, and business effectiveness can be represented as:

$$INEFFICIENCY = \frac{CURRENT\ PERFORMANCE\ -\ MINIMUM\ PERFORMANCE}{CURRENT\ PERFORMANCE} \tag{1}$$

$$EFFICIENCY = \frac{MINIMUM\ PERFORMANCE}{CURRENT\ PERFORMANCE} = 1 - INEFFICIENCY \tag{2}$$

$$EFFECTIVENESS = \frac{CURRENT\ PERFORMANCE}{IDEAL\ PERFORMANCE} \cong \frac{CURRENT\ PERFORMANCE}{MAXIMUM\ PERFORMANCE} \tag{3}$$

An energy efficiency indicator can be obtained from the ratio of two energy content indicators or energy productivity (Bogetoft and Otto, 2011; Perroni et al., 2016). Based on the map of indicators (Figure 4) and on the longitudinal input-output model (Figure 5a/b), it is possible to create indicators for measuring energy performance. It is important to note that the mathematical basis for creating indicators comes from the theory of index numbers, which is in the same branch as index decomposition analysis (IDA) and structural decomposition analysis (SDA), which originated in the input-output tables of Leontief (Liu, 2004).

The first matrix of indicators (Equation 4) uses the minimum performance/current performance ratio, dividing the minimum energy content matrix of each process by the current energy content matrix. According to Figure 4, the energy content is also referred to as specific energy consumption or energy intensity (Perroni et al., 2016b). This indicator compares the minimum direct energy per unit of production used in the process with the direct energy per unit of production used in a specific period of time. The indicator is named direct energy efficiency (DEE).

$$DEE = \left| \frac{\min_{t=1\to k} [\hat{\boldsymbol{EX}}^{\boldsymbol{1}}]_t}{[\hat{\boldsymbol{EX}}^{\boldsymbol{1}}]_t} \right| \equiv \left| \frac{\min_{t=1\to k} \left[\frac{E_{ij}}{X_j}\right]_t}{\left[\frac{E_{ij}}{X_j}\right]_t} \right| = \frac{\mathit{Minimum\ direct\ energy\ content\ of\ the\ process}}{\mathit{Current\ direct\ energy\ content\ of\ the\ process}} \tag{4}$$

A second proposed indicator is the change in direct energy efficiency (CDEE) (Equation 5), which reflects the change in DEE by dividing the energy content matrix of the current period by the matrix of the previous period, revealing short-term fluctuations, because it is a relatively mobile base.

$$CDEE = \left| -\left\{ \frac{[\hat{\boldsymbol{EX}}^{-1}]_t}{[\hat{\boldsymbol{EX}}^{\boldsymbol{1}}]_{t-1}} - 1 \right\} \right| \equiv \left| -\left\{ \frac{\left[\frac{E_{ij}}{X_j}\right]_t}{\left[\frac{E_{ij}}{X_j}\right]_{t-1}} - 1 \right\} \right| = \frac{\mathit{Current\ direct\ energy\ content\ of\ the\ process}}{\mathit{Previous\ direct\ energy\ content\ of\ the\ process}} \tag{5}$$

A third indicator, indirect energy efficiency (IEE) (Equation 6), comes from the ratio of the flow of indicators matrix of the input-output process model, taking into account the direct energy incorporated into the process plus the indirect energy of all related processes. This indicator can be operationalized by the ratio of the minimum direct and indirect consumption by the direct and indirect consumption in a given period of time. This is a robust indicator, since it works on any level of complexity of the processes listed in Figure 5a, which is the base of the Leontief model (1936, 1966).

$$IEE = \left| \frac{\min_{t=1\to k} \boldsymbol{EDCA^{-1}}}{[\boldsymbol{EDCA^{-1}}]_t} \right| = \frac{\begin{matrix} Minimum\ indirect\ energy\ content \\ of\ the\ process \end{matrix}}{\begin{matrix} Current\ indirect\ energy\ content \\ of\ the\ process \end{matrix}} \tag{6}$$

The role of the IEE indicator is to measure the performance of what the literature calls embodied energy of products (Kara et al., 2010; Rahimifard et al., 2010) or cumulative energy demand (Patel, 2003). In the specific case of the input-output process model, it can also be referred to as embodied energy of processes. In the process (n) of the input-output model of Figure 5a, the indirect efficiency measures the total energy efficiency if all energy sources are aggregated to compute the indicator; in other words, in the process (n), the indicator can measure the joint efficiency (all processes and all energy sources).

A problem with an efficiency indicator is the need to determine in advance the value of the optimal performance. This is clearly the problem with the ideal thermodynamic efficiency indicator in the map of Figure 4. A solution is an approach such as Equation 3: replace optimal performance for maximum performance. One way to overcome this problem is the application of the concept of efficiency called Farrell efficiency (1957), switching the focus of efficiency to the relative energy efficiency (REE). According to Figure 4, there are two approaches for creating relative efficiency: parametric and nonparametric. The most frequently used approach is nonparametric, developed in the researches of Charnes et al. (1978). The data for creating an indicator of relative efficiency can be derived directly from the input-output tables. Considering that the process model of Figure 5a is longitudinal (involving different periods of time), the relative efficiency indicator takes into account the intertemporal frontier, with the possibility of aggregating several *inputs* (different energy sources or other primary inputs) and several *outputs* (besides the production process, byproduct and waste variables can be used). The general formulation of this indicator is given in Equation 7, which is the solution of a mathematical programming problem. This problem is known in the efficiency literature as a multiplier model (Charnes et al., 1978; Bogetoft and Otto, 2010; Zhu, 2014).

$$REE = \left| \begin{array}{lll} max \frac{\sum_{r=1}^{s} u_r \boldsymbol{X}_{ro}}{\sum_{i=1}^{m} v_i \boldsymbol{E}_{ro}} = max & \frac{Outputs\ of\ process}{\begin{matrix} Inputs\ of\ process \\ (energy = Oil, Gas, Electricity \ldots) \end{matrix}} \equiv & Energy\ produtivity \\ \quad st: & & \\ \frac{\sum_{r=1}^{s} u_r X_{rt}}{\sum_{i=1}^{m} v_i E_{it}} \le 1 & t = 1, \ldots, k & \end{array} \right| \tag{7}$$

$$u_r,\ v_i \ge 0 \qquad r = 1, \ldots, s \qquad i = 1, \ldots, m$$

Unlike the previous indicators (DEE, CDEE, and IEE), where the structure is based on energy content, the REE indicator is based on maximizing energy productivity, where the measure of efficiency is achieved by the maximum energy productivity, considering that the output (X_{ro}) has a weight (u_r), while the input (E_{ro}) has a weight (v_i); this is subject to the condition that the productivity is defined the same way in other time periods (X_{rt} *and* E_{it}), whether it is less than or equal to the unity (Charnes et al., 1978). The implementation can be done using the multiplier model or the envelopment model (Bogetoft and Otto, 2011; Zhu, 2014). According to the map of indicators of Figure 4, the parametric indicators are also based on the productivity ratio.

4.2 Simulation approach of the longitudinal input-output process model structure

Since the longitudinal input-output process model incorporates the structure (framework) where the energy performance occurs, as well as the relevant indicators (based on the map of indicators of Figure 4), the continuous operation of the approach can be described by a system. Based on the methodology of the representation/approach of Figure 2, a system is “a set of bounded interrelated elements with emergent properties being represented within the context of the paradigm” (Shehabudden et al., 1999, p. 8). Because the longitudinal input-output process model is a mathematical model, one way of showing how the model could be used to monitor energy performance is using computational tools. Within the proposed processes approach, the energy performance can be monitored by the indicators created in the longitudinal input-output process model.

Table 2 shows a simple case of actual processes involved in manufacturing tiles (Albino et al., 2004; Kuhtz et al., 2010). The tile manufacturing was divided into five processes: mixing (M), in which the argil, reusable wastes, and other material (depending on the type of tile being produced) are powdered and sieved, and then mixed with water and clay; pressing and drying (N), in which first the clay mixture is pressed and then sent for drying; burning (O), which is a continuous process in which the tile is fired to evaporate the remaining water, with preheating, firing, and cooling as part of this process; polishing (P), in which the tiles are polished in two stages—the first is a rough polishing and the second is a more refined polishing; and selection and packaging (Q), in which the tiles are selected according to color and quality and then packed by automated machines.

Table 2 shows the matrix of processes (Z), energy matrix (E), and the output vector of each process (X), and Figure 6 is a simulation approach to generate the model data. In the processes matrix, all process outputs M to P are consumed by the subsequent processes, so that there is only demand (Y) for the process Q. Table 2 explores a production cycle, as in Figure 5a, with a simple one-way model , representing an EE.

Table 2 – Processes matrix and energy matrix for tile manufacturing

Product		**Z – Production processes**					**Demand**
	10^4	**M**	**N**	**O**	**P**	**Q**	**Y**
M – Mixing	**t**	16,300	-16,300	0	0	0	**0**
N – Drying	**t**	0	15,600	-15,600	0	0	**0**
O – Burning	**t**	0	0	15,130	-15,130	0	**0**
P – Polishing	**t**	0	0	0	14,740	-14,740	**0**
Q – Packing	**t**	0	0	0	0	14,760	**14,760**
Energy	**10^4**	**E – Energy matrix**					
E – Electricity	**Kcal**	1.084.129	0	955.066	1.204.588	34.416	3.278.200
T – Thermal	**Kcal**	4.387.224	1.203.847	9.780.426	0	0	15.371.497
O – Oil	**Kcal**	4.387.224	0	0	0	0	4.387.224
D – Diesel	**Kcal**	0	0	1.848.000	0	0	1.848.000
G – Natural gas	**Kcal**	0	1.203.847	7.932.426	0	0	9.136.273
		X – Main product output of the process					
Outputs	**t**	16,300	15,600	15,130	14,740	14,760	

Source: Albino and Kuhtz (2004); Kuhtz et al. (2010)

To calculate the direct and indirect indicators, the operationalization of the equations of lines 1 and 2 of the input-output process model of Figure 5b is necessary. The direct and indirect coefficients of the processes and energy can be seen in Tables 3 and 4.

Table 3 – Intermediate coefficients of the processes and production inverse matrix

Direct coefficients of the processes						**Indirect coefficients of the processes**						**Inverse diagonal of the production**					
$A = a_{ij} = \frac{Z_{ij}}{X_i} = Z\hat{X}^{-1}$						A^{-1}						$\hat{X}^{-1}$					
	M	**N**	**O**	**P**	**Q**		**M**	**N**	**O**	**P**	**Q**		**M**	**N**	**O**	**P**	**Q**
M	1	-1,04	0	0	0	**M**	1	1,04	1,08	1,11	1,10	**E**	0,061	0	0	0	0
N	0	1	-1,03	0	0	**N**	0	1	1,03	1,06	1,06	**T**	0	0,064	0	0	0
O	0	0	1	-1,03	0	**O**	0	0	1	1,03	1,03	**O**	0	0	0,066	0	0
P	0	0	0	1	-1,00	**P**	0	0	0	1	1,00	**D**	0	0	0	0,068	0
Q	0	0	0	0	1	**Q**	0	0	0	0	1	**G**	0	0	0	0	0,068

Note: E = Electricity; T = Thermal; O = Oil; D = Diesel; G = Natural gas

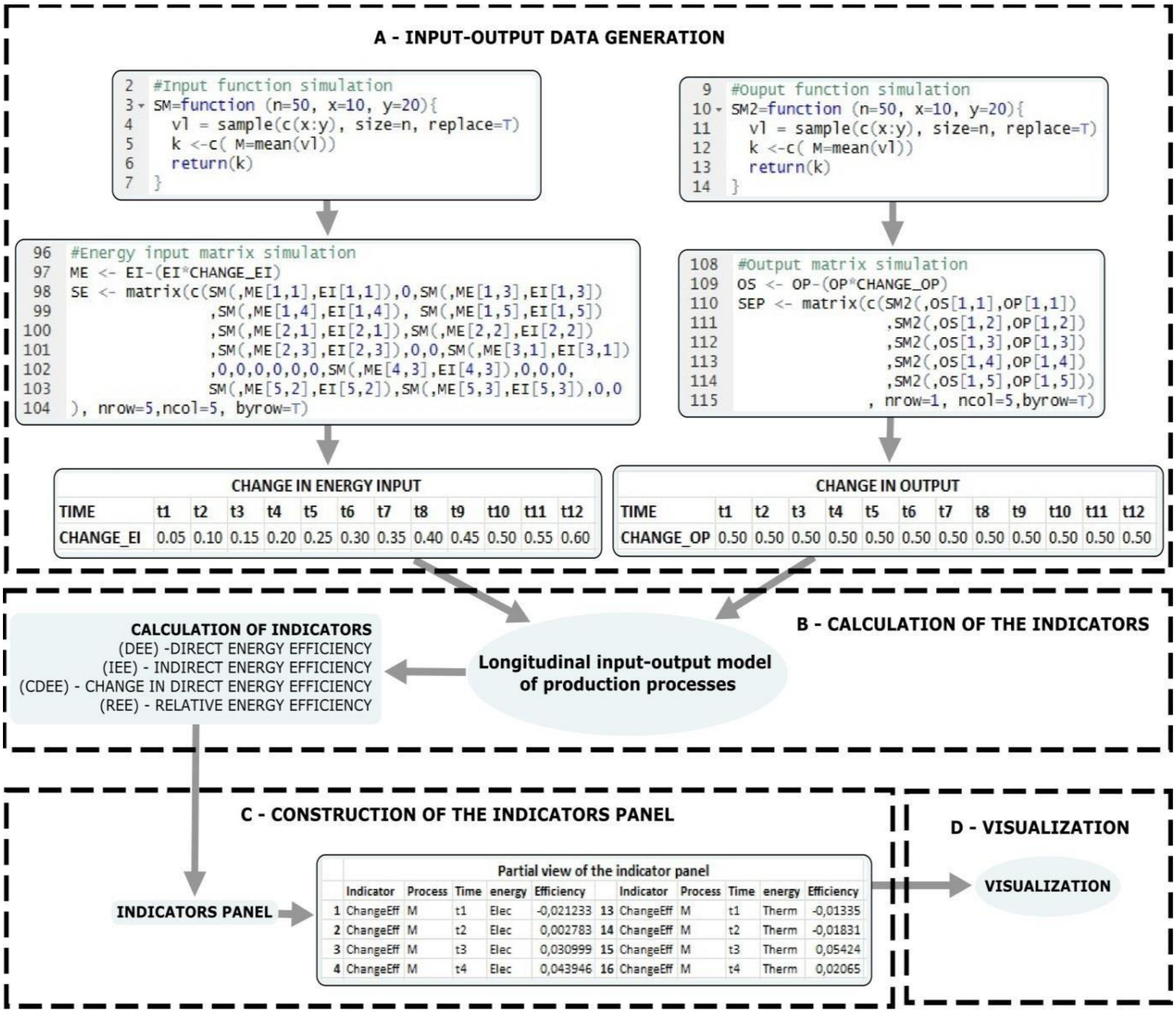
The direct coefficients of Table 4 are physical-thermodynamic indicators of the map of Figure 4, measuring the energy content per production unit of the process. The process Q (packaging) requires 2.332 Kcal of electric energy (2,71 KWh) to pack each ton of tile. The indirect indicators of Table 4 measure the flow of energy, or the embodied energy of products (Rahimifard et al., 2010). The process indicator Q (packaging) is the total energy (direct plus indirect) to manufacture a ton of tiles: 222.100 Kcal of electric energy is used to manufacture a ton of tiles (0,25 MWh) (Kuhtz et al., 2010).

Table 4 – Direct and indirect coefficients of energy input

	Direct energy coefficients					**Indirect energy coefficients**				
	$EDC = e_{ij} = \frac{E_{ij}}{X_j} = E\hat{X}^{-1}$					$EDCA^{-1}$				
	M	**N**	**O**	**P**	**Q**	**M**	**N**	**O**	**P**	**Q**
E	66.511	0	63.124	81.722	2.332	66.511	69.495	134.778	220.067	222.100
T	269.155	77.170	646.426	0	0	269.155	358.402	1.015.961	1.042.842	1.041.429
O	269.155	0	0	0	0	269.155	281.232	289.969	297.641	297.237
D	0	0	122.141	0	0	0	0	122.141	125.373	125.203
G	0	77.170	524.285	0	0	0	77170	603.851	619.829	618.989

Note: E = Electricity; T = Thermal; O = Oil; D = Diesel; G = Natural gas

The researches of Albino et al. (2004) and Kuhtz et al. (2010) present only one set of input-output tables for the processes of tile manufacturing (processes of the EE). The problem is that to represent the longitudinal input-output model, more than one table in different time periods is necessary. The simulation approach of Figure 6 (developed with the R analytics tool) generates the data to operationalize the indicators of Equations 4 to 7 (Jones et al., 2009). The simulation approach works in four steps: (a) input-output data generation; (b) calculation of the indicators of Equations 4 to 7; (c) construction of the indicators panel; and (d) multidimensional visualization of the indicators.



```
#Input function simulation
SM=function (n=50, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))
  return(k)
}
```

```
#Ouput function simulation
SM2=function (n=50, x=10, y=20){
  vl = sample(c(x:y), size=n, replace=T)
  k <-c( M=mean(vl))
  return(k)
}
```

```
#Energy input matrix simulation
ME <- EI-(EI*CHANGE_EI)
SE <- matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3])
                   ,SM(,ME[1,4],EI[1,4]), SM(,ME[1,5],EI[1,5])
                   ,SM(,ME[2,1],EI[2,1]),SM(,ME[2,2],EI[2,2])
                   ,SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1])
                   ,0,0,0,0,0,0,SM(,ME[4,3],EI[4,3]),0,0,0,
                   SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0
), nrow=5,ncol=5, byrow=T)
```

```
#Output matrix simulation
OS <- OP-(OP*CHANGE_OP)
SEP <- matrix(c(SM2(,OS[1,1],OP[1,1])
                          ,SM2(,OS[1,2],OP[1,2])
                          ,SM2(,OS[1,3],OP[1,3])
                          ,SM2(,OS[1,4],OP[1,4])
                          ,SM2(,OS[1,5],OP[1,5]))
                         , nrow=1, ncol=5,byrow=T)
```

CHANGE IN ENERGY INPUT

TIME	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
CHANGE_EI	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60

CHANGE IN OUTPUT

TIME	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
CHANGE_OP	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Partial view of the indicator panel

	Indicator	Process	Time	energy	Efficiency		Indicator	Process	Time	energy	Efficiency
1	ChangeEff	M	t1	Elec	-0,021233	13	ChangeEff	M	t1	Therm	-0,01335
2	ChangeEff	M	t2	Elec	0,002783	14	ChangeEff	M	t2	Therm	-0,01831
3	ChangeEff	M	t3	Elec	0,030999	15	ChangeEff	M	t3	Therm	0,05424
4	ChangeEff	M	t4	Elec	0,043946	16	ChangeEff	M	t4	Therm	0,02065

Figure 6 - Simulation approach of the longitudinal input-output process model structure
Note: See appendix A for partial code of R analytics tool
Source: The authors

The starting point for the generation of the input-output data comes from the Table 2 processes, maintaining the same output structure (output matrix simulation in Figure 6) and energy matrix (energy matrix simulation in Figure 6). The simulation function has the role of generating random numbers among the values established in Table 2 and a second value established by a rate of change (ME = EI-EI×CHANGE_EI, where ME is the new energy matrix, EI is the energy matrix and CHANGE_EI is a rate of change) and output change (OS = OP-OP×CHANGE_OP, where OS is the new output vector, OP is the output vector and CHANGE_OP is a rate of change). When the value of *n* of the simulation function is 1, the data take any value between x and y; in other words, between the energy matrix of Table 2 and the chosen rate of change in value. When the value of *n* is large (say 10,000,000), the data generated tends to a central measure (average). This concept is known as the central limit theorem (Jones et al., 2009; Robert and Casella, 2010). According to the central limit theorem, when the value of *n* in the simulation function of inputs (energy) and outputs tends to infinite, a change will occur only on the energy input, having the next maximum variation of 30% in the last period (12) and the minimum variation of 2,5% in the first period (1). The time period in actual cases will depend on the processes in the analysis. The time period cannot be shorter than the time required to finish the production cycle (see Figure 5a). The time period can be represented by weeks, months, quarters, etc.

4.3 Multidimensional visualization of the indicators approach

The indicators panel of the simulation approach in Figure 6 is a way of organizing the data to be viewed. The visualization is helpful, since the large amount of information prior to visualization can hinder one's comprehension. Considering 12 time periods, by using Table 2 it is possible to create 132 indicators for direct energy efficiency (Equation 4). Two techniques that enable multiple viewing of the longitudinal input-output process model are the layered grammar of graphics (Wickham, 2009, 2011) and the strucplot framework techniques (Friendly, 1994; Meyer et al., 2006).

In the grammar of graphics, a graphic is a data mapping using esthetic attributes (color, shape, size, etc.) of geometric objects (bar, point, line, etc.). A graphic is an abstract mapping for the visualization of data in which a number of components can be combined to produce useful images (Wickham, 2009; Grolemund, 2012). The structural plot approach was created to view contingency tables of multiple entries, or multi-way contingency tables, in which the main visualization is the mosaic plot. The mosaic plot is composed of a series of rectangles that proportionately represent each cell of a data matrix (Friendly, 1994; Meyer et al., 2006).

The visualization process is important for monitoring energy performance by identifying the results of possible improvement actions through energy management, involving the implementation of EEMs and EETs. The literature revision of Bunse et al. (2011) identified, among other factors, the lack of computational display mechanisms to represent indicators. As identified by Wee et al. (2012), due to a further decline of traditional energy resources such as oil, coal, and natural gas, renewable sources such as biomass, geothermal, wind, and solar will tend to grow in the energy matrix of the EE. A visualization system will help in the structural comparison, identifying the changes in the energy matrix of the EE. The visualization can be useful to monitor the progress of the indicators of the EE processes over time.

Chart 1a represents the energy matrix of Table 2. The horizontal length of the rectangles measures the energy consumption in the process while the vertical length measures energy sources. The horizontal lines at the edges and in the middle of Chart 1a show that the process does not consume the specific energy.

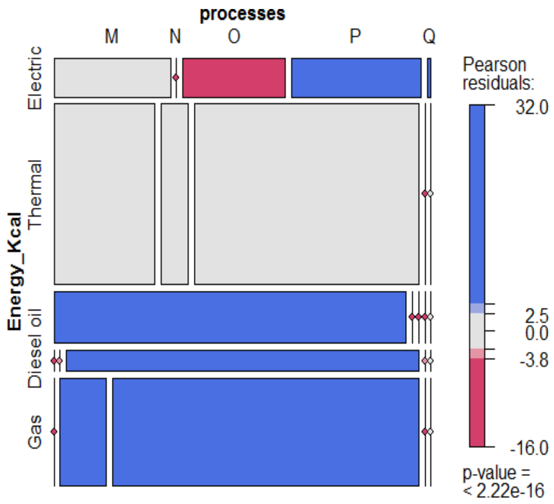


Chart 1a – Energy matrix

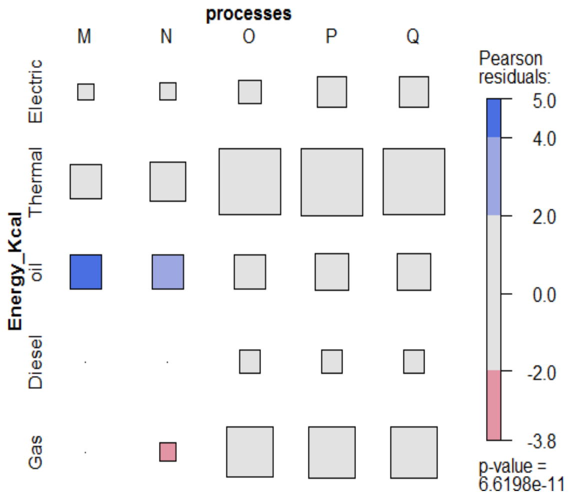


Chart 1b – Energy flow

Chart 1b is a mosaic based on the tile plot (Meyer et al., 2006), which is based on the energy flow (indirect coefficients of Table 3, $EDCA^{-1}$ of Figure 5b). This chart shows the direct and indirect energy absorption by the processes, or the energy unit flow (energy content up to the process under analysis), with the rectangles of the Q process (packaging) in proportion to the total unit energy content of the EE (Albino et al., 2002). In Charts 1a and 1b, blue represents energy consumption that is higher than expected, and red represents energy consumption that is below expectations.

Charts 2 to 5 were prepared based on the grammar of graphics (Wickham, 2009; Grolemund, 2012). Chart 2 shows the DEE indicator panel (Equation 4), representing a total of 132 performance indicators, considering all processes and energy sources. Chart 2 has the potential to represent as many as 300 indicators, since the blanks indicate that the process does not consume the particular source of energy. The colors indicate efficiency levels (literally, an efficiency scale), with one color representing the least efficient periods (red) and another the more efficient periods (green).

The comparison of indicators is possible because the created indicators are dimensionless and in the range between 0 and 1, as is typical for efficiency indicators. Chart 3 shows the change in relation to Chart 2 (Equation 5, CDEE), making it easier to see the evolution or, in other words, where the efficiency decreased and increased.

Chart 4a shows the calculation of the REE indicator (Equation 3), as created using DEA, assuming constant returns to scale (Charnes et al., 1978; Bogetoft and Otto, 2010; Zhu, 2014). Comparing Chart 4a and Chart 2, the energy source dimension (electricity, thermal energy, oil, diesel, and gas) disappears, since it is possible to aggregate different entries for the calculation of the indicator (Perroni et al., 2016a). The DEA represented in Chart 4a is considered an intertemporal frontier analysis, measuring the evolution of efficiency in relation to energy inputs in different periods of time. Other inputs (water, raw materials, organizational capacity, byproducts, etc.) could be considered as well as other outputs (waste, byproducts, noise, pollution, etc.) (Zhu, 2014).

Chart 4b is entitled “Global efficiency” because it takes into account all energy sources and all processes, lacking the efficiency evolution in time. The calculation of Chart 5b is the flow efficiency indicator (Equation 6, IEE) for process Q (packing), considering direct efficiency and indirect efficiency.

Chart 5 shows the CDEE indicator for process O (firing) using the waterfall chart technique (Wickham, 2011). The path of learning can be visualized through Chart 4.

With the proposed panels, it is possible to discuss a hierarchy of indicators based on the created dimensions: energy source, process, and time. Chart 2 shows the individual indicators for the energy sources used in each process. In Chart 4a, energy sources are aggregated representing the efficiency evolution of the processes, and in Chart 4b, both energy sources and processes are aggregated, so that only the dimension of time is present. This is possible because the dimensionless indicators of Equations 4 to 7 are in the interval 0,1.

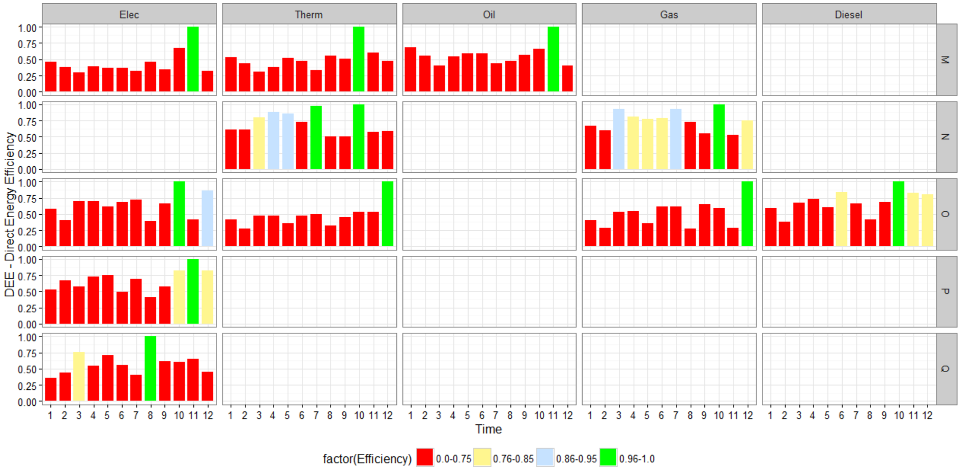


Chart 2 – Direct energy efficiency

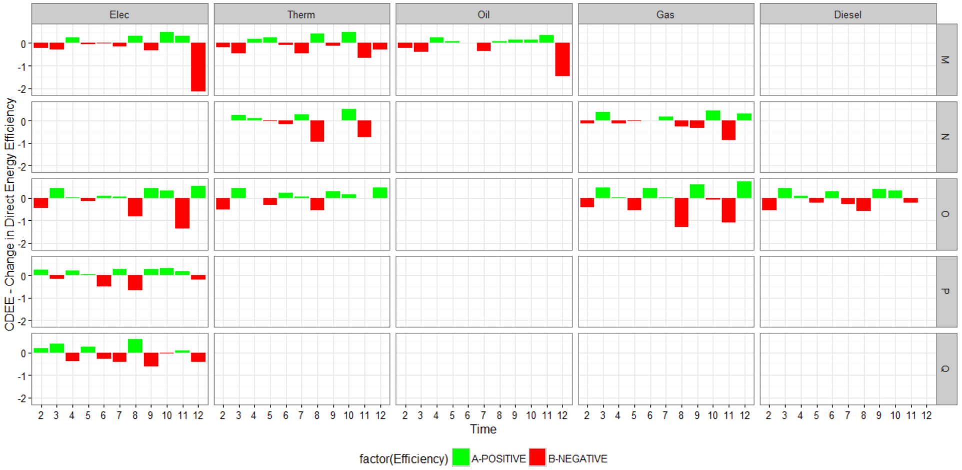
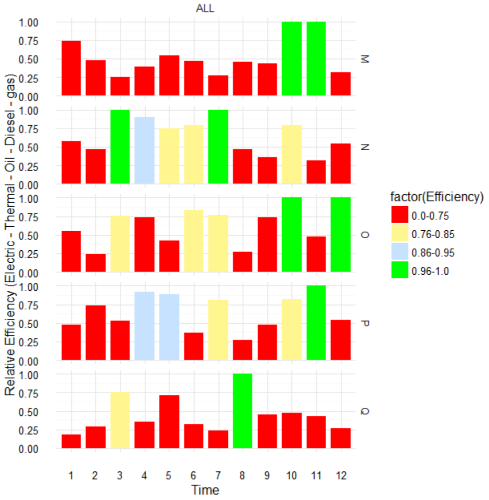


Chart 3 – Change in direct energy efficiency



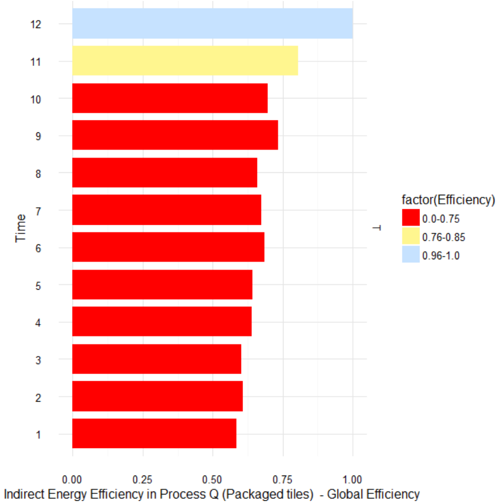


Chart 4a – Relative efficiency

Chart 4b – Global efficiency

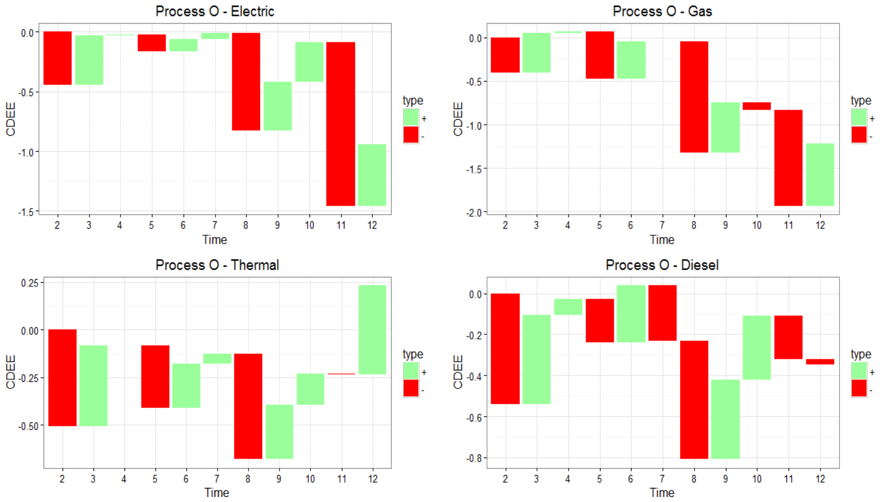


Chart 5 – Change in direct energy efficiency for process O

Source: Simulation approach of the longitudinal input-output process model structure
Note: (n = 1) in the simulation approach of Figure 6

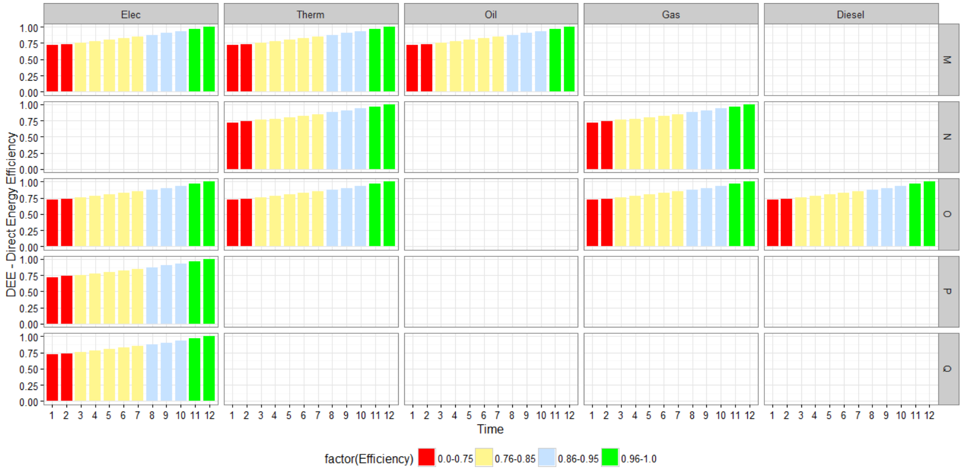


Chart 6 – Direct energy efficiency

Chart 7 – Change in direct energy efficiency

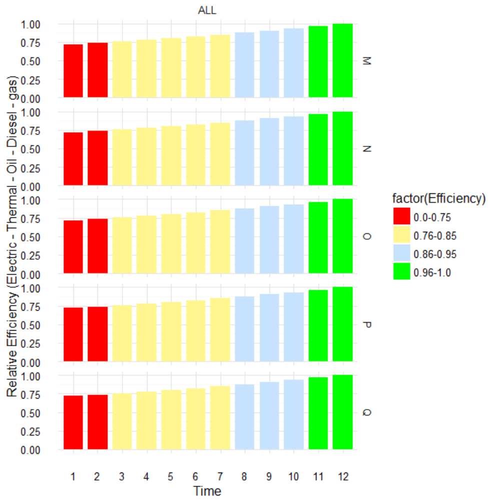


Chart 8a – Relative efficiency

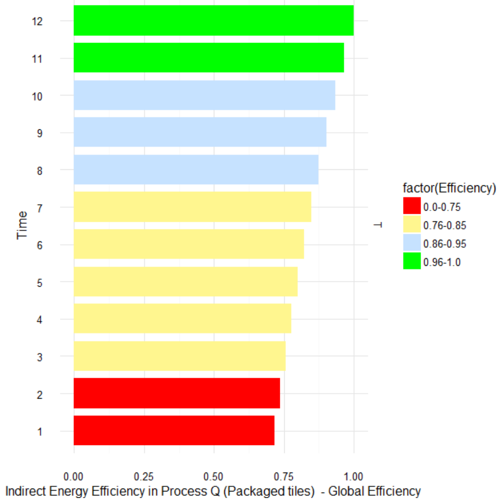


Chart 8b – Global efficiency

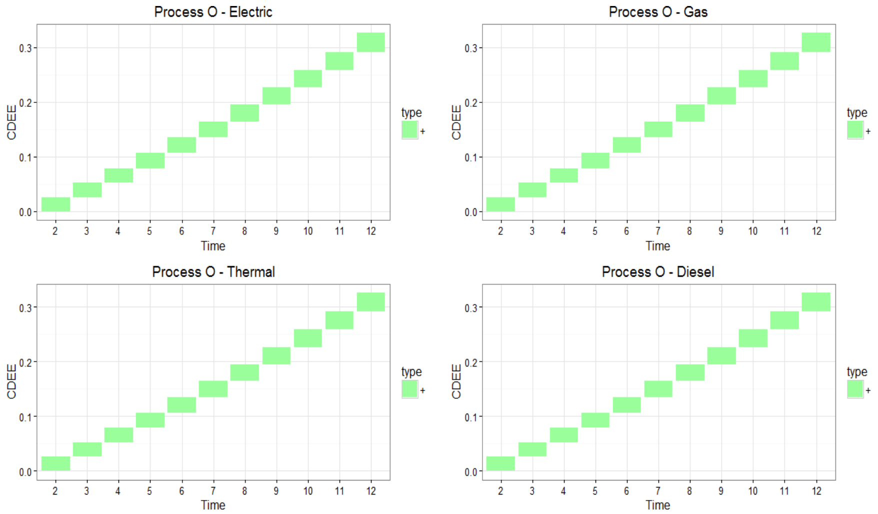


Chart 9 – Change in direct energy efficiency for process O

Source: Simulation approach of the longitudinal input-output process model structure

Note: (n = 10,000,000) in the simulation approach of Figure 6

Charts 2 to 5 take a value of $n = 1$ in the simulation approach of Figure 6. For comparison purposes, Charts 6 to 9 show what happens to the indicators when the value of n in the simulation model of Figure 6 takes a large value ($n = 10,000,000$). In Charts 6 to 9, all calculated efficiency values converge, with a 100% concordance among the indicators. It may be noted that there is a correlation between the indicators in terms of evolution; thus, it can be confirmed that all created indicators capture the evolution of energy performance, and when there is a drop in energy performance (Charts 2 to 5) the indicator panel system created with the grammar of graphics can capture the change in performance (Wickham, 2009).

5 Discussion

This study seeks to fill a gap in the literature on energy management in the context of the production of goods and services, which presently lacks the proposal and discussion of frameworks, models, and indicators capable of integrating energy management into business production management (Bunse et al., 2011). The purpose of the study is to develop a processes approach for the continuous measurement of energy performance. The main energy performance indicator is energy efficiency. The issue of energy efficiency is positioned within the sustainability research program, which can be understood as the research programs of Lakatos (1978). Sustainability is a *sine qua non* to energy efficiency. New perspectives of the potential applicability that can be developed within this research program are made possible, since energy consumption is related to other variables such as population growth, increase in wealth, climate change, and so on.

Figure 2 shows how research problems can be represented and addressed (Shehabudden et al., 1999). The representation of the energy performance problem was created through the development of three inductive structures: (a) a framework that relates the dynamics and structure of the energy performance of the processes; (b) a map of indicators of energy efficiency of the processes; and (c) a model that integrates the represented issues both in the framework and in the map. The model selected to represent the problem was the input-output process model (Lin and Polenske, 1998; Albino et al., 2003; Kuhtz et al.. 2010).

The framework of processes in Figure 3 indicates that energy management must be strategically planned, unlike what the literature on management and energy efficiency have suggested, even in large companies (Ates and Durakbasa, 2012; Rudberg et al., 2013). Based on Bititci et al. (2000), energy performance management has to be considered at a strategic level. The continuous improvement process is suggested by the literature and energy management (Kannan and Boie, 2003; Gordic et al., 2010; Negai et al., 2013), given the heterogeneity of processes requiring solutions in terms of customized EEMs or EETs (Vikhorev et al., 2013), and private external issues such as technology providers or financing policies, among many others (Cagno et al., 2013). Another relevant issue represented in the framework is the structure in which the energy performance occurs, and since virtually all production processes use energy, the energy can be analyzed as a flow, which is the EE, or a network of processes (O'Neill and Sackett, 1994). Thus, the EE can have a common or aggregate energy performance (Folan and Browne, 2005) associated with the embodied energy of products (Rahimifard et al., 2010) or the cumulative energy demand (Patel, 2003).

The map of indicators was proposed because, as recognized by the literature, there has been a lack of discussion and proposals of indicators (Bunse et al., 2011), besides the fact that there are many terms to represent energy performance (energy efficiency, energy productivity, energy content, energy intensity, specific energy consumption, and relative efficiency), which could cause confusion in the area (Patterson, 1994; Phylipsesen et al., 1997; Boyd et al., 2008; IEA, 2014b). The purpose of the map of indicators is to provide an indicator structure capable of feeding the input-output model. The limitation raised by Patterson (1996) is acknowledged, in which any indicator designed to measure energy performance and energy efficiency will be a *proxy* of this performance and, thus, based on the indicator chosen, there could be advantages and disadvantages. The seeming advantage of an indicator can in fact be a disadvantage; for example, the longitudinal comparison of the physical-thermodynamic indicators is much more realistic than the longitudinal comparison of the purely economic indicators.

The input-output process model (Lin and Polenske, 1998; Albino et al., 2003) is a simplified deductive way to integrate both the framework structure (Figure 3) and the map of indicators (Figure

4). Given the divisibility hypothesis of the processes, as many processes as necessary can be added, and yet the operationalization of the model will remain the same. In its original format, the input-output process model can represent physical-thermodynamic, economic-thermodynamic, and economic indicators. In Figure 5a, the time variable was added to the model, turning it into a longitudinal input-output process model. This change was necessary because a continuous improvement system requires reevaluations over time. Figure 5a depicts a simplified model because it represents a production cycle, which is a *one-way* model (Albino et al., 2003); thus, the production cycle could be used to delimit the period of time for the system/structure to be reevaluated.

The approach for the continuous measurement of energy performance uses the concepts introduced to create indicators and formulate a simulated system to represent the indicators in visualization panels. The proposal, especially the efficiency indicators (DEE, CDEE, and IEE), was created because the physical-thermodynamic, economic-thermodynamic, and economic indicators of the map of Figure 4 are performance indicators and not efficiency indicators as defined by enterprise efficiency. An efficiency indicator results from the ratio of two performance indicators (Bogetoft and Otto, 2010; Perroni et al., 2016a). The fact that the indicators generate numbers in the range 0–1 facilitates comparison over time.

The approach to simulation uses the structure of tile manufacturing, which is described in five processes (Table 2). The simulation generates a set of 12 tables similar to Table 2, performs the matrix calculations according to Tables 3 and 4, calculates indicators (Equations 4 to 7), and builds a panel of indicators that feeds the visualization system built with the R software.

A visualization system is needed to make sense of a large number of proposed indicators. Visual information requires less cognitive load to the individual memory than non-visual information, facilitating interpretation (Wickham, 2011; Glolemund and Wickham, 2014). Considering the energy structure of Table 2, 132 indicators are generated for DEE alone. The created graphics in panels facilitate the identification of specific points where there is improvement or decline in performance.

The advantage of the proposed processes approach is flexibility; the structure is capable of representing continuous energy performance of the EE, and is flexible enough to cover most of the indicators of energy efficiency of processes in Figure 4. The KPI indicators can be aggregated with DEA or with the input-output model flow indicators, forming a hierarchy of indicators that can be compared. The thermodynamic indicator is the indicator that the approach in principle cannot handle. Within the framework of the input-output model, new indicators can be created based on the principles of energy content or stochastic frontier, depending on the need of the analyzed network of processes and on data quality. Some proposed indicators can be adopted regardless of the context of a network of processes, such as the DEE indicator or DEA indicators.

In the Introduction, it was assumed that it is possible to identify both measures and technologies, which can improve the energy performance of the processes when implemented. If it is not possible to identify measures and technologies that can be adopted, the performance can reach saturation, at least in the short term. In times of stability, the indicators can be used as a guide, so that the performance does not regress. Another relevant issue is that the more predictable the indicators, the more the input-output process model could be used for planning and forecasting, which are the original functions proposed by Leontief (1966).

Some limitations can be raised regarding the application of the approach. The first concerns the economic, behavioral, and organizational barriers that hinder the identification and ideal adoption of measures (EEMs) and technologies (EETs) for energy efficiency raised by Cagno et al. (2013), which need to be reviewed within the scope of the energy management of each EE process. A second limitation regards the representation of the model since, in specific contexts, it is not sufficient to evaluate only the energy sources, but also create indicators of generation/use of waste and related resources (water, waste generation, cogeneration, use of energy-intensive materials, etc.). The good news is that the flexibility of the input-output model allows the logic of the EE energy matrix to be extended to other matrices (materials, waste, and byproducts) with ease (Figure 5a). A third limitation regards the representation of the input-output model of Figure 5a, as the processes have simple dependencies (one-way model), forming a production cycle (process sequence). The great advantage of the input-output model is in representing processes with mutual dependence (multi-way model) (Albino et al., 2003), created by a network of processes (network of production processes), both local and global. In the case of a network of processes, a third form of visualization emerges, which is the use of social network analysis (Borgatti and Li, 2009).

Proposed future study includes the implementation of the approach in a network of processes with multiple dependencies (multi-way), analyzing energy, primary inputs, waste, and byproducts.

6. Conclusion

The objective of this study was to develop a processes approach for continuous measurement of energy performance. The main energy performance indicator is energy efficiency. The article began with the assumption that the hypothesis of energy efficiency belongs within the broad sustainability research program. The research uses a methodological adaptation developed by the Institute for Manufacturing at the University of Cambridge, in which it is assumed that complex issues such as energy efficiency are solved by multiple structures, making use of induction to represent the problem using frameworks, models, and maps, and deduction to address the problem in a practical way, implemented by processes, procedures, techniques, and tools.

The representation was made by integrating a processes framework in which the dynamics and structure of energy performance were considered, a map of indicators to position the chosen indicators, and a longitudinal input-output process model. The approach uses the input-output procedure originally proposed by Leontief, as well as the matrix techniques to propose indicators in order to continuously measure energy performance. The approach was implemented by a real process structure with simulated data using the R analytics tool. To facilitate the understanding of the indicators, a visualization system was also proposed.

The tests showed that the developed processes approach is able to continuously monitor energy performance, identifying points where the continuous improvement system suffers interruptions, allowing the proper plan of action to be implemented.

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Appendix A - Partial code of R analytics tool

Import the original data- Kuhtz et al. (2010)

```
data <- read.csv(file="C:/ENG. PRODUÇÃO/LIVROS/ARQUIVOS DE
LIVROS/R/Mosaic/DataFrameEIOM.csv", header=T, sep=";",dec=",")
attach(data)
```

Create an energy matrix object [INPUTS]

```
EI <- (as.matrix(data[Produtos == "Energy inputs",-(1:2)]))
```

Create an output object [OUTPUT]

```
OP <- (as.matrix(data[Produtos == "Gross Output",-(1:2)]))
```

Calculation of direct coefficients

```
ym <- diag(1,5,5)
diag(ym) <- 1/OP
coefTecEnergy_inputs <- EI%*%ym
lin <-c("Electric", "Thermal", "oil", "Diesel","Gas" )
col <- c("M", "N", "O", "P", "Q")
dimnames(coefTecEnergy_inputs) = list(Energia_Kcal=c(lin), processo=c(col))
```

Calculating the flow (indirect) coefficients

```
Produto <- as.matrix(data[Produtos == "Produto",-(1:2)])
coefTecProduto <- Produto%*%ym
FluxoProduto <- solve(coefTecProduto)
FluxoEnergia <- coefTecEnergy_inputs%*%FluxoProduto
lin <-c("Electric", "Thermal", "oil", "Diesel","Gas" )
col <- c("M", "N", "O", "P", "Q")
dimnames(FluxoEnergia) = list(Energia_Kcal=c(lin), processo=c(col))
```

Generating data sets (CHANGE_EI=0.05)

```
ME <- EI-(EI*0.05)
SE<-
matrix(c(SM(,ME[1,1],EI[1,1]),0,SM(,ME[1,3],EI[1,3]),SM(,ME[1,4],EI[1,4]),SM(,ME[1,5],EI[1,5]),SM(,ME[
2,1],EI[2,1]),SM(,ME[2,2],EI[2,2]),SM(,ME[2,3],EI[2,3]),0,0,SM(,ME[3,1],EI[3,1]),0,0,0,0,0,0,SM(,ME[4,3],EI
[4,3]),0,0,0,SM(,ME[5,2],EI[5,2]),SM(,ME[5,3],EI[5,3]),0,0), nrow=5,ncol=5, byrow=T)
OS <- OP-(OP*0.50)
SEP<matrix(c(SM2(,OS[1,1],OP[1,1]),SM2(,OS[1,2],OP[1,2]),SM2(,OS[1,3],OP[1,3]),SM2(,OS[1,4],OP[1,4]),
SM2(,OS[1,5],OP[1,5])), nrow=1, ncol=5,byrow=T)
ym2 <- diag(1,5,5)
diag(ym2) <- 1/SEP
coefTecEnergy_inputsSimul <- SE%*%ym2
dimnames(coefTecEnergy_inputsSimul) = list(Energia_Kcal=c(lin), processo=c(col))
dimnames(SEP) = list(produto=c("Output"),
processo=c("M", "N", "O", "P", "Q"))
B1 <- SEP
A5 <- coefTecEnergy_inputsSimul
P <- B1
produto<-matrix(c(P[1],-P[1],0,0,0,0,P[2],-P[2],0,0,0,0,P[3],-P[3],0,0,0,0,P[4],-
P[4],0,0,0,0,P[5]),nrow=5,ncol=5, byrow=T)
coefTecProduto <- Produto%*%ym2
FluxoProduto <- solve(coefTecProduto)
FluxoEnergiaSimul <- coefTecEnergy_inputsSimul%*%FluxoProduto
dimnames(FluxoEnergiaSimul) = list(Energia_Kcal=c(lin), processo=c(col))
FE5 <- FluxoEnergiaSimul
```

Global indicator

```
onze <- 2:12
doze <- 1:12
tFLE <- t(FLE)
apI <- apply(tFLE[,1:5],1, sum)
GENERGY<-
cbind((min(apI)/apI[1]),(min(apI)/apI[2]),(min(apI)/apI[3]),(min(apI)/apI[4]),(min(apI)/apI[5]),(min
```

```
(apI)/apI[6]),(min(apI)/apI[7]),(min(apI)/apI[8]),(min(apI)/apI[9]),(min(apI)/apI[10]),(min(apI)/apI[11]),(min(ap
I)/apI[12]))
GlobalEnergy<-
data.frame(expand.grid(indSimples=c("Global"),processo=c("T"),tempo=c(doze),energy=c("energy" )),
eff=c(GENERGY))
```

Process M - Direct Efficiency Indicator

```
energyME <- t(as.matrix(oo2[Fonte == "Electric",-(6)]))
ElecM <- energyME[1,]
ELM <- cbind((min(ElecM)/ElecM[1]),(min(ElecM)/ElecM[2]),
(min(ElecM)/ElecM[3]),(min(ElecM)/ElecM[4]),
(min(ElecM)/ElecM[5]),(min(ElecM)/ElecM[6]),(min(ElecM)/ElecM[7]),(min(ElecM)/ElecM[8]),(min(ElecM)/
ElecM [9]),(min(ElecM)/ElecM[10]),(min(ElecM)/ElecM[11]),(min(ElecM)/ElecM[12]))
efficELM <-
data.frame(expand.grid(indSimples=c("IndGen"),processo=c("M"),tempo=c(doze),energy=c("Elec")),eff=
c(ELM))energyMT <- t(as.matrix(oo2[Fonte == "Thermal",-(6)]))
ThermM<-energyMT[1,]
THM<-cbind((min(ThermM)/ThermM[1]),(min(ThermM)/ThermM[2]),
(min(ThermM)/ThermM[3]),(min(ThermM)
/ThermM[4]),(min(ThermM)/ThermM[5]),(min(ThermM)/ThermM[6]),(min(ThermM)/ThermM[7]),(min(Ther
mM)/ThermM[8]),(min(ThermM)/ThermM[9]),(min(ThermM)/ThermM[10]),(min(ThermM)/ThermM[11]),(mi
n(ThermM)/ThermM[12]))
efficTHM <- data.frame(expand.grid(indSimples=c("IndGen"),processo=c("M"),tempo=c(doze), energy=
c("Therm")),
  eff=c(THM))
energyMO <- t(as.matrix(oo2[Fonte == "oil",-(6)]))
OilM <- energyMO[1,]
OIM<-
cbind((min(OilM)/OilM[1]),(min(OilM)/OilM[2]),(min(OilM)/OilM[3]),(min(OilM)/OilM[4]),(min(OilM)/
OilM[5]),(min(OilM)/OilM[6]),(min(OilM)/OilM[7]),(min(OilM)/OilM[8]),(min(OilM)/OilM[9]),(min(OilM)
/OilM[10]),(min(OilM)/OilM[11]),(min(OilM)/OilM[12]))
efficOIM <-
data.frame(expand.grid(indSimples=c("IndGen"),processo=c("M"),tempo=c(doze),energy=c("Oil")),
  eff=c(OIM))
```

Process M – DEA

```
ElectricM <- oo2[(Fonte =="Electric"),][,1]
oilM <- oo2[(Fonte =="oil"),][,1]
ThermalM <- oo2[(Fonte =="Thermal"),][,1]
tedM <- as.data.frame(cbind(ElectricM, oilM, ThermalM))
xM <- with(tedM, cbind( ElectricM, OilM, ThermalM))
yM <- matrix(with(oo3, M))
teM <- dea(xM,yM,RTS="crs")
DEAM <- teM$eff
```

Graphic Panel - Direct Energy Efficiency

```
ind2<-todos[(todos$indSimples =="IndGen") ,]
x <- ind2$eff
Efficiency <- cut(x, breaks = c(0,0.75,0.85,0.95, 1), labels = c("0.0-0.75","0.76-0.85","0.86-0.95", "0.96-1.0"))
ind2$Efficiency <- Efficiency
k <- ggplot(ind2, aes(factor(tempo), eff)) + facet_grid(processo ~ energy)
k + geom_bar(stat = "identity", aes(fill=factor(Efficiency),width=0.8)) + scale_fill_manual(values =
(c("red","khaki1","slategray1", "green")))+ theme_bw()+labs(title = "") + xlab("Time") + ylab("DEE - Direct
Energy Efficiency ")+theme(legend.position = "bottom", legend.box = "horizontal")
```

Process 0 - Starircase graphic:Electricity

```
balance <- data.frame( desc = c(2:12), amount = c(EFOSinal[1,]))
balance$desc <- factor(balance$desc, levels = balance$desc)
balance$id <- seq_along(balance$amount)
balance$type <- ifelse(balance$amount > 0, "+", "-")
balance$type <- factor(balance$type, levels = c("+","-"))
balance$end <- cumsum(balance$amount)
balance$start <- c(0, head(balance$end, -1))
balance$type <- as.factor(balance$type)
```

```
p1 <- ggplot(balance, aes(desc, fill=type)) + geom_rect(aes(x=desc,xmin = id - 0.45, xmax=id + 0.45, ymin=end, ymax=start))
pp1 <- p1 + scale_fill_manual(values = (c("palegreen1", "red")))+ theme_bw()+ theme(legend.position = "right", legend.box = "horizontal")+ labs(title = "Process O - Electric") + xlab("Time") + ylab("Change in Efficiency")
```