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MATHEUS BELTRAME CANCIGLIERI

A SEMANTIC RECONCILIATION APPROACH TO SUPPORT INTEROPERABILITY ACROSS MULTIPLE DOMAINS THROUGHOUT AN INTEGRATED PRODUCT DEVELOPMENT PROCESS

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Dissertation presented to the Industrial and Systems Engineering Graduate Program of the Pontifical Catholic University of Paraná (PPGEPS/PUCPR), as a partial requirement for the degree of Master in Industrial Engineering and Systems.

Supervisor: Prof. Dr. Anderson Luis Szejka

Co-Supervisor: Prof. Dr. Eduardo de Freitas Rocha Loures.

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This dissertation is dedicated to Daniela, to my parents, Osiris and Rosana and my brother Arthur.

Moonlight drowns out all but the brightest stars.

J.R.R Tolkien

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"It is not our part to master all the tides of the world, but to do what is in us for the succor of those years wherein we are set, uprooting the evil in the fields that we know, so that those who live after may have clean earth to till."

J.R.R. Tolkien

ABSTRACT

The globalisation has impulsed Product Development Process (PDP) has changed its focus towards more intensive knowledge approach aiming at a time reducing and on the increase of its activities efficiency. The lack of clarity often hinders this approach in the terms used by the different design teams as the information exchange context affects the overall meaning and interpretation of the shared implicit and explicit knowledge. It becomes a significant problem as the design and manufacturing activities are 85% of the products final cost. The lack of clear communication and, consequently, cooperation increases the product's development and manufacturing time and cost and reduces the products' quality. Thus, the essential requirements for effective collaboration among enterprises are agility and interoperability. Therefore, the main objective of this research is to develop a semantic reconciliation approach to support interoperability throughout an integrated product development process allowing the use of computational tools to translate and share information across multiple domains. A systematic literature review and content analysis alongside an experimental case were adopted as technical procedures for this research. The proposed approach translates knowledge between different stages of the product development process, and analyses the consistency of the created knowledge, reducing the misunderstandings and limitations of communication between product development teams. The proposed approach is divided into 3 main stages: i) the Pre-Development Stage; ii) The Development Stage, and iii) the Post Development Stage. Each of these stages corresponds to a step in product design and manufacturing. An experimental case was employed to validate the proposed approach and consisted of the application of the *Development Stage* to support the development of a new three-phased 20kVA UPS. The application confirmed the potential of the proposed approach to improve product quality and reduce the cost and time of design and manufacturing. It has also confirmed that the proposed approach is able to implement an interoperable environment in the company that is capable of efficiently translate and share the information and knowledge across product design and manufacturing processes in a real world.

Key-words: Integrated Product Development Process, Semantic Interoperability, Semantic Reconciliation, Multiple Domains, Product Design, and Manufacturing, Ontology.

TABLE OF FIGURES

ABBREVIATION TABLE

CAD – Computer Aided Design

CAM – Computer Aided Manufacturing

CAPP – Computer Aided Process Planning

CSV – Comma-separated values

IPDP – Integrated Product Development Process

OWL – Web Ontology Language

PDP – Product Development Process

SRIPDM – Semantic Reconciliation Approach for Interoperable Product Design and Manufacture

VBA – Virtual Basic for Applications

XML – Extensible Markup Language

SUMMARY

1 INTRODUCTION

1.1 CONTEXTUALIZATION

The globalisation has impulsed Product Development Process (PDP) to a trend of business collaborative, cooperative alliances or both over the recent years, which has changed its focus towards more intensive knowledge approach aiming at a time reducing and on the increase of its activities efficiency. Yet, this approach is often hindered by the lack of clarity in the terms used by the different design teams as the information exchange context affects the overall meaning and interpretation of the shared implicit and explicit knowledge (ENGINEOUS, 2005; KYOUNG et al., 2009; ZHAO & LIU, 2008; BEAU et al., 2010; SINDEREV, 2008; NAGY & VARGAS, 2011). The knowledge sharing, in consequence, presents two main problems that are known as semantic heterogeneity. These problems are: i) the same term is applied to different concepts (semantic problem) and ii) different terms are applied to the same concept (syntax problem) (HARDING & SHAHBAZ, 2004).

The holistic approach of PDP provides the necessary information to the different stages of the product development and manufacturing, and consequently, the knowledge from each node within the product development and manufacturing may be formalised. The formalisation will result in multiple viewpoints associated to the representation of artefacts and different depictions of similar concepts that lead to the identification of misinterpretations and mistakes during the latter stages of the PDP (CHUNGOORA & YOUNG, 2011; NAGY & VARGAS, 2011; PENCUIC et al., 2014).

Semantic heterogeneity becomes a significant problem as the design and manufacturing activities are 85% of the products final cost. In this context, the information sharing across the different stages of product development and manufacturing must be done precisely to ensure that the product developed has the desired quality with cost and time optimisation.

The emerging semantic web, a specific form of formal logic that can be used accurately in a virtual environment, has used descriptive logic-based ontologies as one of its primary applications to solve the semantic heterogeneity problems. Still, when used in a multiple domain environment they suffer from limitations to share the knowledge effectively between them (DURBHA et al., 2009; ROZENFELD et al., 2006; CHUNGOORA & YOUNG, 2010). In this way, despite the semantic formalism created using ontologies, a limitation appears when the need to work through multiple knowledge domains is presented as the semantic formalism of the ontology cannot ensure the sharing of the information and its meaning through different domains.

Even though the development of ontology mapping methodologies moderates this problem with the use of different ontology throughout the product design and manufacturing may hinder the creation of an interoperable environment. The different domains have different concepts, and the exchange of the information through the product development without the proper processing may result in loss of product quality, more significant development time, and costs.

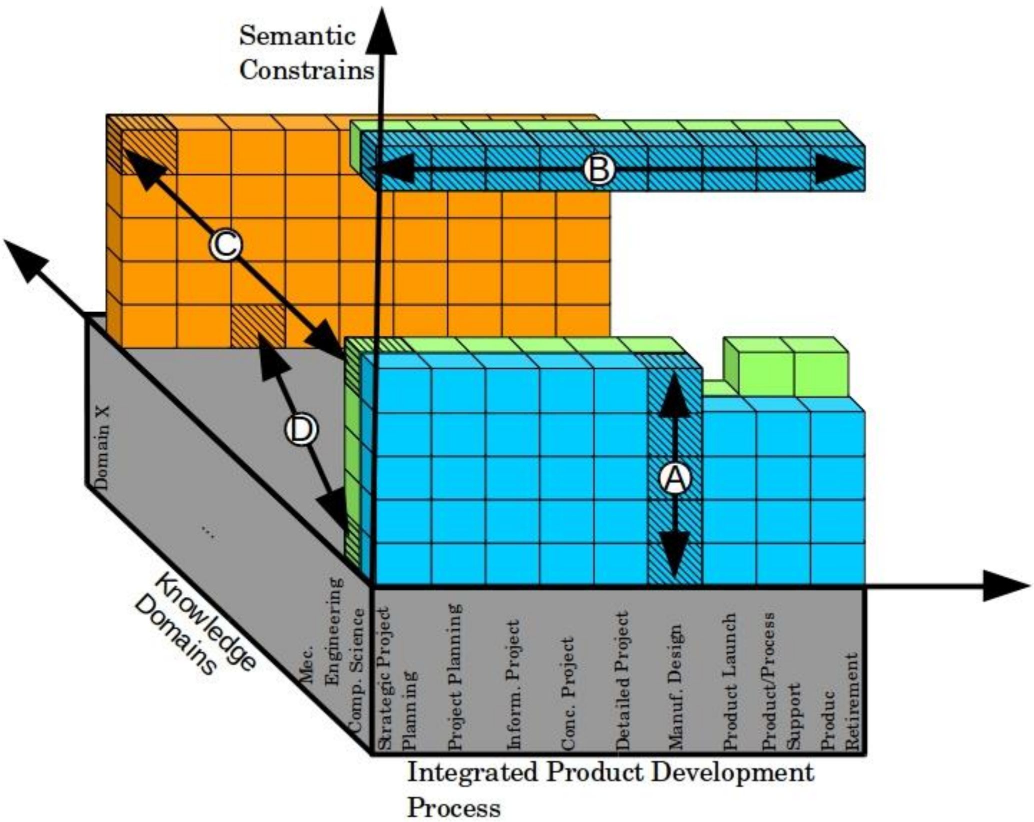
1.2 PROBLEM STATEMENT

The departments involved during the product development and manufacturing in enterprises must manage their resources and, at the same time, need to communicate and cooperate among themselves accurately. The semantic heterogeneity issues represent the biggest problems that interfere with the application of an effective multiple domain communication and cooperation system that can create an actual semantic interoperable environment. The lack of clear communication and, consequently, cooperation increases the product's development and manufacturing time and cost and reduces the products' quality. Thus, the essential requirements for effective collaboration among enterprises are agility and interoperability.

The standardised and formalised knowledge that is captured by an ontology-driven system can be retrieved, shared, and reused in different stages of product development and manufacturing. Also, the information can be captured in its entirety as well as extended as the need arises using the process of relating the concepts through the ontology. This capacity of relating concepts present in the ontology-driven systems improves the collaboration in a multiple domain environment and across network-based designs since it conveys several characteristics, which are often ambiguous, in a non-ambiguous manner. The high degree of expressiveness of an ontology-driven structure enables the establishment of resolvable and meaningful mappings across knowledge models. The expressiveness helps support the consistency of the ontology matching while avoiding the drawbacks of subjectivity in the mapping transaction that are a consequence of the extensive human intervention.

Figure 1 shows the points where the semantic constraints and rules may hinder the development of a product in an interoperable environment of multiple domains. In this Figure, Detail “A” represents the possibility of ambiguous constraints present in the same domain and same product design stage. Detail “B” shows the possibility of having heterogeneous constraints in the same domain but at different stages of the product development process. Detail “C” characterises the heterogeneity between constraints in the same development stage, however, between different knowledge domains, and detail D represents the heterogeneity between constraints in different stages of the product design and at different domains.

Figure 1 – Diagram of Interoperable Limitations Regarding Product Design and Manufacture, Multiple Domains, and Semantic Constraints.



Source: The author, 2018.

In this context, this research aims to explore the question: ***“Is it possible to develop an approach that allows the semantic reconciliation of information that can efficiently translate, convert and share the information across the Integrated Product Development and Manufacturing and its domains?”***

1.3 OBJECTIVES

1.3.1 Main Objective

The main objective of this research is to develop a semantic reconciliation approach to support interoperability throughout an integrated product development process allowing the use of computational tools to translate and share information across multiple domains.

1.3.2 Specific Objectives

To reach the main objective of the research and develop the semantic reconciliation approach was divided into specific objectives:

- To perform a Systematic Literature review of the relevant topics: Semantic Reconciliation; Multiple Domains and Product Development (Concurrent Engineering; Integrated Product Development Process; Computer Aided Design and Manufacturing; Design for Manufacturing and Assembly; Semantic Interoperability; Semantic Reconciliation);
- To identify the main requirements to create a semantic reconciliation environment;
- To propose a semantic reconciliation approach to integrate multiple domains across the product development process;
- To develop an experimental computational system for implementation of the proposed approach;
- To validate the system and develop an approach through an experimental case in an electronics manufacturing scenario.

1.4 MOTIVATION

Organisations depend on their ability to successfully manage their resources in order to assure their competitiveness in a growing global competitive environment. For this reason, information systems have become more critical inside the organisations assuming the roles of an interface (responsible for internal and external information exchange) and functional engines (responsible for managing processes and business activities). Additionally, the evolution of these systems, from “islands of automation” into enterprise-level systems has created the need to transform heterogeneous information into homogeneous databases and, also, the need to integrate external and internal information in order to support the decision-making processes of the organisation.

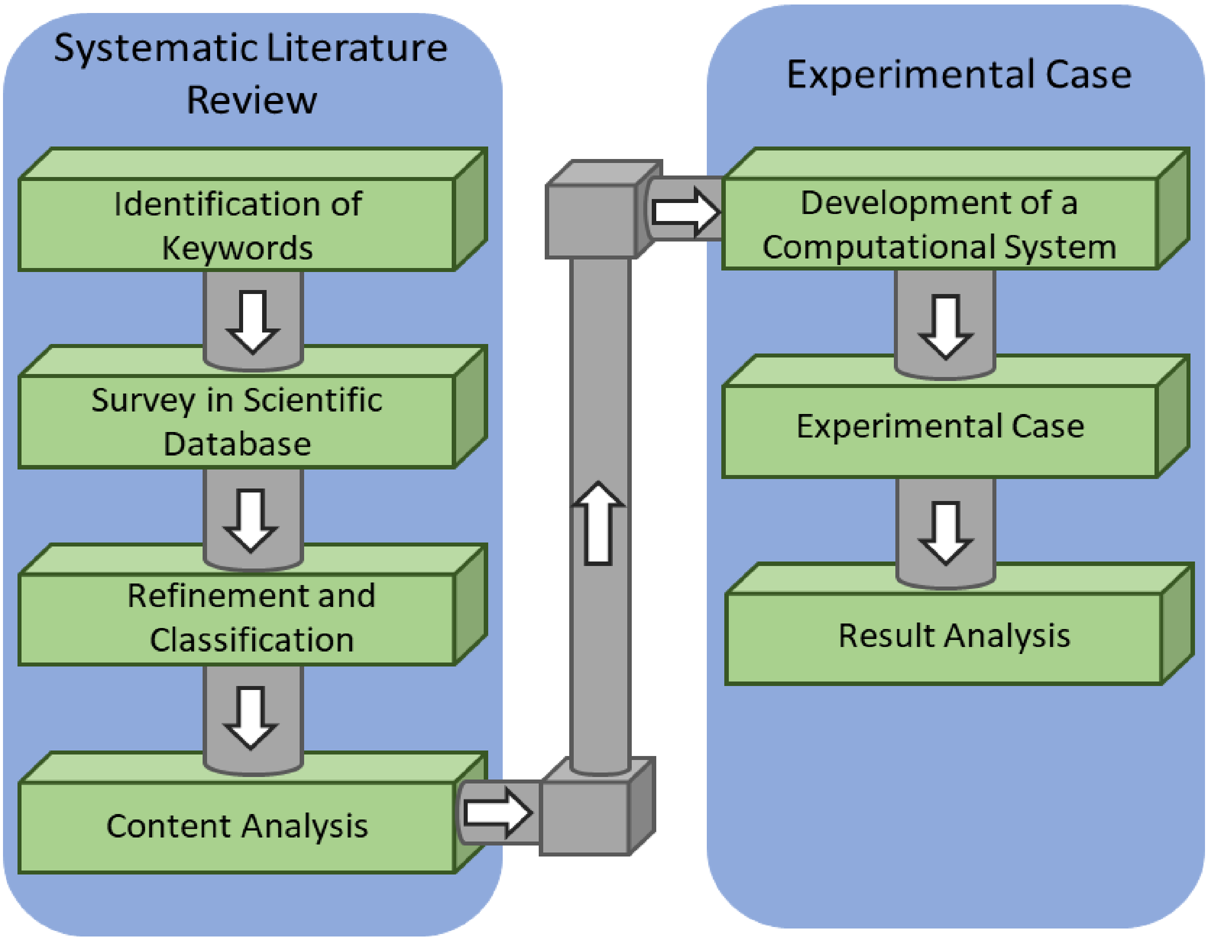
Furthermore, ontology-based models have had an increase in their role of achieving semantic interoperability among the different stakeholders, within and across the product development process, although with emphasis on the product design and manufacture. Nonetheless, the process of integrating and interoperating across several ontologies is still a difficult one as physical and logical differences among information sources complicate information retrieval and formalisation. Even though ontology mapping and matching techniques were developed to tackle the issues of cross-ontology interoperability, they remain weak in their ability to enable relationship formalisation and verification in the cross-model approach for the product design and manufacturing.

Ontologies-models of concepts and their relationships, on the other hand, are a powerful way to organise query formulation and semantic reconciliation as they can capture both the structure and the semantics of information environments and, also, are especially good at dealing with inconsistent semantics.

1.5 METHODOLOGY

The developed research project is considered to be of an applied nature, as it uses already developed and validated concepts and methodologies in order to create practical knowledge to achieve the proposed objectives. Its approach is considered qualitative as it searches a deep comprehension of a specific phenomenon, analysing variables that cannot be numerically measured (such as information consistency, concept relationships). Finally, the technical procedures adopted to achieve the research objectives were a systematic literature review and content analysis alongside an experimental case. The research methodology is shown in Figure 2.

Figure 2 – Technical Procedures of the Research



Source: The author.

A systematic literature review is a methodical, explicit, and reproducible research method that aims to guide the development of future projects, indicating directions that answer specific problems of the research. It is composed of stages of identification and definition of a selection strategy, establishment of inclusion and exclusion criteria, and critical evaluation of the scientific evidence obtained. The objective is reached by searching the already published information using defined questions. The Content analysis is also a qualitative method which purpose to carefully filter the obtained researches and to identify in which perspective each approach will be better classified by portrayed area.

After the systematic literature review and the content analysis, the development and detailing of the Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM) approach were presented and validated through the development of a computational system. This system was used in an experimental case that validates the proposed approach.

1.6 DISSERTATION STRUCTURE

This dissertation is divided into six chapters: 1. Introduction; 2. Literature Review; 3. Systematic Literature Review and Content Analysis; 4. Semantic Reconciliation Approach for Interoperable Product Design and Manufacturing; 5. Experimental Case; 6. Results Analysis and Discussion; and 8. Conclusion.

The first Chapter corresponds to the contextualization, the research problem, objectives, and research motivation, and methodology. Chapter 2 presents the conceptual background to deepen the knowledge in the relevant concepts of the research; this literature review was carried out for the topics: i) Semantic Interoperability; ii) Semantic Reconciliation; iii) Product Development Process; iv) Concurrent Engineering, and v) Integrated Product Development Process. Chapter 3 presents the systematic literature review and the content analysis that support the development of the SRIPDM presented in Chapter Four. Chapter 5 presents the experimental case used to validate the proposed approach. Chapter 6 shows the analysis of the results gathered in the experimental case and presents the discussion of these results. Finally, Chapter 7 presents the research conclusions and future directions for its continuity.

2 CONCEPTUAL BACKGROUND

This Chapter shows the literature review responsible for the presentation of the necessary concepts to the development of this research, showing the essential methods and tools for the completion of the research. The topics approached in this review are: i) Semantic Interoperability; ii) Semantic Reconciliation; iii) Computer Aided Design and Manufacturing; iv) Concurrent Engineering and v) Integrated Product Development Process.

2.1 CONCURRENT ENGINEERING

The intensification of the competitive economic environment due to globalisation has put more pressure on the industries to release new products to the market. It happens because the long-time industry survival in this environment is achieved through new products. Therefore, in the last decades, tools and methodologies to increase the efficiency and reduce the cost and time of the product development process have been developed (AL-ASHAAB et al., 2013). The authors used the Lean Product Development that uses the concepts laid by the Toyota Production System and Concurrent Engineering that aims to parallelise the tasks of the product development to create create a lean product development environment through the application of concurrent engineering. According to Al-Ashaab et al. (2013) and Sobek et al. (1999), concurrent engineering happens when the development team thinks, communicate and search solutions in a parallel way, that is, the development team communicates through the stages of the PDP searching for solutions as soon as they can identify a problem.

Chhabra & Emani (2014), Al-Ashaab et al. (2013), Sobek et al. (1999) and Ward et al. (1995) claim that in a concurrent engineering environment the critical decisions are made as late as possible in order to fully understand the consumer's requirements and design the product to meet them. Ward et al. (1995) and Ward & Sobek (2014) assessed the application of concurrent engineering in the Toyota enterprise and made a comparison between the parallel and sequential product development. In their research, the authors defined five steps to the implementation of a decision system based on concurrent engineering:

• The design team defines several solutions in a system level, which opposes the sequential development, where the design team would define one solution at a time and develop the product from there;

• The design team defines several solutions for each subsystem;

• These solutions parallelly have their viability analysed using design rules and experiments;

• These analyses narrow the solution pool and converge to a single solution;

• Once the solution is chosen, it is changed if absolutely necessary.

Sobek et al. (1999) and Ward & Sobek (2014) develop a systematic framework that compacts these five steps into three principles, each containing 3 phases:

• "Map the Design Space"- is the principle that aims to understand the design possibilities, known as design space;

• "Integrate by Intersection" - is the principle that assures the discovery of functional solutions for the subsystems by the design team;

• "Define Viability before Choosing" - is the principle of choosing the solution set that offers the optimal solutions for the system level.

Additionally, concurrent engineering presents several advantages over the conventional product development processes, as (KENNEDY, 2008; KHAN et al., 2011; SOBEK et al., 1998; WARD et al., 1995):

• Avoids extra costs due to reworks in future stages of PD;

• Efficient communication through the stages of the PD;

• Definition of optimal solutions by the consideration of all the needed functions of the product;

• Promotion of organisational knowledge and learning process;

• Reduction of the failure risk of the product.

To Lida et al. (2007) and Mendes & Toledo (2015), the manufacturing environment has changed during the last couple of years because of the growth in competitiveness on a global scale. The growth associated with the demands of the market of new, higher quality and less costly products, in decreasing lifecycles has stimulated the manufacturing enterprises to change their product development, manufacturing, and distribution drastically. These factors made the product designers alter the products development methods once, in a conventional way, the processes of conceptual design, detailed design, process planning, prototype manufacturing, and tests are sequential steps. On the other hand, through the application of concurrent engineering, these processes become integrated and parallelised. The authors also claim that Concurrent Engineering aims to encourage product developers to consider all the stages of the products lifecycle during the early stages of the PDP.

One of the key aspects for a successful implementation of Concurrent Engineering is the information technology since in order to parallelly develop and manufacture a product is necessary that all the information and knowledge created is shared consistently between all the stages to assure that the correct decision is made (LIDA et al., 2007). In this way, in their research, the authors aim to develop a decision-making support system in a concurrent engineering environment. Also, the authors propose a stand-alone system, that is, a system that does not use any network resources to offer the intended support. The proposed system uses two subsystems: the first subsystem approaches the external information provided through market analysis, material, and external components. This subsystem offers precise information about the external environment to the developers. The second subsystem approaches the internal information, such as conceptual development, assembly project, manufacturing project.

With the advances in computational technologies, several stages of the PDP have become completely automated using virtual environments, such as Computer Aided Design and Computer Aided Manufacturing (CAD/CAM). These systems are improving the products' quality as they use concepts of concurrent engineering considering future stages of the PDP, such as manufacturing and assembly (XUE, 2004). Although the significant progress, these systems focus on the generation and manipulation of geometric information such as 3D modelling and computerised numeric commands (CNC).

A profound understanding of the products lifecycle during the early stages of the development process is necessary for a product development process to occur in a concurrent engineering environment. However, due to uncertainties in these stages, a precise analysis of the possibilities is a hard task, being necessary, in this case, the use of support systems and computational environments to do a proper implementation of the concurrent engineering concepts in the product development (HAQUE et al., 2000, MENDES & TOLEDO, 2014).

2.1.1 Integrated Product Development Process

The competitive industrial environment is characterised by the need to attend the desire of the consumers for innovative products. The product development for the consumer aids the organisation gain competitive advantages and shows the crucial factors for the products' success: time, cost, and quality (EVERSHEIM, 1997, FERNANDES *et al.*, 2017).

With the reduction of the products lifecycle and the increase in new products, the PDP has become an essential tool for the creation of a sustainable competitive advantage. In this context, the product development process happens intending to expand product families and increase sales and, therefore, the enterprise's profit (KOUFTEROS ET AL., 2002, SOMMER *et al.,* 2014). However, the enterprises have not adapted to this new reality and still depend on bureaucratic functional models that inhibit the accurate flow and information and knowledge processing created throughout the product development process. These functional structures do not allow the enterprises to toil the uncertainties of the product development process, especially in the initial stages of the PDP (KOUFTEROS et al., 2002).

Isniditi et al. (1995) and Hassannezhad & Clarckson (2017) suggest that the rapid changes in the market creates uncertainties in the product development process and also that an enterprise needs an organisational structure that can minimise them. Song et al. (2001), on the other hand, suggest that the uncertainties in an organisation are created by the vast quantity of potential environmental changes and not by the speed that they occur. Another contributing factor to the environmental change is the product complexity as the uncertainties and mistakes are easily observed in markets where a product can gain market share quickly because the desired quality, performance and rapidly standards change, which in turn increases the product complexity in a short period. Enterprises that cannot structure their product development process and that are in these rapidly changing environments may lose its leadership and market share (KOUFTEROS et al., 2002).

Product development time and cost reduction are essential to very dynamic markets in order to assure commercial advantage. In these markets, the traditional model, that focus on the product, or even concurrent engineering cannot toil the products' complexity. The long-term success of an enterprise is given by the constant reduction of the product development process cycles, its ability to manage risks and reduce cost while, simultaneously, increases the products' performance. The achievement of these goals depends on the enterprise's capability to identify and manage the environmental changes in the early stages of the PDP (KOUFTEROS et al., 2002).

The industries have changed how they tackle the product development process, from sequential models to parallel ones where there is a focus on multidisciplinary teams working together (LOUREIRO, 2003). For the author, the integrated product development is an approach for an integrated and parallel development process, in which the lifecycle process and the organisational process are considered alongside the product's technical requirements. The author suggests that the approach aims to develop a product; however, it considers elements outside of the development process and uses these elements through resource management. The same author considers that the organisational restrictions are integrated into the product design in a way that the necessary resources for the product development process are analysed in the early stages, which reduces the future adequation costs of the project.

The product development process has gained notoriety in the corporate world, becoming one of the leading competitive factors between industries. In this context, the need to integrate the stages of this process is the vital importance as it can reduce costs and simultaneously allows the development of high-quality products. Thus, several methods were developed in order to assist this integration, and one of the most successful methods is the integrated product development process. (IPDP).

The IPDP consists in the integration of the product development process stages through the work of multidisciplinary teams to increase the quality, reduce the project cost while developing a product that can attend the consumer's needs (MIRALLES & LUCENA, 2007).

To Caporello (1995) and Loureiro *et al.* (2018) only through the use of the techniques and tools proposed by the IPDP a competitive advantage cannot be assured, to assure that these techniques and tools have their desired effect is necessary to quickly identify and adapt the product design to the changes in the market. The author also evaluates that several categories inside the IPDP can be associated and impacted directly by the consumer. These categories change from market to market, and the correct identification and control through the use of the correct toolset may bring competitive advantages.

2.2 COMPUTER AIDED DESIGN AND MANUFACTURING

Computer-aided design and manufacturing are defined as the use of computational systems to aid in the creation, modification, analysis, optimization, and manufacturing planning of a product. These systems consist of both hardware and software which do specific functions as required by the user (BERTOL, 2008).

The use of these graphical computational tools allowed the automation and integration of the product design, which in turn enables the production processes optimisation, reducing development time and without loss in the product manufacturing process (SILVA et al., 2010). The use of these computational tools to aid in the product design is an expanding practice, which supports the product development process as it allows to simulate the products' behaviour virtually, reducing costs and assuring the products' quality without the need of physical prototypes (AMARAL & FILHO, 2010).

The domain of Computer Aided Design (CAD) until the beginning of the '90s was mostly based on the geometric modelling and representation of products and their components. However, currently, some systems have expanded the function of the CAD systems, approaching other aspects such as manufacturing and assembly, and other activities such as decision making and case-based reasoning (SPRUMONT & XIROUCHAKIS, 2002).

To Sprumont and Xirouchakis (2002) and Fischer *et al.* (2018), the CAD systems used in a concurrent engineering environment are connected to allow communication between the teams. It encompasses not only modelling calculation, or simulation standalone applications dedicated to a specific product type or a particular aspect of the product, for example, the design for manufacturing and assembly or the design for environment. Alongside, some systems bring new interfacing methods with the aim of facilitating data acquisition and manipulation, integrating new technologies such as virtual reality devices in order to aid the representation and simulation of the product model.

Even though the current CAD system relies on task-sharing between human and machine, this interface is not entirely considered because the principal purpose of CAD systems is to optimise the interaction between teams, that is, man-man interactions, or to provide and transform information to facilitate human reasoning and decision making. Task sharing is made implicitly by the functions of the CAD system that uses the human point of view and not the couple man-machine, and, thus, are entirely dependant on the system developers (SPRUMONT & XIROUCHAKIS, 2002).

Sprumont and Xirouchakis (2002) conclude that, even though there have been significant improvements in the CAD systems, they are limited in their knowledge processing performances and their cooperation capabilities between man and machine. These limitations can cause inconsistencies in the knowledge acquired and shared through the design teams, which can, in turn, cause a misuse of the manufacturing capabilities of the enterprise, wasting resources and decreasing the final product's quality. On the other hand, Computer Aided Manufacturing (CAM) is used for process planning, material and manufacturing resources planning, and other functions. Furthermore, nowadays, it is of extreme importance to integrate the production functions into a single system in order to plan the processes precisely and share the useful knowledge across the manufacturing stages (MANKUTE, 2014).

2.2.1 Design for Manufacturing and Assembly

Design for Manufacturing and Assembly (DFMA) is a method to support the product design and aids in the parallelisation of the PDP stages because throughout the development of the conceptual design the product manufacturing and assembly is considered. Thus, the focus of the DFMA is to create a design considering the manufacturing capabilities, facilitating the final product's fabrication and assembly (ESTORILO & SIMIÃO, 2006).

According to Dufour (1996) and James *et al.* (2014), the DFMA method's objective is to develop and manufacture the product simultaneously. This method also aids the product optimisation to the manufacturing capabilities of the enterprise, which causes a reduction in manufacturing costs and time and, simultaneously, increases the products' quality. The primary requirements of the product design must be redefined during the application of the DFMA method in order to establish new quality requirements based on simplicity, materials, standardised components and reduction of secondary operations (STEPHENSON & WALLACE, 1995; BOOTHROYD et al., 2002, SPIEGEL, 2016).

The implementation of DFMA brought significant advantages to the enterprises, from the reduction of development and manufacturing costs to the increase in quality and facility in the product's manufacture and assembly. Boschetto (2016) affirms that the DFMA is a series of methods and methodologies used by the design teams to reduce the challenges of the manufacturing process in order to reduce logistic, production, and assembly costs. These methods and methodologies aid the product designers to understand the restrictions created by the manufacturing processes to develop better solutions to the product geometry.

The aim of designing a product for manufacturing is to develop products that comply with consumer’s needs while using more simple processes, reducing production costs. The use of design for assembly methods reduces the production costs by simplifying the assembly processes and by reducing the number of parts and components of the product. These reductions are made through function, geometry, material, and assembly analysis. These two methods must be used simultaneously in order to assure the reduction of costs and time during the product’s development and manufacturing processes (BARBOSA, 2007).

DFMA methods must be applied with greater emphasis during the conceptual stage of the product development process since it is in this stage that the modifications cost and the time taken to implement these modifications are at their lowest value, ensuring a product with a significantly lower price with quicker production (BOOTHROYD et al., 1994). Figure 3 shows the application structure of DFMA in the product development process.

For Catapan et al. (2007), DFMA is a philosophy that uses methods and tools to optimise the manufacturing and assembly of a product and its components. Design for Manufacturing seeks to improve the product, and its manufacturing processes, while the design for assembly seeks the simplifaction of the products’ structure, maintaining the design’s flexibility and effectiveness.

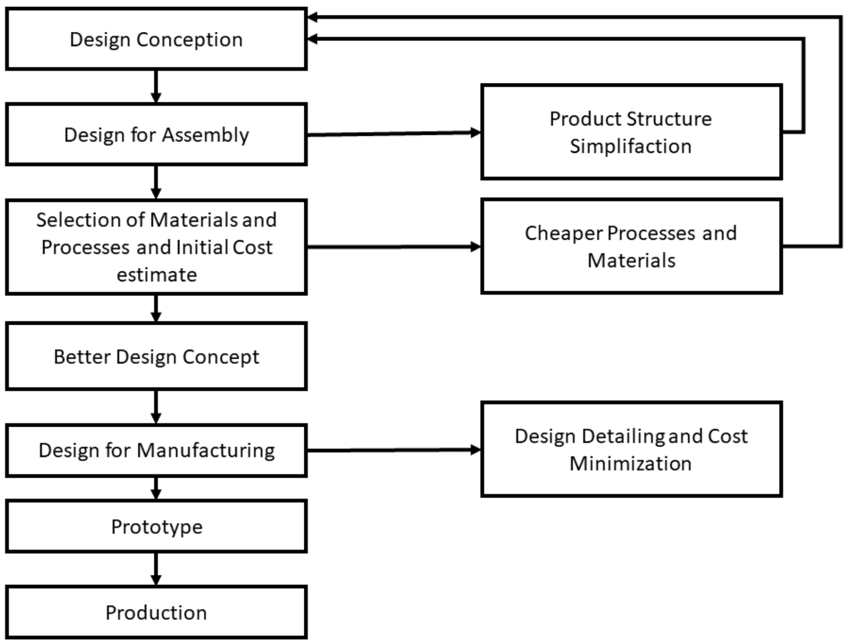
Souza (1998), Forcellini (2003), Catapan (2006) and Spiegel (2016) affirm that the main guidelines for a Design for Assembly (DFA) are:

- Define a minimum component quantity;
- Use standardised components and processes;
- Develop an approach for a modular design;
- Use unidirectional assembly;
- Facilitate component alignment and insertion;
- Eliminate screws, springs, rollers;
- Eliminate adjustments;
- Use and promote concurrent engineering.

While the Design for Manufacturing (DFM) has as main guidelines:

- Compare the different materials and manufacturing processes selected for the product's components;
- Seek standardised materials, finishing, and components;
- Ergonomic components;
- Determine the impact of these materials and processes in the product's cost.

Figure 3- Application Structure of DFMA in the product development process



Source: Boothroyd et al. (1994).

2.3 SEMANTIC INTEROPERABILITY

Even though the product development process presents a holistic approach to provide the necessary information to the different phases of the product design and manufacturing, it has been identified misinterpretations and mistakes during the latter stages of the product development (PENCIUC et al., 2014). These mistakes become significant when the activities of the design and manufacturing cost 85% of the products final cost (ROZENFELD et al., 2006). Consequently, the information sharing across the different stages of product development and manufacturing must be done precisely to ensure that the product developed has the desired quality with cost and time optimisation. It is a semantic interoperability problem for which the meaning associated to the captured information must be shared across different domains inside a system without any loss of meaning and intent during the exchange process (CHUNGOORA & YOUNG, 2010). The most common method to ensure that there is no loss of meaning in the information exchange process has been the definition of standard information models (CANCIGLIERI JR. & YOUNG, 2010; YANG et al., 2008). In this context, the construction of ontologies is a viable solution on the formalisation of these common information models and on the sharing of the formal information throughout the stages of the product development process, which, consequently, provides increased knowledge in the domains of application. (YANG et al., 2008; GOMEZ-PEREZ et al., 2004)

An Ontology is defined as “a lexicon of specialised terminology along with some specification of the meaning of terms on the lexicon” (DURBHA et al., 2009), where the lexicon is the vocabulary of a knowledge domain. In this way, a significant differentiation can be made between ontologies by their degree of expressiveness. In this differentiation, simple ontologies, which formalises only a taxonomy of concepts and basic relations between them are referred to as lightweight ontologies. When a lightweight ontology is enriched through the insertion of axioms in the form of constraints, they are classified as a heavyweight ontology. Nevertheless, the use of ontologies is restricted to the purpose of its application, that is, the knowledge structure formalised in an ontology has little reusability outside the scope of its application (CHUNGOORA & YOUNG, 2010).

Despite the semantic formalism created using ontologies, a limitation appears when the need to work in multiple knowledge domains is presented since the semantic formalism of the ontology cannot ensure the sharing of the information and its meaning through different domains. However, this problem is moderated with the development of ontology mapping methodologies, which can create relationships between terms in different ontologies of different domains (ROZENFELD et al., 2006).

The Web Ontology Language (OWL) relies only on description logic; however, both description logic and rules are required for a semantic web application because they can overcome expressiveness limitations through extensions of different knowledge domains. Nevertheless, each model supports specific reasoning services, and for them to effectively work, there is a need for close integration between the description logic and semantic rules (ZHAO et al., 2008).

The Semantic Web Rule Language (SWRL) extends the description logic of the OWL with the ability to write rules and permitting the addition of horn logic rules to the OWL descriptions. This characteristic allows the construction of more complex relations and can be used to define more precisely the concepts in the ontology. The SWRL rules are an implication between an antecedent and a consequent that can be read when the conditions specified in the antecedent are true, then the conditions on the consequent must also be true (ZHAO et al., 2008; BILETSKIY et al., 2004; BASSILIADES, 2018).

2.3.1 Semantic Reconciliation

The increase in the perception that to make a better decision is essential to have usable ou actionable information, which can be defined as knowledge, in an integrated environment between diverse resources. Thus, the importance of resolving semantic heterogeneity has gained attention in various domains (DURBHA et al., 2009; CHUNGOORA & YOUNG, 2010).

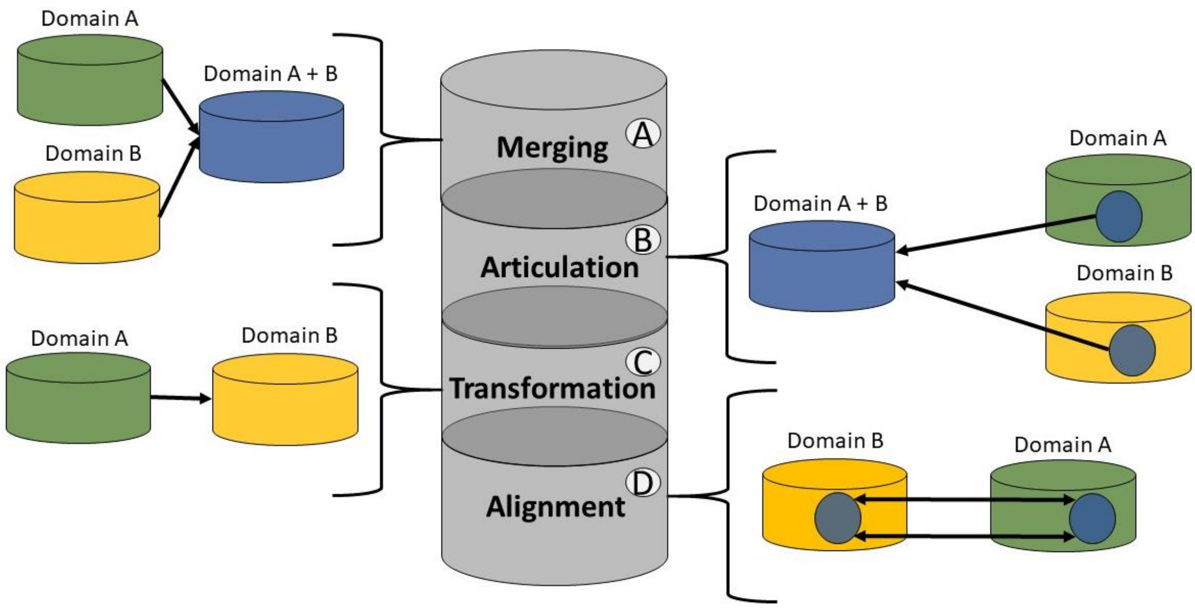
The emerging semantic web, which is a specific form of formal logic that can be used effectively in a virtual environment, has used descriptive logic-based ontologies as one of its primary applications. These ontologies can take advantage of better expressive constructions, although when used in a multiple domain environment they suffer from limitations to share the knowledge accurately between them (DURBHA et al. 2009; ROZENFELD et al., 2006; CHUNGOORA & YOUNG, 2010).

Given two different classification systems, a simple query finds all the data corresponding to a term in both information sources; however, this query can only be efficiently answered if both systems have their semantics well understood. If these systems are conceptualised in two different ontologies, the comparison of terms is a challenge due to the high variation of the detail level and logic between these ontologies (DURBHA et al. 2009; CHUNGOORA & YOUNG, 2010).

To solve this limitation a shared ontology approach can be adopted, which enables terminological reasoning over the definition of classes in the descriptive logic ontologies by considering the axioms, set of relations and set of class definitions defined in the shared ontology (STRUCKENSCHMIDT & HARMELEN, 2005; SONG et al., 2017). Even with the considerable effort that has been input to address the obstacles of semantic interoperability brought by semantic mismatches, there are still several challenges to improve the semantic reconciliation techniques (KUMAR & HARDING, 2013; SONG et al., 2017). Nowadays, the most common techniques are ontology mapping/matching.

Initial research on these techniques has been focused mainly on the overall nomenclature of the ontologies, which lead to various conflicts in a multiple domain environment or even in similar domain ontologies that uses different taxonomies (KUMAR & HARDING, 2013). However, ontology mapping techniques have been a key direction to solve semantic heterogeneity issues using the semantics reconciliation of the ontology-based models. Although several perspectives of the ontology mapping methods have been proposed, there is a consensus over the types of methods that can be applied to an ontology mapping/matching. Figure 4 presents these methods (KYOUNG et al., 2009; CHUNGOORA & YOUNG, 2011).

Figure 4- Ontology mapping/matching techniques categorisation.



Source: Adapted from Chungoora & Young (2011).

Ontology mapping methods can be classified as one of 4 categories or as hybrids of them. The ontology mapping categories are, as shown in Figure 4: i) techniques that merge two ontologies to construct a new ontology from the individual ontologies (Detail “A”); ii) methods that through a transformation function, transforms a given ontology into another based on the rules specified (Detail “C”); III) techniques that establish binary relations between the vocabularies of two ontologies (Detail “B”); and IV) methods that enable specific portions of two ontologies to be reconciled with the use of semantic mappings made through an articulation ontology (Detail D) (CHUNGOORA & YOUNG; 2010, CHUNGOORA & YOUNG, 2011; KYOUNG et al., 2009).

Even though ontology mapping/matching has been vital to solving semantic heterogeneity problems, currently, some methods rely on lexical similarity matching, which is not optimal from a semantic interoperability viewpoint. In a multiple domain environment, similar terms are used across different groups to refer to diverse concepts. Ergo, it is only through the semantics that is associated with these terms that existing differences can be identified, highlighting the need to capture semantics in the first place (CHUNGOORA & YOUNG, 2011). On the other hand, ontological formalisms like the Web Ontology Language (OWL) support built-ins for ontology mapping, but these built-ins have limitations when mapping the semantic content of manufacturing ontologies and their associated knowledge bases (CHUNGOORA & YOUNG, 2011; CHUNGOORA & YOUNG, 2010; SONG et al., 2017).

Moreover, there are requirements to aid the construction of mapping/matching techniques which can be formally interpreted and are focused on identifying potential solutions for semantic mismatches. Therefore, enabling the reconciliation process at several levels, including the instance level, of ontology-based models (CHUNGOORA & YOUNG, 2010; KUMAR & HARDING, 2017).

2.4 CHAPTER DISCUSSION

This Chapter presented a literature review on the main topics for this research: i) Semantic Interoperability; ii) Semantic Reconciliation; iii) Computer Aided Design and Manufacturing; iv) Concurrent Engineering and v) Integrated Product Development Process.

Concerning the Concurrent Engineering and Integrated Product Development the review showed that although progress has been made to reduce errors across the product design and manufacturing while using parallel activities and multidisciplinary teams, these strategies have shown limitations regarding information and knowledge sharing across the different stages and activities of the product design and manufacturing.

The integrated product development associated with digital manufacturing technologies such as CAD/CAM systems can accelerate the product development process at the same time, reducing costs and assuring the products' quality. These technologies also present shortcomings when it is necessary to share information between different systems, even when methodologies such as DFM and DFA are used to optimise and integrate product design and manufacturing.

This review, at the same time, provided a substantial theoretical basis for the research and indicated the need for greater understanding of the problems of information and knowledge sharing in the product development process as well as the technologies used to aid in the solution, its applications, and limitations. In this context, the next Chapter will present a systematic literature review and content analysis that will investigate those topics thoroughly while giving insight on the development of an approach to support information and knowledge sharing in the product development process.

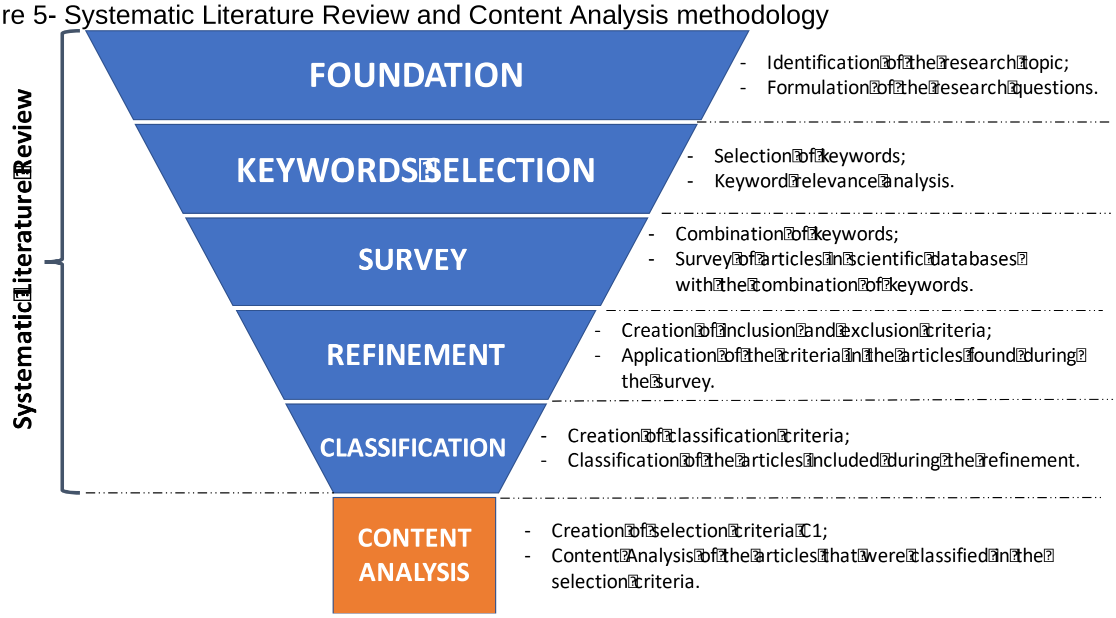
3 IDENTIFICATION OF MAIN RELATED WORKS AND MILESTONES REFERENCES FOR THIS RESEARCH THROUGH A SYSTEMATIC LITERATURE REVIEW AND CONTENT ANALYSIS

Globalisation, collaboration, and cooperation have contributed to the emergence of a knowledge sharing culture in open and large environments (BEAU et al., 2010; SINDEREN, 2008; NAGY & VARGAS-VERA, 2011). However, communication between teams in the product development is often restrained by the clearness in the terms that are used by them, which affects the overall meaning and interpretation of the shared implicit and explicit knowledge.

The concept of semantic interoperability aims to ensure the effective sharing of information in a collaborative and multi-domain environment. Semantic interoperability is currently being applied in the context of Product Design and Manufacturing as a means to reduce mistakes and heterogeneity in the information. There are still, though, problems with implementation in this context regarding the process of semantic reconciliation of information from different sources in a cohesive way.

The barriers for clear communication in PDP are conventional semantic interoperability issues and to overcome them, different approaches regarding semantic interoperability have emerged. Thus, this literature review aims to identify the studies that portray how to create a semantic reconciliation tool between multiple domains, analysing their contributions to the field and their limitations. A systematic literature review and content analysis were employed to achieve the research objective, as shown in Figure 5.

Figure 5- Systematic Literature Review and Content Analysis methodology



Source: The author.

3.1 SYSTEMATIC LITERATURE REVIEW

3.1.1 Foundation

This work considers and adapts different methods from: “Determining the principal references of the social life cycle assessments of products” (Mattioda et al., 2015) and “Semantic interoperability for an integrated product development process: a systematic literature review” (SZEJKA et al., 2017) to conduct a research on the topics of semantic reconciliation and multiple domains.

An interoperable semantic system for product development and manufacturing should consider a systematic way of structuring information that can preserve its meaning, ensuring its relationships, rules, and axioms to provide seamless information interchangeability for interoperable applications that consequently improve the decision-making process. Based on this statement, two main questions have arisen during the research:

i. What are the recent relevant researches regarding the conceptual structure of information from multiple domains and its formalisation across PDP to support the decision-making process?

ii. What are the recent relevant researches regarding the semantic reconciliation process across PDP to support the decision-making process?

3.1.2 Keyword Selection

The first step of the systematic literature review is to identify the relevant keywords to the research field, in this case, the relevant keywords for the areas of: i) product development process; ii) Multiple Domains, and iii) Semantic Reconciliation.

A survey was carried out in the scientific databases, and the relevant terms and keywords for each area were identified in the articles title, abstracts, and keywords sections. The scientific database used for this survey was used the CAPES scientific database, which encompasses 532 national and international scientific bases such as Elsevier, Springer, Science Direct, among others. This database was chosen as it allowed for a more accurate analysis of the research topics because of the vast scientific databases encompassed by it.

After the survey, a similarity analysis was used to count and classified them according to the percentage of appearance frequency. The most frequent terms in the articles, that is, the most relevant terms to each research areas were selected as the search keywords for the research next steps and are shown in Table 1.

Table 1 – Relevant Keywords to the research alongside their individual relevance and the accumulated relevance of the keyword to the topic.

Research Area	Keyword	Relevance to the Research Area	Accumulated Relevance
Multiple Domains	Multiple Domains	34,15%	34,15%
	Cross Domain	26,83%	60,98%
	Heterogeneous Domains	21,95%	82,93%
	Multi-Domain	7,32%	90,24%
Product Development Process	Product Development	33,80%	33,80%
	New Product Development	22,54%	56,34%
	Integrated Product Development	15,49%	71,83%
	Product Design	12,68%	90,71%
Semantic Reconciliation	Semantic Reconciliation	56,52%	56,52%
	Ontology Mapping	13,04%	69,57%
	Ontology Matching	13,04%	82,61%
	Ontology Alignment	8,70%	91,30%

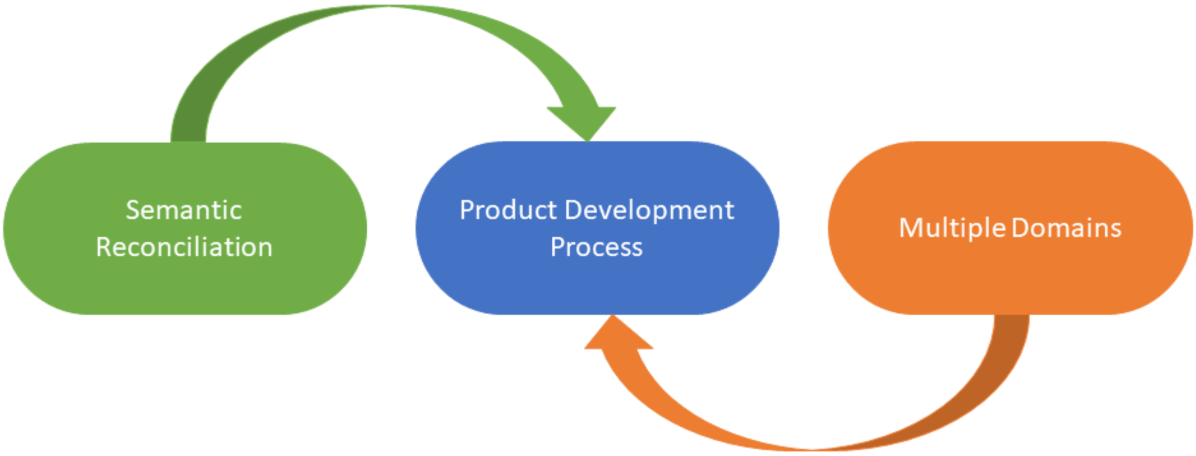
Source: The author.

The survey had, as a result, the identification of the most common keywords used in research on each of the studied fields. In the multiple domains fields, the main keyword is “Multiple Domains” with the relevance of 34,15% while the second main keyword was “Cross Domain” with the relevance of 26,83%. In the Product Development field, the main keywords were: i) ***Product Development*** with the relevance of 33.80%; ii) ***New Product Development*** with the relevance of 22,54%; iii) ***Integrated Product Development*** with the relevance of 15,49%, and iv) ***Product Design*** with the relevance of 12,68%. In the Semantic Reconciliation field, the main keyword identified by the survey was Semantic Reconciliation with 56,52% of relevance, followed by Ontology Mapping and Ontology Matching with 13,04% relevance each.

3.1.3 Survey

In the next step, a new survey using the selected keywords was carried out in order to find works related to the research proposed issues. The definition of the relationship between domains was necessary to optimise and achieve the survey best results. The relationships between the domains addressed in this research are illustrated in Figure 6.

Figure 6- Relationship between Problem Domains addressed in the research.



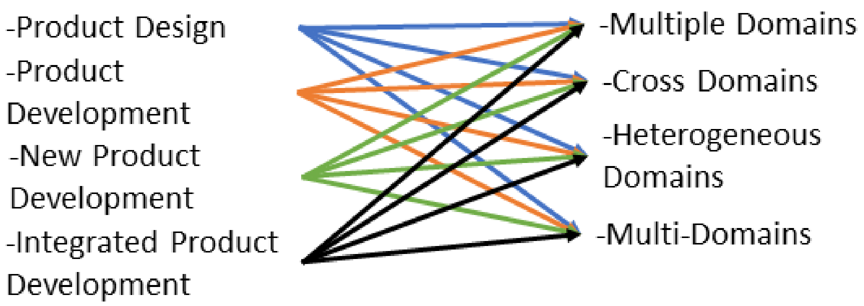
Source: The author.

The focus of this research is on issues of PDP and, in this way, the survey was conducted on the relationships of: i) “Semantic Reconciliation” and “Product Development Process”; and ii) “Multiple Domains” and “Product Development Process.” As the core of the research is the product development process, the relationship between "Semantic Reconciliation" and "Multiple Domains," was not approached as it would generate results outside of the core research area.

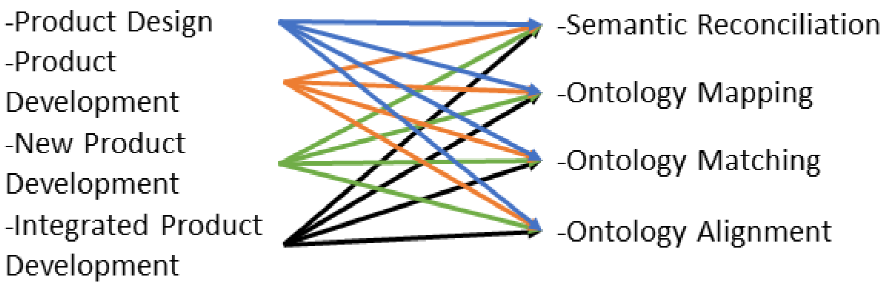
Combinations of the selected relevant keywords from each domain were used as input in the scientific databases for the identification of the scientific papers related to PDP, multiple domains, and semantic reconciliation, as shown in Figure 7. The searching was focused only on articles and covered ten years (2007-2018). This timeframe was selected because the semantic interoperability field gained relevance in the global scientific community during this period.

The articles selected for each Product Development and Multiple Domains keywords combination is shown in Table 2, totalling 1237 articles. This result had its main contribution from: i) ***“Product Development and Multiple Domains”*** combination with 270 articles found; ii) “***Product Development and Multi-Domain”*** combination with 215 articles; and iii) ***“Product Development and Cross Domain”*** combination with 190 articles found.

Figure 7- Keyword Combination used for the Survey.



(a) Combination of Product Development and Multiple Domain Keywords.



(b) Combination of Product Development and Semantic Reconciliation Keywords.

Source: The author.

Table 2. Articles found with the PDP and Multiple Domains keyword combination.

Product Development and Multiple Domains			
Keywords			**Results from Database**
Product Development	AND	Multiple Domains	270
Product Development	AND	Cross Domain	190
Product Development	AND	Heterogeneous Domains	10
Product Development	AND	Multi-Domain	215
New Product Development	AND	Multiple Domains	75
New Product Development	AND	Cross Domain	64
New Product Development	AND	Heterogeneous Domains	4
New Product Development	AND	Multi-Domain	51
Integrated Product Development	AND	Multiple Domains	6
Integrated Product Development	AND	Cross Domain	3
Integrated Product Development	AND	Heterogeneous Domains	0
Integrated Product Development	AND	Multi-Domain	3
Product Design	AND	Multiple Domains	115
Product Design	AND	Cross Domain	106
Product Design	AND	Heterogeneous Domains	5
Product Design	AND	Multi-Domain	120
		Total	**1237**

Source: The author.

The total of 192 articles selected for each Product Development and Semantic Reconciliation keywords combination is shown in Table 3. This selection is greatly influenced by: i) ***"Product Design and Ontology Mapping"*** combination with 46 research found; ii) ***"Product Development and Ontology Mapping"*** combination with 40 articles found; and iii) ***"Product Development and Ontology Matching"*** combination with 28 articles.

Table 3. Articles found with the PDP and Semantic Reconciliation keyword combination

Product Development and Semantic Reconciliation			
Keywords			**Results from Database**
Product Development	AND	Semantic Reconciliation	4
Product Development	AND	Ontology Mapping	40
Product Development	AND	Ontology Matching	28
Product Development	AND	Ontology Alignment	20
New Product Development	AND	Semantic Reconciliation	1
New Product Development	AND	Ontology Mapping	6
New Product Development	AND	Ontology Matching	6
New Product Development	AND	Ontology Alignment	1
Integrated Product Development	AND	Semantic Reconciliation	0
Integrated Product Development	AND	Ontology Mapping	0
Integrated Product Development	AND	Ontology Matching	1
Integrated Product Development	AND	Ontology Alignment	0
Product Design	AND	Semantic Reconciliation	6
Product Design	AND	Ontology Mapping	46
Product Design	AND	Ontology Matching	21
Product Design	AND	Ontology Alignment	12
		Total	**192**

Source: The author.

The combination of articles found with the combination of keywords of the three fields resulted in a total of 1429 researches that will be used for further analysis in the next stages.

3.1.4 Refinement

The next stage was the refinement of the data acquired in the previous step to select the articles that are closely related to the proposed research issues. An inclusion and exclusion criteria were defined from the research questions and the general characteristics of the articles found during the survey stage. The criteria are presented in Table 4.

The application of inclusion criteria selects, from the pool gathered in the survey stage, articles with characteristics that might answer the research proposed questions while the exclusion criteria exclude the works that do not address issues relevant to the study or are duplicated. The articles that attend all the inclusion criteria are selected for further analysis. The inclusion and exclusion criteria were applied in the article's title, abstract, and keyword sections, and from the 1429 articles selected during the survey, only 182 attended the inclusion criteria (Table 4).

Table 4. Inclusion and Exclusion criteria used in this research for the refinement of the survey

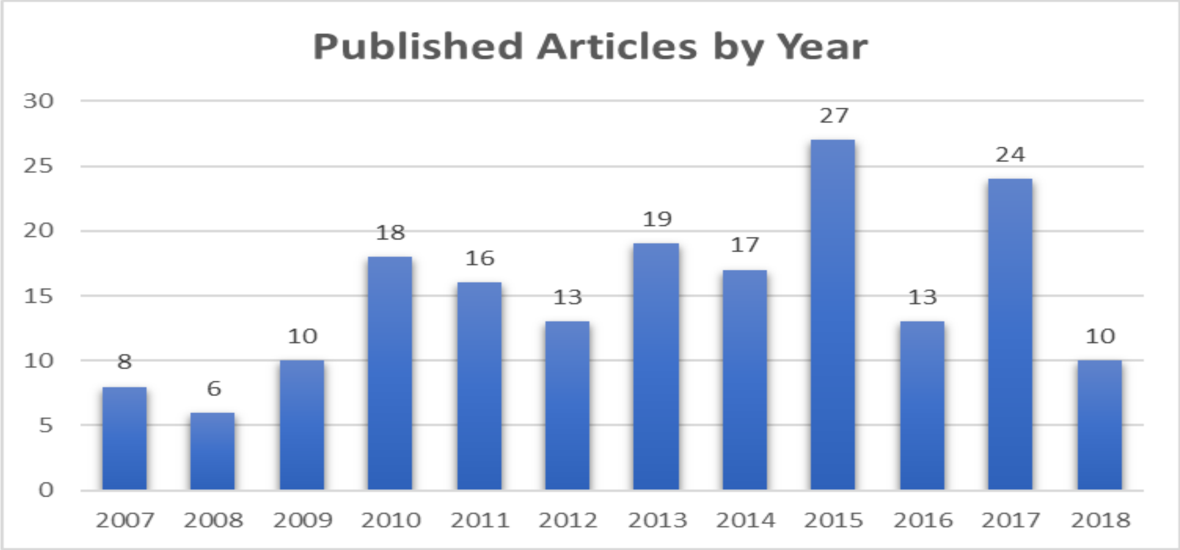
Inclusion Criteria	Exclusion Criteria
Published between 2007and 2017	Non-English papers
Multiple Domain Keywords	Redundant papers
Product Development Process Keywords	Does not approach Product Development
Semantic Reconciliation Keywords	Duplicated papers
Primary Studies	Not reviewed by pairs
Secondary Studies	Conference Papers

Source: The author.

The selected 172 articles were examined about the year of publication and countries represented by the authors of each article as a means to understand the current world scenario of the research topic.

The year of publication analysis (Figure 8) shows, despite some fluctuations, a significant increase in the articles published on the research topic in the last ten years, representing a greater understanding in the scientific environment towards the approached issues. Additionally, there are issues that have not been addressed yet, requiring more scientific investigation on the topic, even though the increase in maturity by the scientific community is presently happening.

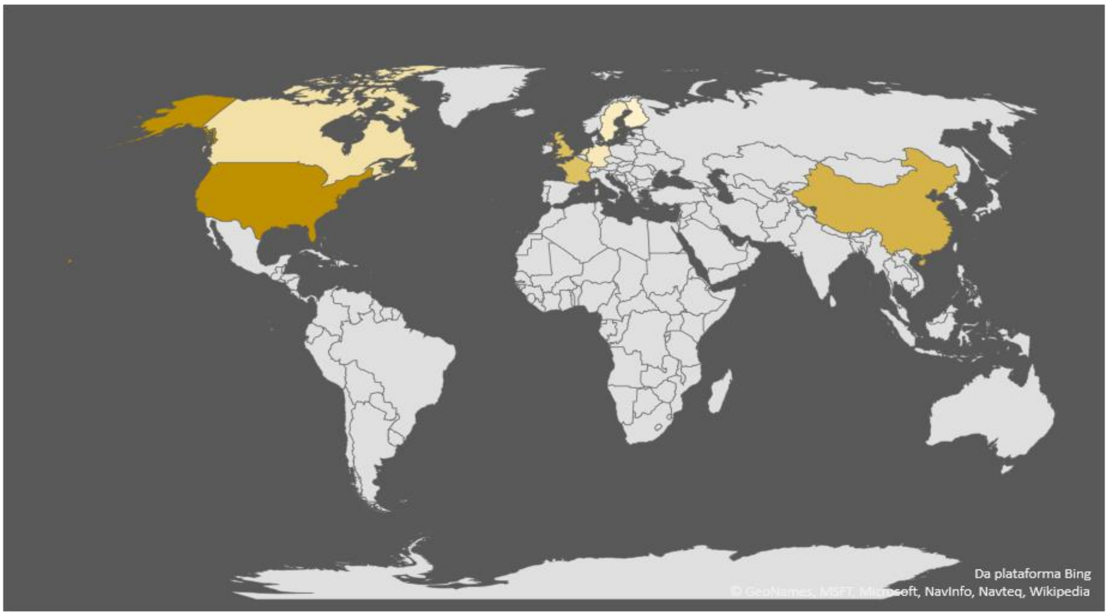
Figure 8 - Number of articles published by year.



Source: The author.

The analysis of publications per country helps the identification of the most relevant research groups across the globe as well as the understanding of their motivation and context. The United States of America and China concentrated the majority of the research and are closely followed by European countries, revealing the importance of the studied topics to the most developed and industrialised countries. Figure 9 corroborates with this analysis showing that most publications come from the northern hemisphere, especially the USA and Europe.

Figure 9- Focus area of selected publications.



Source: The author.

From these analyses, it is possible to understand the current scenario of semantic reconciliation of multiple domains applied to the integrated product development process in a global view. Also, it is possible to verify the viability and feasibility to conduct further research on this topic as it is a pertinent theme and growing in relevance.

3.1.5 Classification

The articles selected during the previous step were classified according to criteria for determining their degree of relevance to the research issues. The criteria definition took on consideration the articles' characteristics observed during the survey and the issues proposed during the foundation stage. So that, the classification criteria were divided into articles addressing: i) Multiple Domains (D) and ii) Semantic Reconciliation (SR).

The Multiple Domain criterion is divided into three sub-classifications:

- (**D1**) **Particular Cases** – research concerning the product information exchange between two specific domains;
- (**D2**) **Ability to be General** - research concerning the product information exchange among different domains that can be adapted to other domains;
- (**D3**) **General Approach** – research concerning the product information exchange among different domains, and the proposed approach do not need adaptation to other domains.

The semantic reconciliation criterion was also split into three sub-classifications:

- (**SR1**) **Knowledge Sharing without Semantic Reconciliation** – research concerning knowledge sharing between two or more domains without a formalised semantic reconciliation approach;
- (**SR2**) **Specific Semantic Reconciliation** - research concerning knowledge sharing between two or more domains with a formalised semantic reconciliation approach between them without the ability to be adapted to other domains;
- (**SR3**) **Generalized Semantic Reconciliation** – research concerning knowledge sharing between multiple domains with a formalised semantic reconciliation approach that can be adapted to other domains.

The 182 selected articles represent a refined pool of information regarding the theme studied, but there was the need for determining their degree of relevance to the research issues and their contribution to the development of new researches. So that, the selected 182 research papers were submitted to analysis and classification by the criteria presented in Section 3.3, and a sample of the outcome is shown in Table 5. The complete Table of classification of the 182 selected articles is provided in the Appendix “A”.

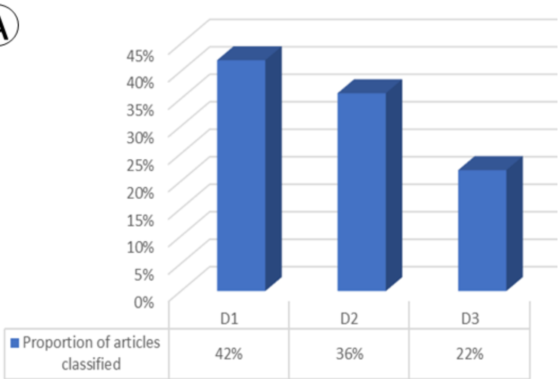
The classification results of the 182 articles are shown in Figure 10. Detail “A” shows the classification of the articles by the multiple domains criterion, while Detail “B” shows the classification of the articles by the semantic reconciliation criterion.

Table 5. Classification of the 172 selected articles.

Authors and Year	Multiple Domains Issues			Semantic Reconciliation Issues		
	D1	D2	D3	SR1	SR2	SR3
Abdul-Ghafour et al. (2014)	X			x		
Abele et al. (2017)	X	X	X	x		
Adagha; Levy and Carpendale (2017)	X			x		
Afshari and Peng (2015)	X	X		x		
Ahmad; Wynn and Clarkson (2013)	X	X			x	
Ahmed-Kristensen and Storga (2009)	X	X		x		
Ai et al. (2011)	X	X		x		
Aksulu and Wade (2011)	X			x		
Al Presher (2012)	X			x		
Al-Zaher; ElMaraghy and Pasek (2013)	X			x		
...	...	...	...	...	...	...
...	...	...	...	...	...	...

Source: The author.

Figure 10. Graphical representation of the classification results referent to multiple domains issues and semantic reconciliation issues.

Ⓐ


(a) multiple domains issues.

Ⓑ


(b) semantic reconciliation issues.

Source: The author.

The classification results showed that:

- 42% of the research analysed were classified as D1, that is, they approach the multiple domains issues regarding two specific domains without the ability to become a generic approach for other domains;
- 36% were researching about approach between two specific domains and have the ability to become a generic approach (D2);
- 22% represents the research with a generic approach to multiple domains issues represent.

These results indicate that a generic approach for these issues is being researched in order to solve them, but there is still a significant amount of research being conducted to solve specific problems that have arisen between specific domains.

Regarding the semantic reconciliation issues (Detail B), the results showed that:

- 72% of the research analysed have knowledge sharing processes between specific domains but do not have knowledge translation tools (SR1);
- 5% of the research have a generic tool for knowledge translation and share across multiple domains (SR3);
- 23% do have a formalised knowledge translation process between two specific domains (SR2).

These results show that there has been little to no effort to create a knowledge translation tool that can be used throughout different domains and can effectively create an actual interoperable environment. The research is concentrated on tools that can only share knowledge without considering whether the knowledge shared is interpreted correctly or not. This fact represents a problem as misunderstandings can arise without semantic reconciliation tools, which in turn can increase the cost of the product that is being developed and decrease its quality.

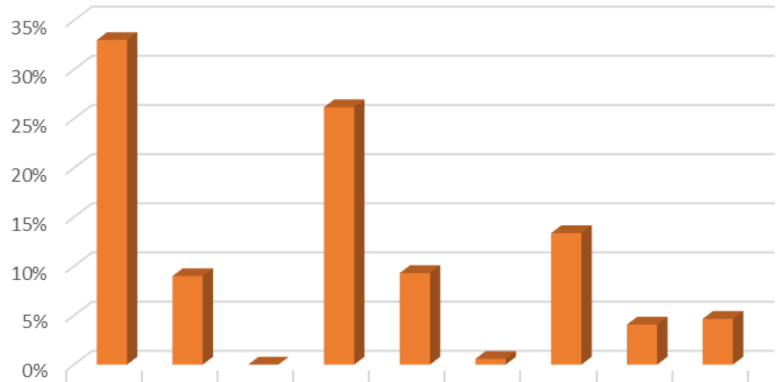
In the sequence, the 182 articles were classified according to the relationship of multiple domains and semantic reconciliation issues to determine results is depicted in Figure 11.

As it is shown in Figure 11, from the 182 analysed research:

- 33% of them approach specific domain issues and consider only the knowledge sharing and not its translation (D1 and SR1);

- 9% approach specific domain issues and consider some knowledge translation tools (D1 and SR2);
- 58% of the research can become generic approaches when regarding multiple domains issues (D2 and SR1 + D2 and SR2 + D2 and SR3 + D3 and SR1 + D3 and SR2 + D3 and SR3);
- 72% do not consider the knowledge translation tools (D1 and SR1 + D2 and SR1 + D3 and SR1);
- 6% already have generic approaches to the semantic reconciliation issues (D2 and SR3 + D3 and SR3);
- 13% have formalised knowledge translation tools that can be generalised (D2 and SR2 + D3 and SR2).

Figure 11. Graphical representation of the classification results related to the relationship of multiple domains and semantic reconciliation issues.



	D1 and SR1	D1 and SR2	D1 and SR3	D2 and SR1	D2 and SR2	D2 and SR3	D3 and SR1	D3 and SR2	D3 and SR3
Proportion of articles classified	33%	9%	0%	26%	9%	1%	13%	4%	5%

Source: The author.

It is possible to observe in the results that there are research gaps in multiple domains issues and semantic reconciliation issues, especially in the D2 and SR2; D3 and SR2; D2 and SR3; D3 and SR3 relationships (Figure 11).

A closer analysis of these criteria led to the elaboration of a selection criterion (C1) intending to find the most relevant researches to answer the research proposed questions. C1 criterion is composed of criteria D2 or D3 simultaneously classified as SR2 or SR3 since these criteria approach the knowledge translation and share throughout several domains in a general matter or with the ability to have a generalist approach to these issues. Criterion C1 does not encompass D1 and SR1 because of these classification criteria present limitations in their approach to the problem investigated in this research.

The C1 criterion was applied to the 182 articles and resulted in the selection of 28 that have approaches were closer to the research problem. Table 6 presents the 28 selected articles alphabetically ordered.

Table 6: Selected Articles for further analysis based on the C1 criterion, alphabetically ordered.

	Authors	Year	Title
1	Ahmad; Wynn and Clarkson	2013	Change impact on a product and its redesign process: a tool for knowledge capture and reuse.
2	Bruun et al.	2015	Plm system support for modular product development.
3	Caetano et al.	2017	Representation and Analysis of Enterprise Models with Semantic Techniques: An Application To Archimate, e3value And Business Model Canvas.
4	Cardoso and Bussler	2011	The mapping between heterogeneous XML and OWL transaction representations in b2b integration.
5	Chen	2010	Knowledge integration and sharing for collaborative moulding product design and process development
6	Chen; Chen and Chu	2009	Development of a mechanism for ontology-based product lifecycle knowledge integration.
7	Chungoora and Young	2011	Semantic reconciliation across design and manufacturing knowledge models: a logic-based approach.
8	Dartigues-Pallez et al.	2007	CAD/CAPP Integration Using Feature Ontology. (Computer-Aided Design Systems and Computer-Aided Process Planning)
9	Demoly; Matsokis and Kiritsis	2012	A mereotopological product relationship description approach for assembly oriented design.
10	Goel et al.	2012	Cognitive, collaborative, conceptual, and creative — four characteristics of the next generation of knowledge-based cad systems: a study in biologically inspired design.
11	Huang and Huang	2013	Exploring the effect of boundary objects on knowledge interaction.
12	Imran and Young	2015	The application of common logic-based formal ontologies to assembly knowledge sharing
13	Jiang; Peng and Liu	2010	Research on ontology-based integration of product knowledge for collaborative manufacturing.
14	Jiao et al.	2009	Coordinating product, process, and supply chain decisions: a constraint satisfaction approach.
15	Li et al.	2017	Enabling automated requirements reuse and configuration
16	Li; Zhao and Tong	2017	Simulation-based scheduling of multiple change propagations in multistage product development processes.
17	Monticolo et al.	2014	An agent-based system to build project memories during engineering projects
18	Monticolo et al.	2015	A meta-model for knowledge configuration management to support collaborative engineering
19	Pasqual and de Weck	2012	Multilayer network model for analysis and management of change propagation.
20	Peng et al.	2017	A collaborative system for capturing and reusing in-context design knowledge with an integrated representation model.
21	Rahmani and Thomson	2012	Ontology-based interface design and control methodology for collaborative product development.

	Authors	Year	Title
22	Ruiz et al.	2017	Reuse of safety certification artifacts across standards and domains: a systematic approach.
23	Tchoffa et al.	2016	Digital factory system for dynamic manufacturing network supporting networked collaborative product development.
24	Tessier and Wang	2013	Ontology-based feature mapping and verification between CAD systems
25	Tian and Voskuijl	2015	Automated generation of multiphysics simulation models to support multidisciplinary design optimisation.
26	Witherell et al.	2013	Aiero: an algorithm for identifying engineering relationships in ontologies.
27	Xie and Ma	2015	Design of a multi-disciplinary and feature-based collaborative environment for chemical process projects.
28	Zhang et al.	2017	A cross-domain recommender system with consistent information transfer.

Source: The author.

These 28 selected articles will be thoroughly examined in the next Section, the Content Analysis Step.

3.2 CONTENT ANALYSIS

The pertinence of the 28 selected articles resulted from the Systematic Literature Review (Table 6) for the research problem was analysed through a regression analysis to assure robustness in the selection. This analysis was conducted weighing the value of research's contribution in relation to the frequency of keywords, number of citations of the research through the years, the depth of the approach in the studied topic and whether the research contributes to the development of knowledge with the presentation, description, and order of instruments, as defined by Teixeira and Canciglieri Jr. (2019).

The identified function for the regression analysis had a mathematical adherence of (adjusted r^2) 87% to the data. The regression analysis equation is shown in Expression 1 (Regression of the 28 selected articles).

$$\boldsymbol{Y = 9,04 - 1,382x - 0,785z - 5,38w - 8,12n + 0,333xz + 0,256nz + 6,93zw} \quad (1)$$

Where:

- Y is the classification score of the article;
- X is the frequency of keywords found in the research;

- Z is the citation score of the research;
- W is the score for the Approach Depth;
- N is the score for the Knowledge Creation.

This analysis confirmed the robustness of the research and also can aid in the identification of other research that may be important for the continuation of the research approach of semantic reconciliation of multiple domains to support the product development process.

The proposed question of Section 3.1.1 was answered through two analyses carried out on the 28 selected articles. The first analysis regarding the first question examined the entire articles about their contributions and limitations to the resolution of the multiple domains and semantic reconciliation issues. To answer the second question, an analysis of the references of these 28 articles was performed and a ranking system developed in order to identify the most relevant authors in the studied topics.

3.2.1 Author Analysis

An analysis of the references of the 28 selected articles was conducted to identify the main authors researching semantic reconciliation of multiple domains to support the product development. This analysis consisted of the detection of the articles that are cited in the 28 selected researches and ranking them by the number of citations. Table 7 presents the value system was used to rank the author citations in the article.

Table 7. The ranking system used to value the references

Number of Citations	Value of the Reference
1	1
2	1,1
3	1,15
4	1,175
5	1,1875
≥6	1,2

Source: The author

If an author has multiple researches references in one of the 28 selected articles, the values of the references are added together to compose the value of the author to the research. The values given to the authors throughout the selected articles are added together and then multiplied by the number of different articles he is quoted. For example, author “X” appears in 4 different articles from the 28 previously selected and received the combined value of “Y”, his final value to the area is equal to 4Y. This multiplication is a way to give more value to those researchers that appear on more works instead of those that are heavily cited in one or another research. Table 8 shows the result of this analysis.

Table 8 – Author Citation Classification.

Authors	Citation Score	Citation in Different Articles	Total Score	Overall Percentage
Sriram, RD	18,53	9	166,73	3,43%
Young, RIM	18,88	7	132,13	2,72%
Clarkson, PJ	26,61	4	106,45	2,19%
Yang, H	8,30	7	58,10	1,20%
Eckert, C	17,30	3	51,90	1,07%
Kim, KY	8,30	6	49,80	1,02%
Shah, JJ	9,34	5	46,69	0,96%
Eynard, B	11,40	4	45,60	0,94%
Goel, AK	21,80	2	43,60	0,90%
Eppinger, SD	10,65	4	42,60	0,88%
de Weck, OL	9,60	4	38,40	0,79%
Harding, JÁ	7,00	5	35,00	0,72%
Authors with Total Score between 30 and 34,99	16,85	4	67,40	1,39%
Authors with Total Score between 25 and 29,99	37,85	4	151,40	3,11%
Authors with Total Score between 20 and 24,99	42,28	4	169,12	3,48%
Authors with Total Score between 15 and 19,99	115,76	3	347,28	7,14%
Authors with Total Score between 10 and 14,99	113,06	3	339,18	6,98%
Authors with Total Score between 5 and 9,99	271,28	1	271,28	5,58%
Authors with Total Score between 1 and 4,99	2699,10	1	2699,10	55,52%

Source: The author.

Through this analysis, the relevant authors of semantic reconciliation of multiple domains to support the product development process were identified. The most relevant authors are:

1. Sriram, RD (3,43%);
2. Young, RIM (2,72%);
3. Clarkson, PJ (2,19%);
4. Yang, H (1,20%);
5. Eckert, C (1,07%);
6. Kim, KY (1,02%);
7. Shah, JJ (0,96%);
8. Eynard, B (0,94%);
9. Goel, AK (0,90%);
10. Eppinger, SD (0,88%).

3.2.2 Content Analysis

A thorough investigation of the full content of each 28 selected articles was performed, to define the recent relevant researches regarding the conceptual structure of information from multiple domains and its formalisation across PDP to support the decision-making process pointing out the research contribution and limitation to the studied topics. This analysis is shown in Table 9.

Table 9. Content Analysis of the 28 selected articles

Author		Year	Contribution	Limitation
1	Ahmad; Wynn and Clarkson	2013	- Mapping model for information required to assess change impact - Information change tracing tool through four different domains	- Limitation of the tool application in the product development reworking as it does not contemplate the early stages of information gathering and knowledge creation of the process
2	Bruun et al.	2015	- Support for the modular design of elements used throughout a family of products. - Requirements translation through four different views throughout the product lifecycle	- The proposed system does not have a consistency analysis, being liable to errors during the knowledge translation.
3	Caetano et al.	2017	- Integration and specialisation of different ontologies into a single application ontology using ontology mapping processes - Functions which act as transformation maps that state the relationships between concepts in the different ontologies	- The functions developed to act as the transformation rules cannot be regarded as universal since they were developed to map and translate the concepts' behaviour and relationships in a specific context and purpose
4	Cardoso and Bussler	2011	- The pre-defined mapping between specific domain ontologies that represent internal information of an organisation and external information that it shares with other organisations in its supply chain and can be reused when the need arises.	- An ontology with the taxonomy of the business that is being integrated must be developed since the requirement for the pre-defined mapping works.
5	Chen	2010	- The formalisation of the information on four levels while their integration is made through the mapping of similarities in these levels. - Integrates all the stages of the product development and the relevant domains to the creation of moulded products	- The specific application of the approach limits its application to only moulded products
6	Chen; Chen and Chu	2009	- Distinct ontology layers representing the enterprise, system operation, and mechanism operation knowledge that are integrated through similarity mappings of concepts, essential information, and relationships - Development of a global ontology to create an integrated product development environment	- The proposed system does not have a consistency analysis and is liable to errors during the knowledge translation.
7	Chungoora and Young	2011	- A multi-layer approach where the essential and basic information is specialised through similarity mapping models. These specialised ontologies create an integrated environment between the design and manufacturing teams	- The research does not contemplate knowledge traceability and information consistency analysis

Author		Year	Contribution	Limitation
8	Dartigues-Pallez et al.	2007	- Feature ontology that works as a representation of the common knowledge between designers and process planners and their specific knowledge - Mapping rules that transform geometric information from a CAD software into process planning information in a computer-aided process planning software	- The mapping approach presented is limited to the translation of geometric information into process planning information, that is, the translation process works only downstream while the upstream counterpart is not present in the research
9	Demoly; Matsokis and Kiritsis	2012	- The formalisation of the elements' relationships within a product design that is translated into an assembly sequence and shared through an ontology - Information consistency analysis made through semantic rules	- Does not account for knowledge sharing between different domains and different stages of the product development
10	Goel et al.	2012	- Translation of biological knowledge into technological constraints to develop a product. - Development of functional models and formalisation of relationships between biological and technological knowledge through a structure behaviour function	- The acquisition of requirements from the early stages of the product development used to select biological information is not contemplated in the research. - The translation process is possible only from the biological knowledge to mechanical knowledge
11	Huang and Huang	2013	- Development of a min-max model to calculate the knowledge creation efficiency - Translation of multiple inputs of different domains into one single output domain	- The research does not contemplate knowledge traceability and does not use a formalisation of product development.
12	Imran and Young	2015	- The identification of general semantic concepts to create a reference ontology for the assembly process - Knowledge translation process between the two domains studied	- The translation process is specific to a single manufacturing step and its relevant domains and views. - The interoperable environment created focuses only on the assembly process and does not share the knowledge with the earlier and later stages of product development
13	Jiang; Peng and Liu	2010	- Similarity calculations made in specific domain ontologies to create an integrated environment. - information consistency ensured by the similarity calculations being made in three steps: concept name similarity, essential information similarity, and relationships similarities	- The focus of the research on the manufacturing is its limiting factor as it only formalises, translates and shares the information within the domains of this step of the product development, not accounting the other steps and their domains. - The computational tools used were limited, reducing the approach`s efficiency
14	Jiao et al.	2009	- A domain-based solution that enables seamless mappings between customer groups, product families, final-production and sub-production facilities - Synchronization of factory loading in a multi-site manufacturing supply chain	- Does not account for knowledge sharing between different domains and different stages of the product development

Author		Year	Contribution	Limitation
15	Li et al.	2017	- Automatic creation of hierarchical structure and identification of requirements variability. - Integration between a cardinality-based feature modelling system and UML based variability algorithms	- The proposed system does not contemplate the stages of the product development, focusing only on the product design that results in the traceability and translation of the requirements to be flawed in the latter stages of the product development
16	Li; Zhao and Tong	2017	- Mapping of information relationships through different stages of the PD and across multiple domains and the change propagation through them. - Classification and formalisation of rigid and flexible informational relationships	- The latter stages of the product development (manufacturing, assembly) are not considered in the method and, consequently, do not have their relations and domains formalised in order to be integrated into the proposed approach. - Even though the method can effectively trace the information and the change propagation, the proposed approach does not consider an information consistency analysis after each interaction to assure the translation, and sharing processes do not generate any errors
17	Monticolo et al.	2014	- Integration of multiple models that represent a different view of the product development with its agents, concepts, and relationships - Knowledge capture, translation and reuse environment supported by the proposed multi-agent system	- The proposed approach is specific to a mechanical project, and its associated domains limit its application. - The proposed approach considers the design stage of product development and does not contemplate the product manufacturing. Therefore, there is not a formal structure to capture, translate, and share the knowledge from this and later stages of product development.
18	Monticolo et al.	2015	- Trace the products information through different expert systems while discovering where there are errors in the knowledge translation or knowledge sharing	- Focus on the design stages of the product development and its domain which limits the traceability capability of the system to the focus stage, ignoring the information of early or later stages of the product development process
19	Pasqual and de Weck	2012	- Integration of a network in different layers with formalised relationships inside each layer and formalised critical relationships between the different layers	- The proposed approach does not share alongside the information its context, which is vital to the correct interpretation of the shared information. Thus, it does not share the knowledge created by the product change.
20	Peng et al.	2017	- The capture and share of complete, contextual, and trustworthy knowledge through the combination of considerations of different participants of a project. - Generic information translation for the design domains of the PD	- The knowledge sharing environment created by the proposed system is made through design relationships and does not contemplate the manufacturing and assembly information required in an integrated PD.

Author		Year	Contribution	Limitation
21	Rahmani and Thomson	2012	- A single port ontology that is specialised in specific domain ontologies and their connections are made with the use of rules and similarity checks.	- Focus on the design stages of the product development and its domain which limits the traceability capability of the system to the focus stage ignoring the information of early or later stages of the product development process
22	Ruiz et al.	2017	- Mapping of similar information across several different standards that can be reused and improved throughout different projects while simultaneously being improved	-The mapping approach presented is limited to the safety artefacts and their characteristics and use during a project. The research does not approach the product lifecycle and the domains that it contains
23	Tchoffa et al.	2016	- A computational tool that integrates the different stages and domains of the product lifecycle through the expanse of a dynamic manufacturing network.	- Focus on data translation and sharing. It is not able to share the context of the information sharing through the different stages and domains of the product lifecycle
24	Tessier and Wang	2013	- A hybrid model that uses a single ontology as basic knowledge structure and multiple ontologies with the taxonomy of the diverse CAD systems. - Product feature formalisation and translation between the different CAD systems based on mapping algorithms	- Translation and verification process is made with the domains of one stage of product development. The earlier and later stages cannot efficiently share the knowledge created with the proposed system
25	Tian and Voskuijl	2015	- The use of inference engines to organise the knowledge needed for each submodule of the proposed system - Formalized capture and product information similarities through extract functions	- The proposed system does not approach inconsistency analysis or knowledge translation between all the contemplated domains, limiting itself only to trace the knowledge created and shared through the different domains
26	Witherell et al.	2013	- The use of semantic relatedness quantifications to analyse and rank concept pairs to map engineering relationships. - Measurement and categorisation of 4 groups of information that support an ontology alignment algorithm in order to define semantic relatedness	- The proposed approach does not contemplate the influence of different domains in the engineering relationships within a product development context and can translate and formalise ambiguous information or false information for the project
27	Xie and Ma	2015	- Integration of product and process views and different domains of the product development process through their relationships created by a mechanism in the proposed approach	- The proposed approach does not contemplate information consistency during the translation process, being prone to errors. - The framework is specific to the translation of mechanical and chemical features, which limits its application to these domains

Author		Year	Contribution	Limitation
28	Zhang et al.	2017	- Clustering of items through the target and source domains with relationship consistency analysis. - Unsupervised transfer learning and model optimisation through artificial intelligence algorithms to create a recommendation in the target domain	- The proposed system can only effectively translate knowledge between two domains at a time. - The system aims to receive feedback from one product and recommend another, so that, its application is in the first stages of the product development and does not contemplate the requirements of the other stages of the process.

Source: The author.

The content analysis revealed that the main approach to semantic reconciliation between multiple domains is through concept similarities as evidenced by the research of Ahmad, Wynn and Clarkson (2013), Bruun et al. (2015), Caetano et al. (2017), Cardoso and Bussler (2011), Chungoora and Young (2011), Goel et al. (2012), Imran and Young (2015), Jiang, Peng and Liu (2010), Monticolo et al. (2014), Peng et al. (2017), Ruiz et al. (2017), Witherell et al. (2013) and Zhang et al. (2017). However, this approach is only possible when the concepts, as well as their relationships, are well defined and formalised.

Additionally, the analysis showed that most of the researches focus on one stage of the product development and its relevant domains and do not consider the information sharing with the latter stages of the development or the consistency of the information that is inputted in the studied stage as shown by the research conducted by: Ahmad, Wynn and Clarkson (2013), Bruun et al. (2015), Caetano et al. (2017), Cardoso and Bussler (2011), Goel et al. (2012), Huang and Huang (2013), Jiang, Peng and Liu (2010), Jiao et al. (2009), Li et al. (2017), Monticolo et al. (2015), Pasqual and de Weck (2012), Peng et al. (2017), Rahmani and Thomson (2012), Ruiz et al. (2017), Tchoffa et al. (2016), Tessier and Wang (2013), Tian and Voskuijl (2015), Witherell et al. (2013), Xie and Ma (2015) and Zhang et al. (2017). Furthermore, most research utilises computational tools aligned with ontological approaches to translate the information between domains, which exclude human errors and misunderstandings in the process.

3.3 CHAPTER 3 DISCUSSION

The Systematic Literature Review and Content Analysis revealed that, in the product development scenario, information must be translated and shared across different stages of the product development process and their domains without any loss of meaning and intent, even though mistakes have been identified in product requirements across the product development process due to the knowledge translation process.

Furthermore, most research analysed use computational tools aligned with ontological approaches to translate the information between the relevant domains. However, even with the increase in research over the years, semantic reconciliation across multiple domains and the product development process still has very little development, since the significant research have been done in specific domains and specific activities of the PDP.

The whole process of systematic literature review and content analysis made clear that there are problems to be solved in the research field regarding knowledge translation and semantic reconciliation across general multiple domains and encompassing all the product development process. It provided a solid theoretical foundation and supported the creation of a semantic reconciliation approach that can effectively translate the knowledge throughout the product development process and across its domains, which will be explored in the next Chapter.

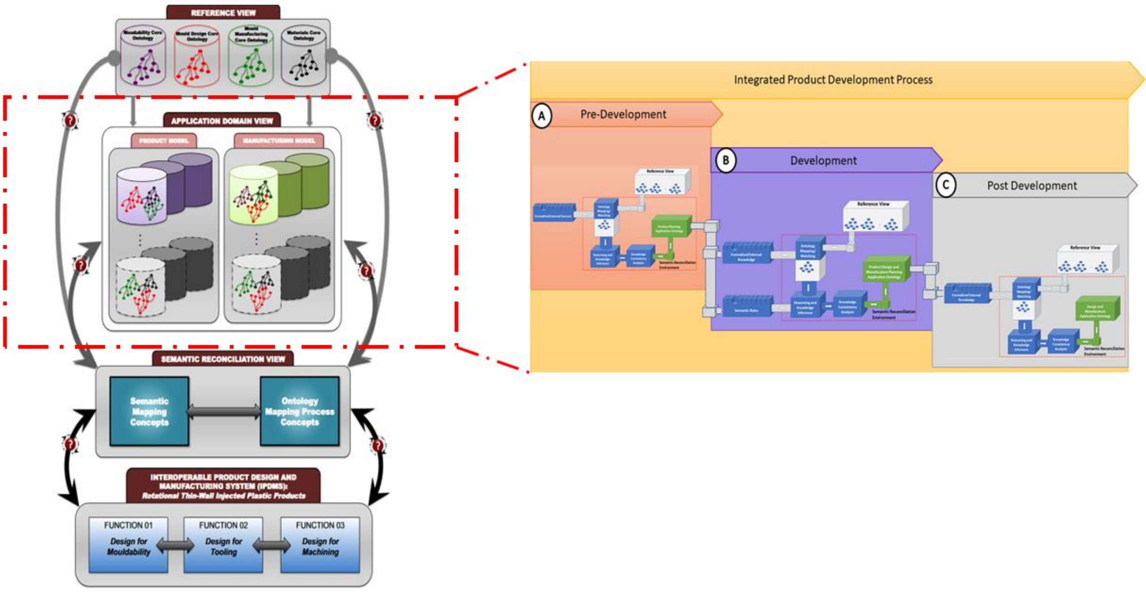
4 SEMANTIC RECONCILIATION APPROACH FOR INTEROPERABLE PRODUCT DESIGN AND MANUFACTURING

Knowledge sharing concepts have grown in importance in the last few years, but the lack of clarity in the terms that are used by the product development teams undermine their communication. Furthermore, there has been a considerable increase in the knowledge detailing, and, consequently, the semantical obstacles that hinder the sharing has also increased and become one of the main problems for the efficient knowledge sharing.

These semantical obstacles are mainly related to the heterogenic nature of the knowledge, which has its meaning captured and interpreted in a divergent way by the many different departments charged with the product development process, increasing the costs and development time.

This research had an initial exploration based on the work developed by Szejka (2016), which proposes a framework for semantic information interoperability in product design and manufacturing (Appendix B). In his framework, the author specialises reference models into application ontologies which create the interoperable product design and manufacturing environment. Although the framework approaches all steps of the creation of the interoperable environment, it presents limitations in the application domain, approaching superficially the ontology mapping processes needed for the specialisation process. In light of this, the present research explores the development of an approach that expands the framework’s Application Domain View by addressing the mapping and specialisation in detail. Figure 12 demonstrates the conceptual location of the proposed approach in the framework for semantic information interoperability in product design and manufacturing.

Figure 12: Conceptual location of the proposed approach in the framework for semantic information interoperability in product design and manufacturing

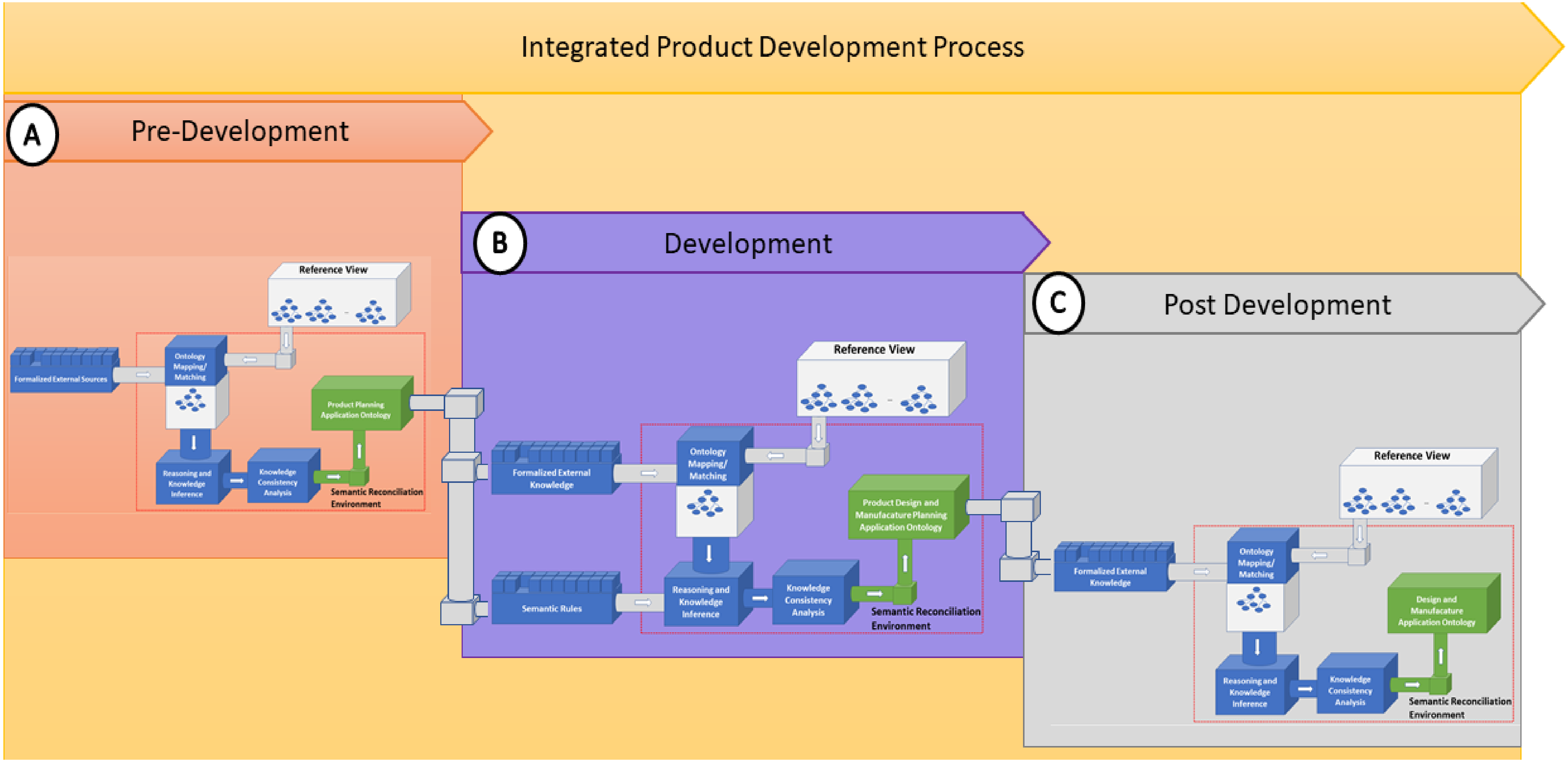


Source: The Author

In this context, the proposed approach of **Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM)**, presented in Figure 13, aims to apply the concepts and tools explored in the previous Chapter to develop a semantic reconciliation environment. It can consistently translate knowledge between different stages of the product development process, and analyse the consistency of the created knowledge, reducing the misunderstandings and limitations of communication between product development teams.

The proposed approach is divided into 3 main stages: i) the Pre-Development Stage (Figure 13 - Detail “A”); ii) The Development Stage (Figure 13 – Detail “B”); and iii) the Post Development Stage (Figure 13 – Detail “C”), as proposed by Pereira (2014) and Pereira & Canciglieri Jr. (2014). Each of these stages corresponds to a step of product design and manufacturing since the requirements survey until its manufacture and use.

Figure 13 – Semantic Reconciliation Approach for Interoperable Product Design and Manufacturing.



Source: The author.

The Pre-Development Stage corresponds to the gathering of information and consumer requirements needed to start the development of a new product. The Development Stage corresponds to the analysis of consumer requirements, product design, prototyping, testing, and manufacturing planning. The last stage, Post-Development, corresponds to the product`s manufacturing, in testing and consumption processes. These stages of the proposed approach will be explored in more detail in Sections 4.2 (Pre-Development), 4.3 (Development), and 4.4 (Post Development).

For each of these stages, information gathering from external sources such as consumer needs and supplier processes and external lead time is necessary for an optimal development process. These external knowledge sources need to be formalised and transformed into a single semantic representation, in this research, the Web Ontology Language (OWL), before their interaction with internal knowledge sources can happen. However, the focus of this research is the translation of formalised knowledge across different domains throughout the product development process, and in this way, the author is assuming that the formalisation process of the external knowledge is already correctly defined.

The experimental case (Chapter 5) will be used to validate the proposed approach focused on the Development Stage due to the amplitude and complexity of the research theme of the Product Development Process. The Development Stage was considered the most critical stage of the three presented because concentrates the majority number of the areas involved in the development process and would better demonstrate that a correct and effective translation of the formalised knowledge can assure better quality and cost of the product

The next Sections will explore the proposed approach, addressing in 4.1 the Reference View; the Pre-Development Stage in 4.2, and Development Stage and Post-Development Stage in 4.3 and 4.4 respectively.

4.1 REFERENCE VIEW

In order to improve the semantic interoperability in an integrated product development environment through ontologies, a knowledge basis is significantly important to further integrate domains and serve as reference on product design and manufacturing (AHMAD, WYNN and CLARKSON, 2003; CAETANO et al., 2017;

CARDOSO AND BUSSLER, 2011; CHEN, CHEN and CHU, 2009; CHUNGOORA & YOUNG, 2011; GOEL et al., 2012; IMRAN & YOUNG, 2015; RAHMANI & THOMSON, 2012; TCHOFFA et al., 2016). The Semantic Reconciliation System for Interoperable Product Design and Manufacturing (SRIPDM) defines this knowledge basis as “Reference View” for its system, which is greatly based on the formalisation provided by ontologies. The ontologies that compose the reference view are divided in three main models: i) ***Management ontologies***; ii) ***Design Ontologies***; and iii) ***Manufacturing Ontologies***. Each model is composed of multiple ontologies that represent an aspect of the category and will later be merged or specialised according to the need and application.

The Reference View gathers information from within the enterprise alongside real-world information and represents it in a high-level abstraction of different domains through ontological models. These models are considered the knowledge core of the proposed approach.

In the Reference View is important to create, firstly by conceptually defining each ontological model, then building the hierarchical structure and the entities' information, and finally, add semantical properties to the model in order to enable it for further instantiation and reasoning (NOY & MCGUINESS, 2001). To the authors, to define the conceptual model, to organise data and improve comprehension in further stages, a simplified UML diagram provides a visual representation that can gather a vast quantity of information and represent entities in the ontological model.

The creation of an ontology structure requires a specific language, for this research the chosen language was the Ontology Web Language (OWL), which can be more easily achieved by using dedicated software such as Protégé, from Stanford University.

The first model in specific language developed in an ontology programming interface, composed just by the entities' structure and information, is designated as “Lightweight Ontology.” However, the reference view ontologies need to establish semantics for its information and process in formal axioms in the form of semantic rules. The semantic rules are divided mainly into two groups: i) “Existence Rules”, which validate the ontology as a model that abstracts reality and focuses on the semantics between entities, these rules do not change during the stages of the IPDP; ii) “Application rules”, which are focused on the specialization of the Reference View.

This latter group must be created after the Reference View is well defined in its aim and domain intersections, to avoid inconsistencies.

In the context of an interoperable system focused on product development and manufacture, the Reference View is the very first step in order to achieve further interoperability, offering benefits as:

- Information sharing through all phases of IPDP;
- Information traceability;
- More autonomy and improved communication.

4.2 PRE-DEVELOPMENT STAGE

In the first stage of the Product Development and the proposed SRIPDM approach, the user requirements alongside management information are gathered and used as a base of information for the product development and manufacturing processes. Figure 14 shows the semantic reconciliation process used in this stage.

In the Pre-Development stage, the SRIPDM should gather market information and should formalise it in a structure that can be understood by the product development teams. This formalised information must be used as an input, alongside the knowledge and information structured in the reference view, for the first ***ontology mapping\ matching*** process that aims in creating a specialised knowledge model to support the product development planning process (Figure 14 Detail "A").

As shown in Figure 14 - Detail "A", the next stage of the Pre-Development approach should translate the market requirements into product requirements, which is made through reasoning and knowledge inferences. The ***reasoning and knowledge inferences*** use the data relationships modelled in the reference view models in order to classify and translate the market information.

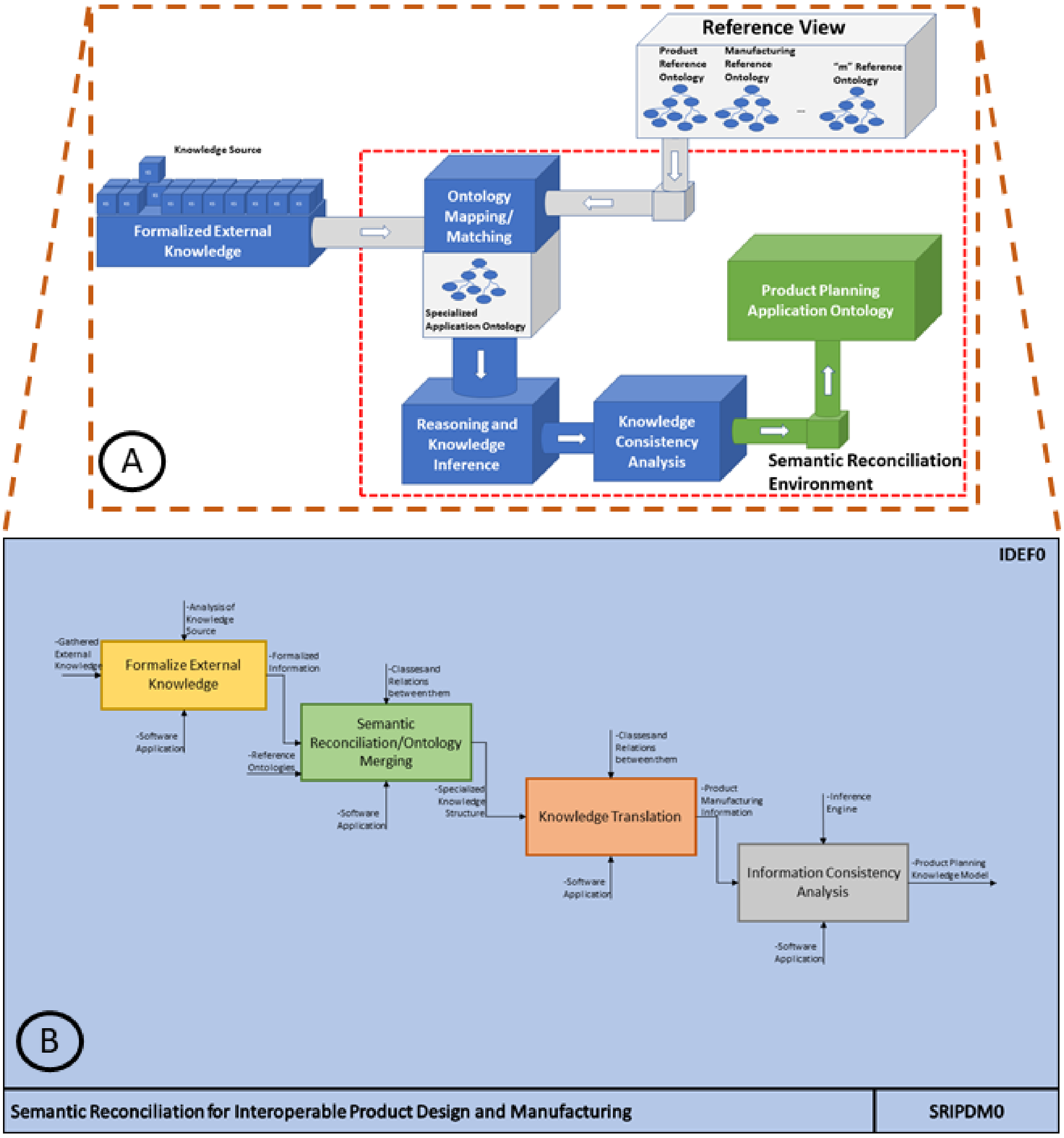
Lastly, the information created through this process should pass through a ***consistency analysis***, also using reasoning and knowledge inferences, where the information inputted must be compared to the information created and analysed the differences between them. After the consistency analysis is completed, the ***product planning application ontology*** can be used as an information source for customer relationship management and as an input in the next stages of the product development process (Figure 14 - Detail "A").

Figure 14 - Detail "B" presents the processes of the Pre-Development Stage in an Integrated Definition Language (IDEF), more precisely in IDEF0 (as shown in Appendix C), which is a function modelling methodology used to describe manufacturing, business or information processes. According to Figure 14 - Detail "B", the first process of the proposed SRIPMD approach is the ***formalisation of external knowledge***, which depends on the computational applications and on the knowledge source that is being formalised. The market information can be gathered through tools as the Quality Function Deployment (QFD), user feedback on older versions of the product. This information is formalised into structures that can be used as input in further stages. Depending on the source of information, the formalised structure always changes into compatible formats.

The next process is the ***semantic reconciliation/ontology merging,*** where the models from the reference view are merged. In the Pre-Development Stage, for the merging process are used two models from the reference view: i) Management Model; and ii) Design Model. The ontologies from these models are put together, using a computational application, creating an application ontology to aid in the product development process planning. Lastly, the formalised information, from the previous process, is inputted into this application ontology (Figure 14 - Detail "B").

The third process of the Pre-Development stage of the approach refers to ***knowledge translation***. This process uses reasoning and knowledge inferences in the classes and relationships from the application ontology in order to translate the market information into the product's technical requirements. After the translation, the information created is submitted to a **consistency analysis** and using reasoning processes the product's technical requirements are compared to the internal knowledge of the enterprise and market information, checking differences that could thwart the product development process. When the Consistency Analysis is completed, the final product planning model can be used in the latter stages of the product development process (Figure 14 - Detail "B").

Figure 13 – Semantic Reconciliation Method for the Pre-Development Stage.

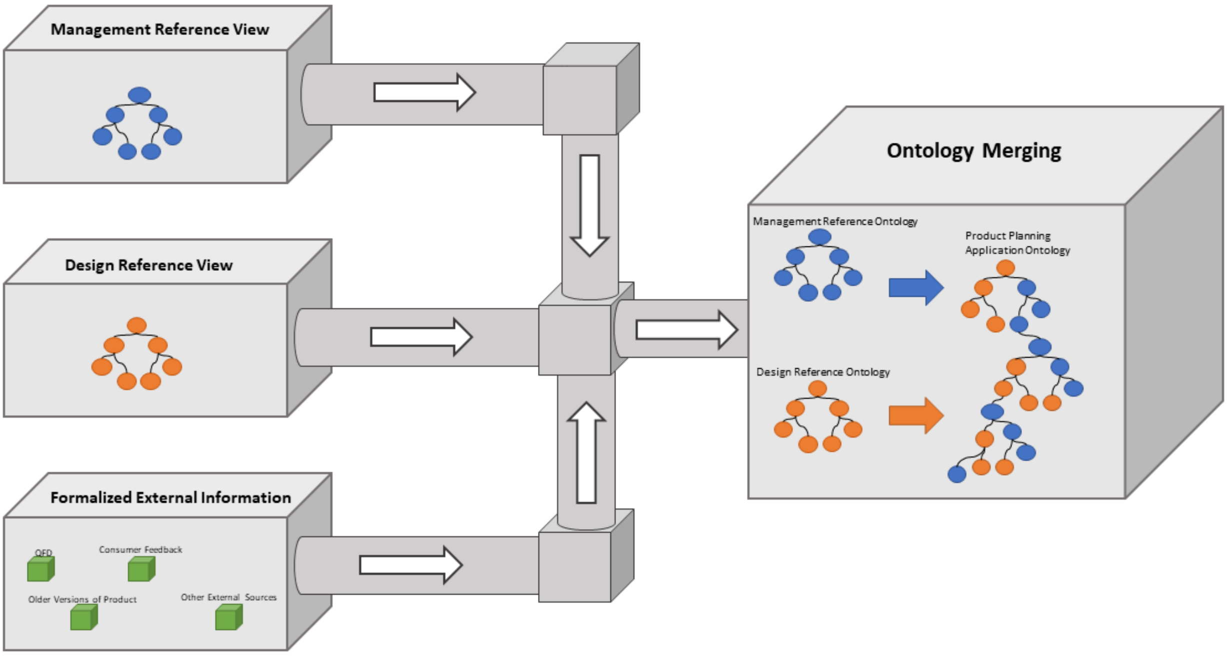


Source: The author.

4.2.1 Ontology Mapping/Matching in the Pre-Development

During the Pre-Development Stage, the management and design models from the reference view need to be specialised in order to offer support for the product development process. In this context, the proposed approach uses an ***ontology merging*** process. This process takes the hierarchical structure and relationships from the ontology of both models and creates a new specialised ontology. After the ontology merging process of the reference view ontologies is complete, the formalized external information is inserted into the new ontology and used in the translation process and consistency analysis (BRUNN et al., 2015; CHEN, CHEN & CHU, 2009; CHUNGOORA & YOUNG, 2011; JIAO et al., 2009; LI et al., 2017; MANTICOLO et al., 2014). Figure 15 shows the ontology merging process used in the Pre-Development Stage.

Figure 15- Ontology Merging Method used in the Pre-Development Stage



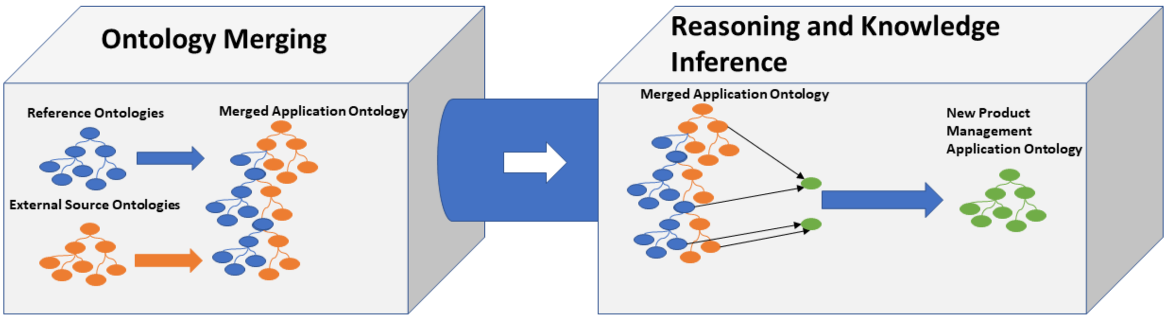
Source: The Author.

As the Pre-development stage is the most uncertain stage of the product development, an ontology merging is required as a form of assuring that the external information can be correctly mapped and integrated to the correct management concepts and relationships. The result of the merged ontologies is an application ontology with all the information from the two sources (CHUNGOORA & YOUNG, 2011). However, to properly use this ontology, it must first be refined into an optimised model. It happens because after the ontology merging process, some formal structures and relationships, which are not applied in the project, are presented into the new application ontology. These structures and relationships must be deleted from the ontology in order to create an optimised model.

4.2.2 Reasoning, Knowledge Inference and Consistency Check in the Pre-Development

The refinement of the merged application ontology is made from another ontology mapping method, the knowledge translation (BRUNN et al., 2015; CAETANO et al., 2017; CARDOSO & BUSSLER, 2011; CHUNGGORA & YOUNG, 2011; JIAO et al., 2009; LI et al., 2017; PASQUAL & DE WECK, 2012; PENG et al., 2017; RUIZ et al, 2017; TIAN & VOSKUIJL, 2015; WITHERELL et al., 2013). This translation occurs through a similarity analysis made by the inference engine in three levels: i) ***critical concept similarities*** **-** the critical requirements gathered from the external sources are compared to the critical knowledge presented in the ontology; ii) ***relationship analysis*** - the relationship between concepts in the external sources are compared to the relationship presented in the reference view ontologies and any similar relations are selected; iii) ***concept relationship*** **-** the concepts of the external sources are analysed regarding its similarity to the reference view ontologies. Figure 16 depicts the Knowledge translation and Inference for the Pre-Development Stage.

Figure 16 – Knowledge translation and Inference for the Pre-Development Stage



Source: The author.

The inference engine runs a consistency verification in the new product management application ontology in order to verify the ontology consistency after the translation process is completed. It is verified if there is no ambiguous or wrong information within the ontological structure as it would hinder the next stages of the product development, raising the PDP cost and time while decreasing the final product quality (JIANG, PENG & LIU, 2010).

If there is an inconsistency in the application ontology, it must be adjusted and verified which information from the external sources or reference view was responsible for this error and must correct it. After the adjustment process, the consistency analysis will be carried out again to avoid ambiguous information. If there was no inconsistency, the ontology is shared with the next stage of the IPDP.

The resulting ontology from this stage shares the management and user restrictions regarding the product to be developed. These restrictions are regarding product family, material cost, among several other requirements that the design and manufacturing must meet for the product to be a viable solution for the enterprise and the consumer. These restrictions are shared mostly as semantic rules that will be used during the knowledge inference of the next stage, but the hierarchical structure is shared to assure that restrictions not encompassed in the semantic rules are also attended.

4.3 DEVELOPMENT STAGE

The next stage of Product Development and the proposed SRIPDM approach consists of the product design, and its prototyping, tests, and manufacturing planning. It comprises the critical stages of the IPDP, being the stage where the interoperable environment proposed by the application of the SRIPDM can aid the most (BRUNN et al., 2015; CHEN, CHEN & CHU, 2009; CHUNGOORA & YOUNG, 2011; JIAO et al., 2009; LI et al., 2017; MANTICOLO et al., 2014; CAETANO et al., 2017; CARDOSO & BUSSLER, 2011; CHEN, 2010; JIANG, PENG & LIU, 2010; JAIO et al., 2009; RUIZ et al., 2017; TESSIER & WANG, 2013; WITHERELL et al., 2013).

In the Development Stage, the proposed approach should, firstly, should **formalise the external knowledge** that is gathered in this stage from CAD/CAM software, tests, design documentation and other sources of design knowledge that an enterprise might use. These sources must be formalised in a structure that can be understood by the design teams and other systems involved in the product design. As shown in Figure -17 Detail “A”.

The product planning ontology created in topic 4.2 should create the mapping requirements that will be used for the ***ontology mapping/matching*** of this stage. In the development stage, the mapping process used is the ontology alignment. This process should create an optimised design and manufacturing ontology by “cutting” relevant hierarchical structures and relationships from the design model and from the manufacturing model from the reference view and creating a new application ontology from these cuts that should aid the product design and manufacturing planning (Figure 17 - Detail “A”).

After the ontology alignment process, the proposed SRIPDM approach must translate the design information gathered and formalised in earlier processes and translate the information into manufacturing information. This process is possible through the use of semantic rules in the ***reasoning and knowledge translation process***. The insertion of the rules allows the insertion of complex relationships into the application ontology. These rules come from the product planning ontology created in Section 4.2 (Figure 17 - Detail “A”).

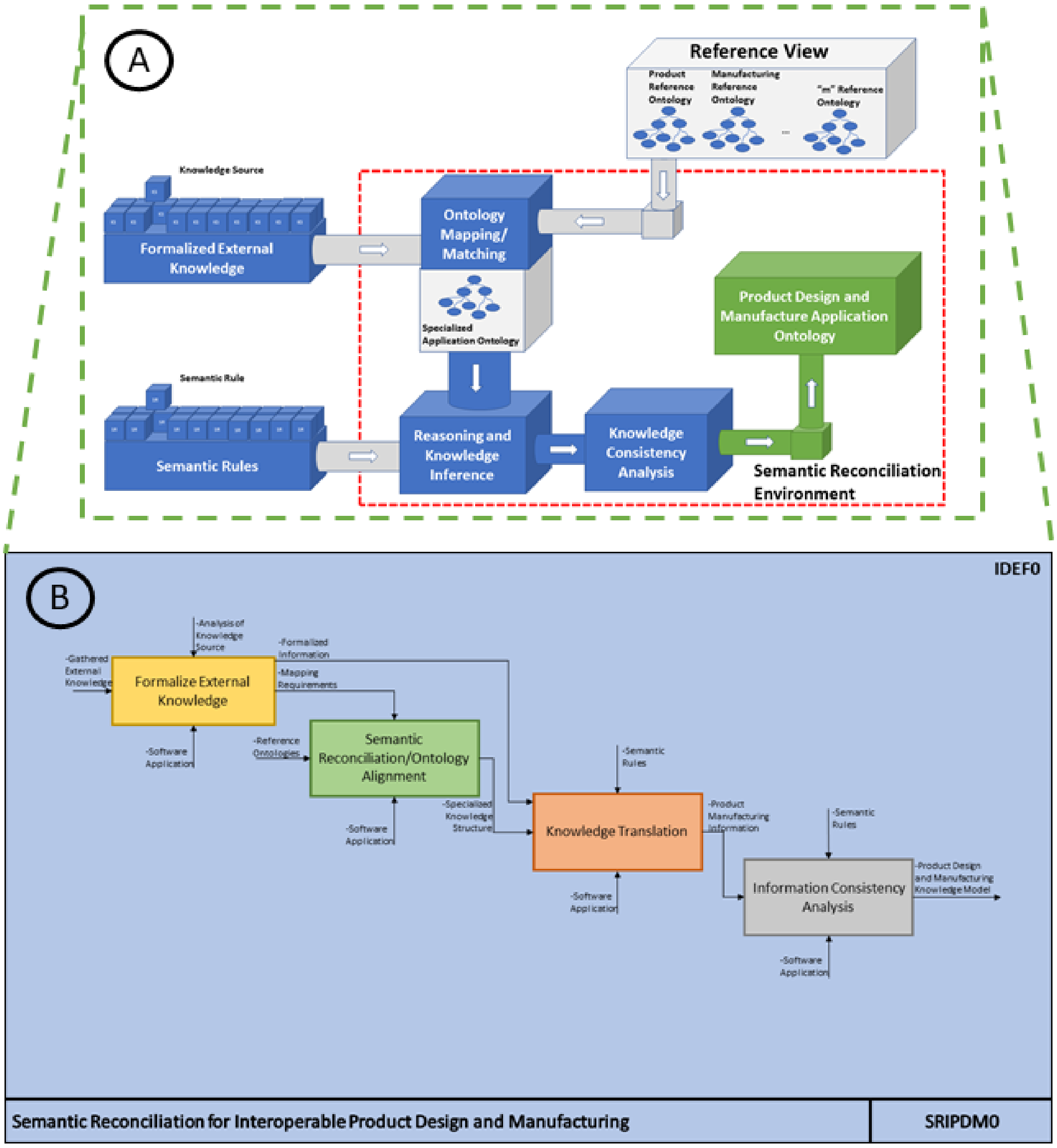
After the translation, the information is submitted to ***consistency analysis*** to assure that the manufacturing knowledge created through the knowledge translation processes are coherent with the design knowledge that was inserted into the application ontology. This analysis is, as in the earlier stage, must be done through reasoning and knowledge inferences that should compare the two information and in the case of inconsistencies that would thwart the product development process it should warn the design teams of it. Lastly, after the consistency analysis, a ***product design and manufacturing application ontology*** model is created and can aid in the design and manufacturing planning processes.

According to Figure 17 - Detail “B”, the first process of the proposed SRIPDM approach is the gathering of the necessary information from each source of the development and the formalisation of it. The ***formalisation of external knowledge*** happens through computational applications and is dependent on the knowledge source form, which the information is being gathered. It happens because the information structure of each source differs from each other. This formalised information will be inserted into the application ontology and used in the translation and consistency analysis processes.

The product planning ontology is used as a mapping requirement for the ontology alignment process used as the algorithm for the ***ontology mapping/matching*** process. This process uses the reference view ontologies from the design model and the manufacturing model and selects the relevant hierarchical structures and relationships from them and creates a new ontology with the selected structures. The new ontology is already optimised for the use of the design teams (Figure 17 Detail “B”).

The formalised design information is inserted into the new ontology and through reasoning and knowledge inferences and translated into manufacturing information. The semantic rules guide the ***knowledge translation*** process. The created knowledge passes through a ***consistency analysis***, that is, it is also guided by semantic rules alongside the classes and relationships presented in the application ontology. After the completion of the consistency analysis, the application ontology can be used to aid in the further stages of the product design and manufacturing (Figure 17 Detail “B”).

Figure 17- Semantic Reconciliation Method for the Development Stage.



Source: The author.

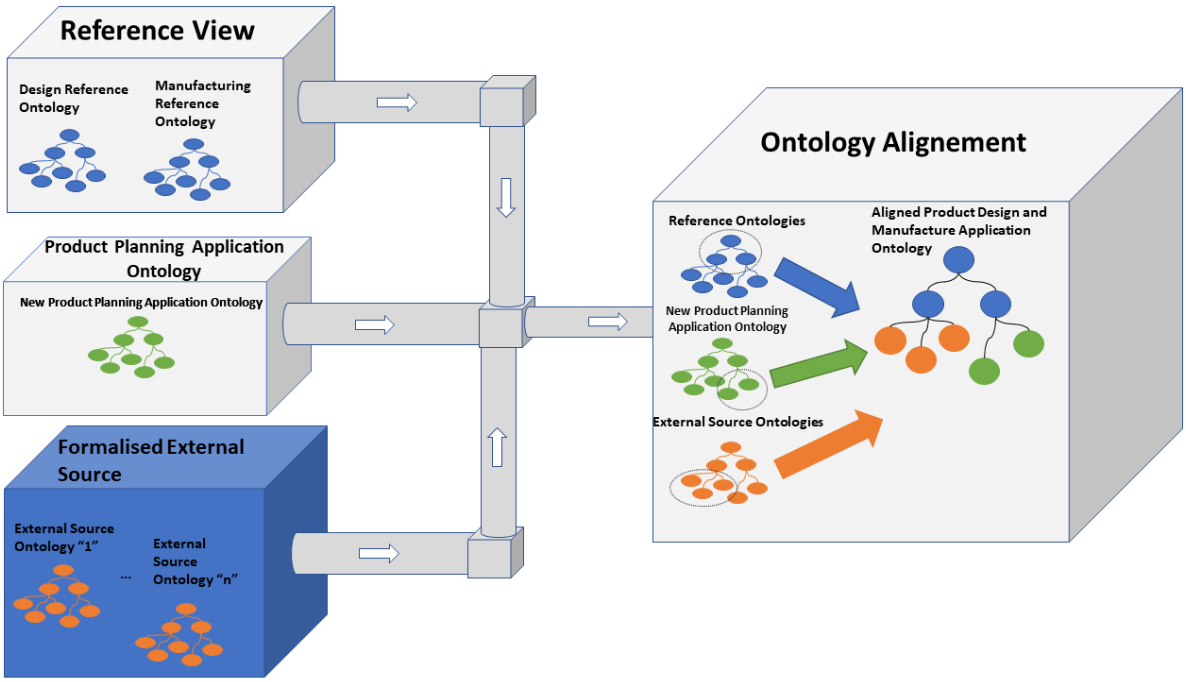
4.3.1 Ontology Mapping\Matching in the Development Stage

With the necessary knowledge gathered and formalised, the proposed approach uses an ontology alignment to create the application ontology (CAETANO et al., 2017; CARDOSO & BUSSLER, 2011; CHUNGOORA AND YOUNG, 2011; DARTIGUES-PALLEZ et al., 2007; DEMOLY, MATSOKIS & KIRITSIS, 2012; HUANG & HUANG, 2013; IMRAN & YOUNG, 2015; JIANG, PENG & LIU, 2010; JIAO et al., 2009; RAHMANI & THOMSON, 2012; RUIZ et al., 2017; TCHOFFA et al., 2016).

The ***ontology alignment*** process, shown in Figure 18, uses the reference view ontologies from the design model and manufacturing model, selecting the relevant structures and relationships and creates a new application ontology. This new ontology has then inserted into it the formalised knowledge gathered from the design sources and the semantic rules from the product planning application ontology.

In this stage, which is not as uncertain as in the pre-development, the ontology alignment is used since the resulting application ontology does not need to be refined for an optimised knowledge inference process.

Figure 18 – Ontology Alignment Method used for the creation of the Development Stage Application Ontology.



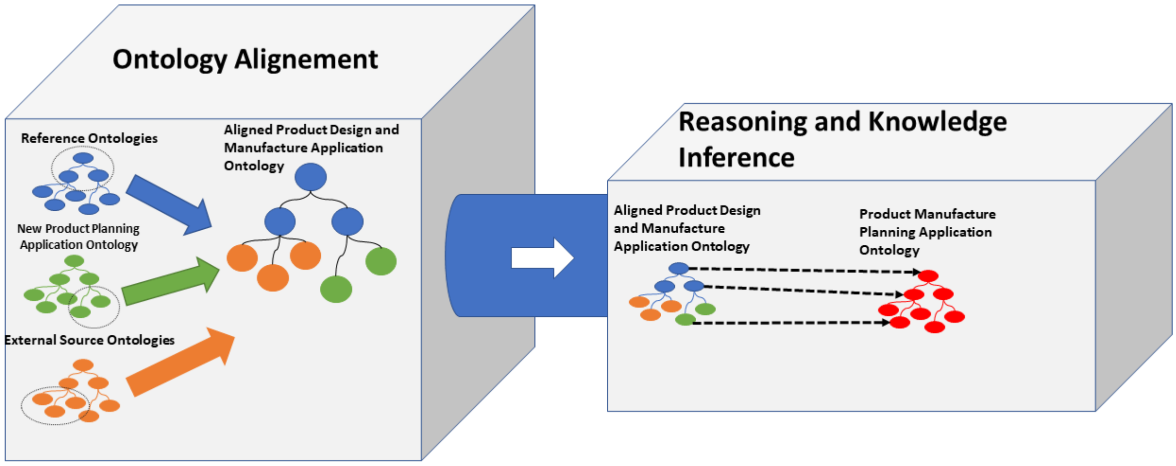
Source: The author.

4.3.2 Reasoning, Knowledge Inference and Consistency Check in the Development Stage

After the alignment shown in step 4.3.1, the knowledge translation should be applied in order to transform the design information into manufacturing information (BRUNN et al., 2015; CAETANO et al., 2017; CARDOSO & BUSSLER, 2011; CHUNGGORA & YOUNG, 2011; JIAO et al., 2009; LI et al., 2017; PASQUAL & DE WECK, 2012; PENG et al., 2017; RUIZ et al., 2017; TIAN & VOSKUIJL; 2015; WITHERELL et al., 2013). This process, depicted in Figure 19, uses reasoning and knowledge inferences to make a similarity analysis made by the inference engine in three levels: i) ***critical concept similarities*** that are the critical concepts and information gathered from the design sources are compared to the manufacturing knowledge presented in the ontology; ii) ***relationship analysis*** - the relationship between concepts in the design sources are compared to the relationships presented in the application ontology and any similar relations are selected; and iii) ***concept relationship -*** the concepts of the design sources are analysed regarding its similarity to the application ontology.

The manufacturing knowledge created is then prioritised through the semantic rules, and a process planning will be done for the next step. A consistency verification in the design and manufacturing planning application ontology should be carried out in order to verify the information consistency. If there is an inconsistency in the application ontology, it must be adjusted and verified which information from the external sources or reference view was responsible for this error and must correct it. After the adjustment process, the consistency analysis should be performed again in order to avoid ambiguous information. If there were no inconsistency, the ontology would be shared with the next stage of the IPDP.

Figure 19 – Design Knowledge to Manufacturing Knowledge Translation Process used to Plan the Manufacturing Steps of the Product.



Source: The author.

The resulting ontology from this stage shares the product design and manufacturing planning to the fabrication process, where the product will be mass-produced. This planning must be shared through the hierarchical structure of the design and manufacturing planning application ontology.

4.4 POST - DEVELOPMENT STAGE

The last stage of the Product Development and the proposed SRIPMD approach consists of the product manufacturing, usage tests and its use by the consumer (BRUNN et al., 2015; CAETANO et al., 2017; CARDOSO & BUSSLER, 2011; CHUNGGORA & YOUNG, 2011; JIAO et al., 2009; LI et al, 2017; PASQUAL & DE WECK, 2012; PENG et al., 2017; RUIZ et al., 2017; TIAN & VOSKUIJL, 2015; WITHERELL et al., 2013). This stage encompasses the production and quality control of the product, and the semantic reconciliation process used in this stage is illustrated in Figure 20.

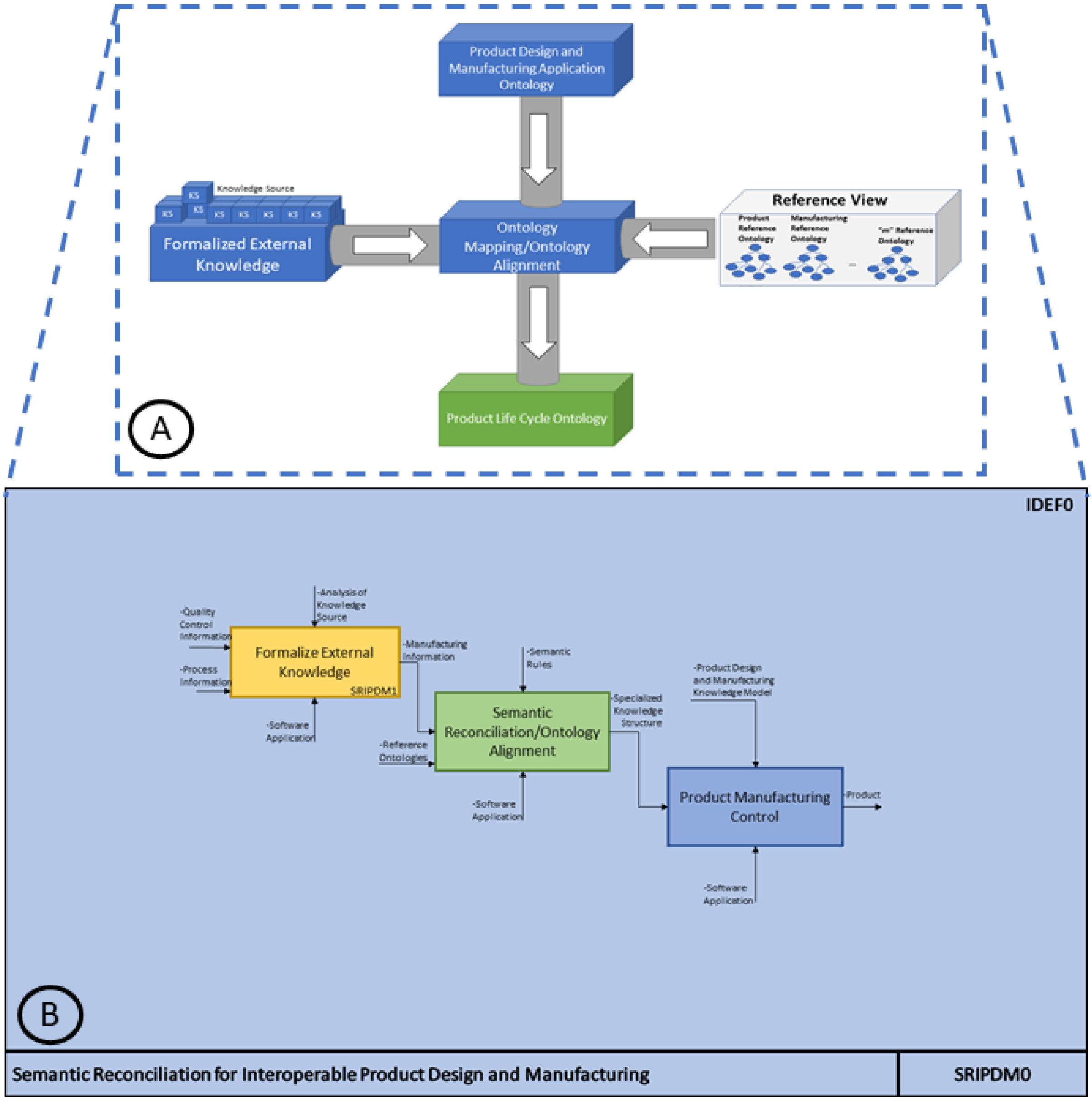
The proposed approach should, as in topic 4.2 and 4.3, **formalise the external knowledge** that is gathered in the Post-Development Stage. The information of this stage should come from the production planning, the manufacturing processes, quality control of the product, and user feedback. The information must be formalised through a computational application and structured in a way that can be understood to the production and design teams, as shown in Figure - 20 Detail “A”.

The product planning ontology created in topic 4.2 that created the mapping requirements for the product design and manufacturing application design in topic 4.3 should also create the mapping requirements that will be used for the ***ontology mapping/matching*** of this stage. In the Post-Development Stage, as in the development stage, the mapping process used should be the ontology alignment. This process should create an optimised manufacturing ontology by selecting the relevant hierarchical structures and relationships from the “product design and manufacturing application ontology” and from the manufacturing model from the reference view and creating a new application ontology from this selection that should aid the manufacturing process control. The formalised information is, after the ontology mapping process, inserted into the ontology and should be used to control the manufacturing process, product quality and be used to create requirements for new products or version of the product (Figure 20 - Detail “A”).

According to Figure 20 - Detail “B”, the first process of the proposed SRIPDM approach is the gathering of the necessary information from each source of the products manufacturing, quality control and usage and the formalisation of this information. The ***formalisation of external knowledge*** is performed by computational applications and is dependent on the knowledge source form from the information is being gathered. It occurs because the information structure of each source differs from each other, and consequently, the formalisation process requires different structures. This formalised information will be inserted into the application ontology and used for the management of the products manufacturing and technical assistance.

The product planning ontology inputs the mapping required for the ontology ***alignment process***. This process uses the reference view ontologies from the manufacturing model and the “product design and manufacturing application ontology”, selecting the relevant hierarchical structures and relationships from them and creates a new ontology with the selected structures. The new ontology is already optimised for the use of the design, management, and manufacturing teams (Figure 20 - Detail “B”).

Figure 20 – Semantic Reconciliation Method for the Post Development Stage.



Source: The author.

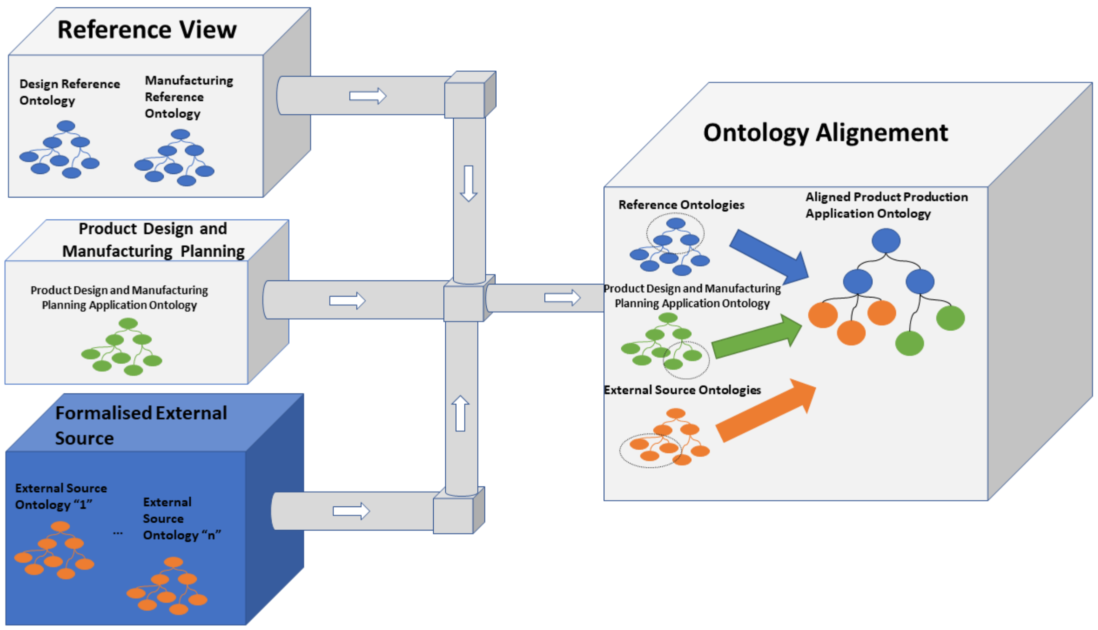
4.4.1 Ontology Mapping\Matching in the Post Development Stage

With the necessary knowledge gathered and formalised in an ontology, the proposed approach uses, similarly to the development stage, an ontology alignment to create the application ontology for this stage, as shown in Figure 21.

The ***ontology alignment*** process uses the reference view ontologies from the manufacturing model and the “design and manufacturing application ontology” selecting the relevant structures and relationships and creating a new application ontology. The formalised knowledge gathered from the manufacturing and the users alongside the semantic rules from the “product planning application ontology” is inserted into the product lifecycle application ontology and should aid the manufacturing, and quality control and also provide new requirements for the design teams for new products or new versions of the product.

As the Development stage, the Post Development is not as uncertain as the pre-development, therefore, the ontology alignment is used since the resulting application ontology does not need to be refined for an optimised knowledge inference process.

Figure 21 – Alignment Method for the Post Development Stage used for the creation of the Product Production Application Ontology.



Source: The Author.

In the next Chapter, an experimental case in the Technology-based Company will be carried out to corroborate the proposed Semantic Reconciliation for Interoperable Product Design Manufacturing (SRIPDM) approach explored conceptually in this Chapter.

5 VALIDATION OF THE PROPOSED APPROACH THROUGH AN EXPERIMENTAL CASE IN A TECHNOLOGY BASED ENTERPRISE

This Chapter presents the experiment used to validate the proposed SRIPDM approach. This experiment was carried out in a Brazilian Capital Technology Company that is focused on the development and manufacturing of Uninterruptible Power Supplies (UPS) and was called Company "X" in this research.

The experimental case consists in the application of the ***Development Stage*** (second stage of the proposed approach), presented in Figure 17, to support the development of a new three-phased 20kVA UPS system shown in Figure 22. The first version of this product was developed in 18 months (end of 2015- early 2017) from which six months were consumed by corrections and reviews in the design during the development. The total cost of product development was approximately US$ 35.000,00 (Thirty-five thousand American Dollars) wherein 33% was spent in those corrections and reviews. From 2017 to 2018, 93 products were produced and sold and had a return rate of 25% during the warranty period.

Figure 22- Product selected for the experimental case (uninterruptible power supplies - 20kVA UPS system).

Source: The author.

5.1 EXPERIMENTAL SYSTEM (20KVA UPS SYSTEM)

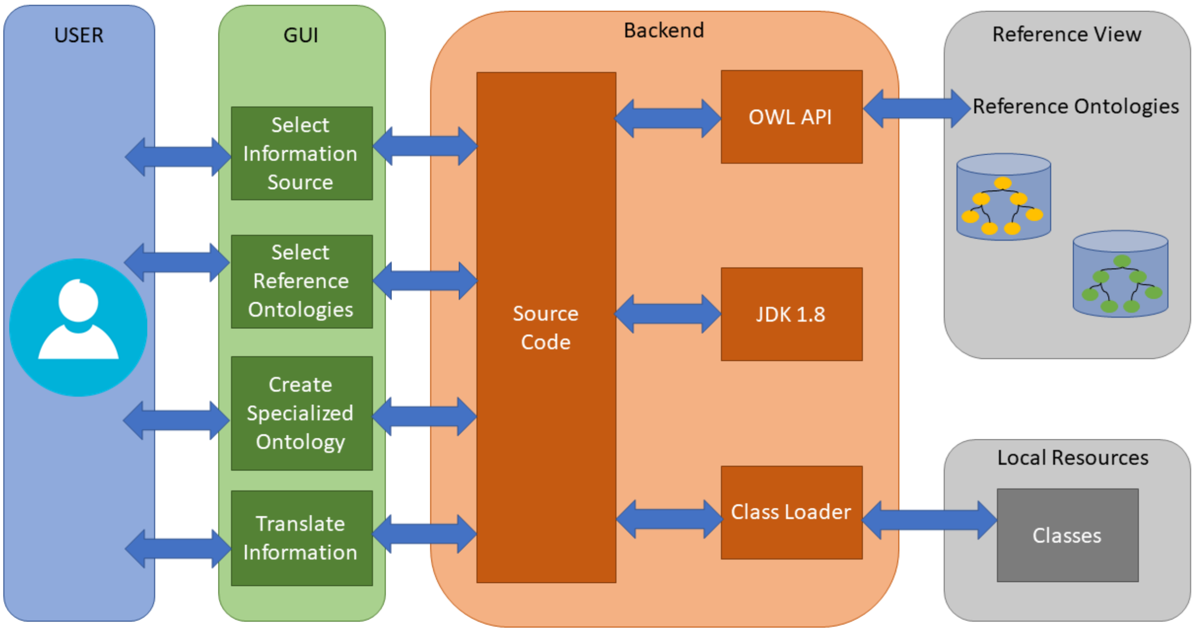
The experimental software, named as Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM) was developed following the proposed approach depicted in Chapter 4. Next, a list of the relevant software applications used to develop the experimental tool is presented:

- ***Protégé 5.2.0 -*** Developed at Stanford University, this software provides an environment to handle and model ontologies in OWL;
- ***Coolbeans 8.2.0 -*** A more user-friendly version of Netbeans. Coolbeans is an environment of JAVA programming (primarily), with high flexibility due to its modularity. Coolbeans have good integration with Apache JENA, a crucial resource for this research;
- ***Apache JENA -*** An open source JAVA framework to build and manipulate semantic applications. Different APIs (Application Programming Interface), such as OWL API, RDF API, SPARQL API, compose Apache JENA. The experimental tool developed relies heavily on the OWL API of Apache JENA.

The experimental proposed software used Protégé to develop the reference view ontologies. Coolbeans was used in association with Apache JENA to develop the user interface and main functionalities of the system. Firstly, an architecture of the system was developed in a block diagram in order to plan the functions and behaviour of the experimental software, as depicted in Figure 23. The block diagram shows the main functionalities and elements of the experimental software. The user is able of interacting with a graphical user interface (GUI) that presents the main functionalities of the system. It offers the following functionalities: i) ***select the reference ontologies*** - that will be used to create the specialized ontology and will aid the activities of the product development process; ii) ***select the information sources -*** that will be used to in the specialized ontology (CAD/CAM, test, etc); iii) ***through ontology mapping techniques*** - it will create a specialized ontology; and iv) ***translate*** - design knowledge into manufacturing knowledge.

In the backend, the source code will coordinate the activities of the system, using the OWL API, the tools of the JAVA Development Kit version 1.8 (JDK 1.8) and the class loader that brings libraries and additional files to the system. The backend will use the Reference ontologies in the process of composing the specialised application ontology.

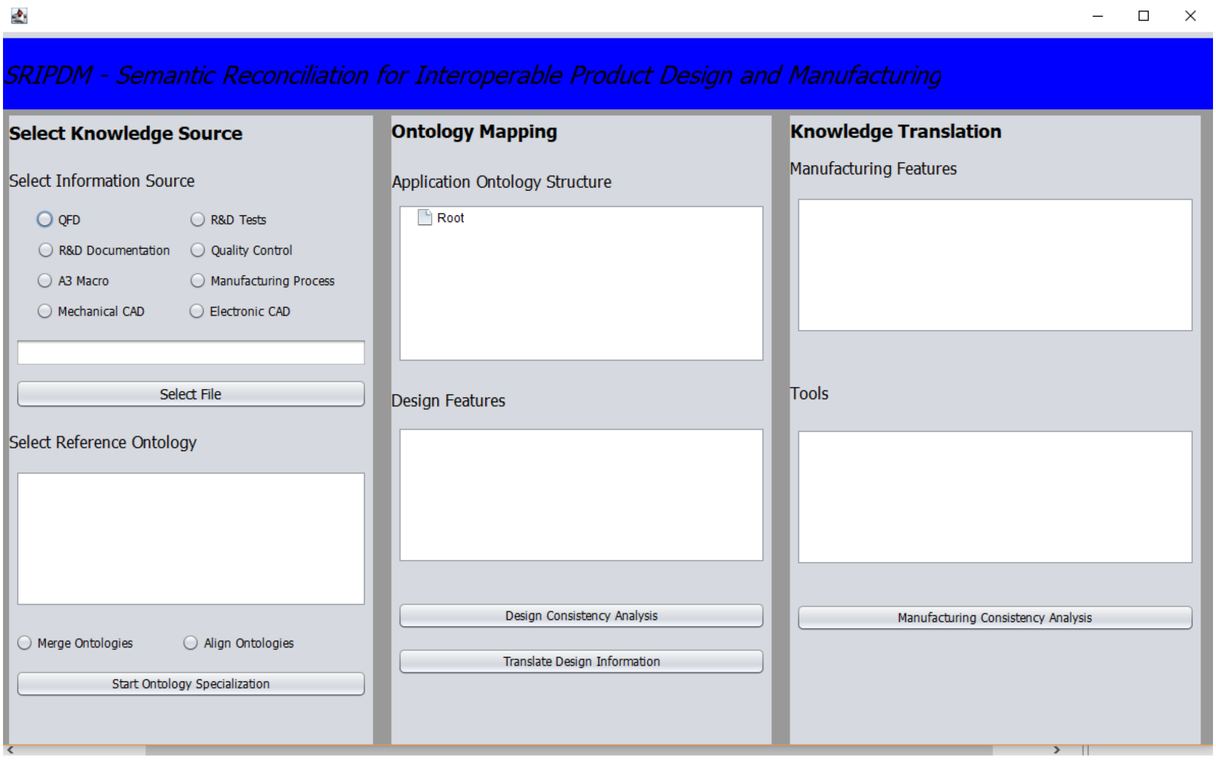
Figure 23 -Block Diagram of the Experimental System.



Source: The Author.

The next step in the creation of the proposed experimental software was acquiring the tools for creating and setting the environment for development. In this stage, the Apache JENA had to be manually installed in the JAVA development platform. Sequentially, the development of the proposed experimental software proceeded to the creation of the source code and creation of the Graphical User Interface (Figure 24). The interface is divided into three main sections: i) ***knowledge and information input*** - where the information created through the development process can be added into the specialised ontology. The user can select which of the reference ontologies they want to use to create the application ontology; ii) ***ontology mapping*** - where the structure of the application ontology is shown to the user alongside the formalised design information. The user can check the consistency of the product design according to the product requirements and process restrictions; and iii) ***knowledge translation -*** where the design information is translated into manufacturing information and shown to the user. This information is presented in feature format, and for each feature, the suggested tool is offered for the user to choose between them.

Figure 24 – SRIPDM User Interface.



Source: The author.

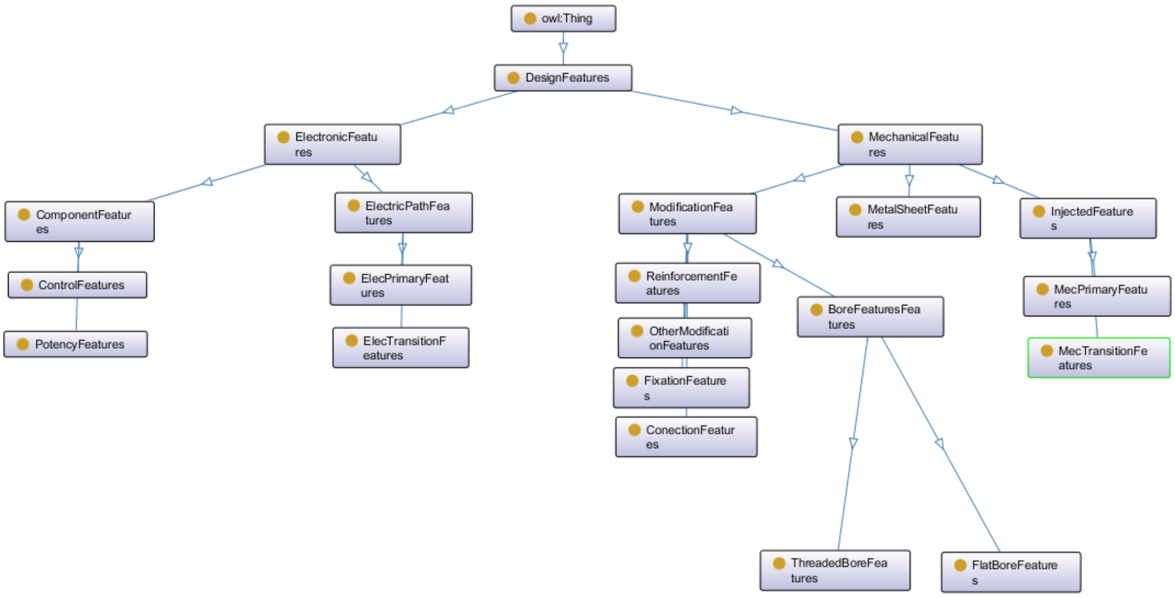
5.2 REFERENCE VIEW

As presented in topic 4.1, the reference view gathers information from within and outside the enterprise and represents them in a high-level abstraction of different domains through ontological models, which are considered the system's knowledge.

For the experimental case, the reference view used two of the three models showed in topic 4.1: i) ***Design Model***; and ii) ***Manufacturing Model***. Each of these models is composed of two ontologies. The design model is composed of a "***Design Features Reference Ontology***", and a "***Product Reference Ontology***", while the manufacturing model is composed of a "***Manufacturing Feature Reference Ontology***", and a "***Manufacturing Reference Ontology***". All the ontologies developed for this research are presented in Appendix D.

The **Design Features Reference Ontology** abstracts the knowledge created during the product design stage and formalises it in a hierarchical structure, as shown in figure 25. This structure allows, after the specialisation process, to automatically formalise the information captured in the Computer Aided Design environment. For the experimental case, two environments need to be considered, one for the UPS mechanical structure and another for the electronic boards used in the product.

Figure 25 – Design Features Reference Ontology Structure.



Source: The author.

Figure 25 also shows that the Mechanical features and Electronic features compose design features reference ontology. The Mechanical features are divided into modification features, metal sheet features, and injection features.

Modification features represent modifications that are performed on the product such as bores for screws and other joining parts, or that can aid in the connectivity and temperature control of the product. The modification features also approach reinforcement designs such as ribs or other systems used to maintain the structure of the product and assure its quality. Besides this, in the modification features, there are fixation features that refer to the battery and transformer fixation structures necessary in the product and lastly, the connection features that are modifications used alongside the bore features to assure that each part of the product can be assembled to create the product.

Alongside the modification features, the structure of the design features reference ontology comprehends the ***metal sheet features***. These features comprehend the metal sheet designs used in most of the cabinets of Company's X products. The metal sheet features refer to the sheet and the points where it is folded.

The last set of design features are ***injection features***. These features comprehend the plastic cabinets and their design. These features are then subdivided into primary features and transition features. The primary features are the main design structures in a sketch of the cabinet while the transition features are the joining structures between two primary features.

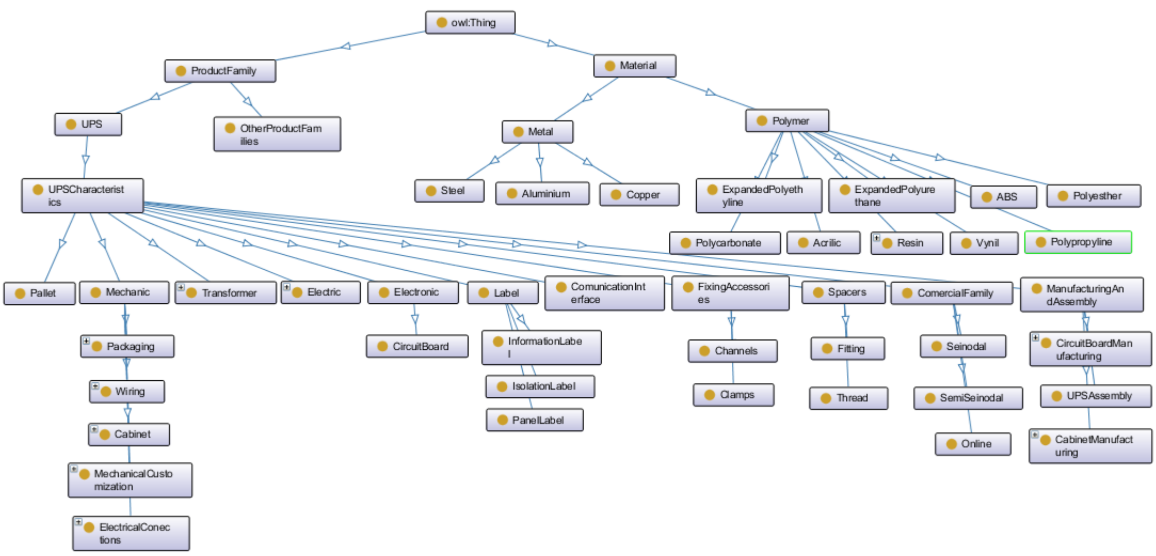
This separation of meta sheets and injection features happens because in Company`s “X” Portfolio there are products that have a metal cabinet and an injected plastic one.

The **Product Reference Ontology** formalises Company “X” product structures alongside with the information of the products families and the possible customisations that can be applied to the diverse families and the validation tests needed to approve the product to be released to the market. The Product Reference Ontology structure is divided into product family and materials (Figure 26).

The ***product family*** is divided into all product families of Company X; in this case, there are the UPS family and other product families. The UPS is then subdivided into the products’ characteristics such as its cabinet characteristics, transformer, electric, labels, communications interface, among other product characteristics.

The ***material*** class is divided into polymers and metals, as they are the only material classes that are used by Company X. the metal subclass comprehends steel, aluminium, and copper while the polymer comprehends some plastics, for example, ABS, polycarbonate, acrylic and some resins used to manufacture Company’s X products.

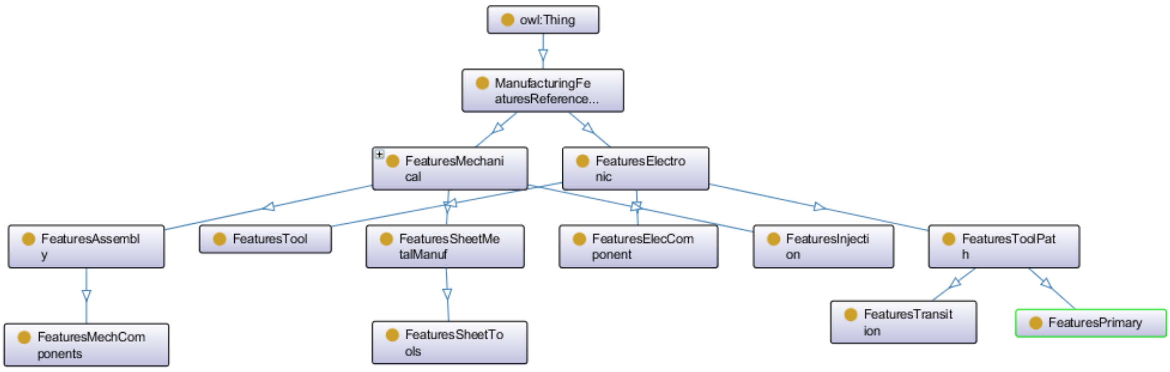
Figure 26 – Product Reference Ontology Structure.



Source: The author.

The **Manufacturing Feature Reference Ontology** formalises the manufacturing processes information in order to aid in the process planning and process optimisation, as shown in Figure 27.

Figure 27 – Manufacturing Feature Reference Ontology Structure.



Source: The author.

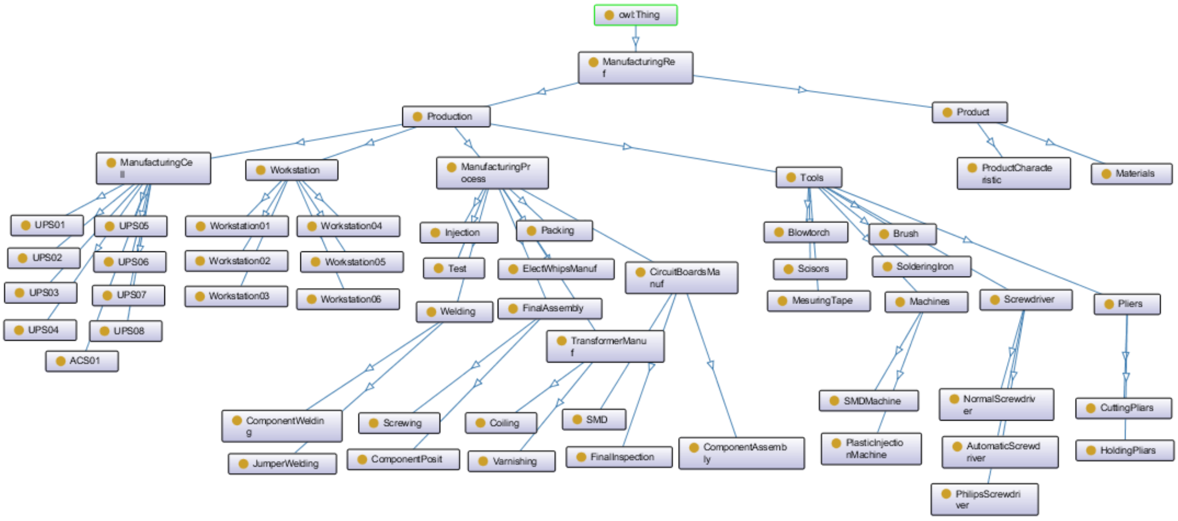
The structure of the Manufacturing Feature Reference Ontology shown in Figure 27, likewise the design features reference ontology, is divided into two different features structures: ***i)Electronic manufacturing features*** structures the electronic manufacturing information and ***ii) Mechanical manufacturing features*** structures the mechanical manufacturing information.

The Electronic feature structure is divided into the component manufacturing information and the electric path. It is worth noting that component manufacturing refers to the process of mounting the component into the circuit board and not to the component manufacturing process. The electric path has its manufacturing referred in the tool path feature structure.

Mechanical Manufacturing is divided into three types of features: the assembly features, the metal sheet manufacturing features, and the injection features. The tools structure refers to the tools needed for the manufacturing of each feature that will be formalised into this structure after the specialisation process.

The **Manufacturing Reference Ontology** formalises the manufacturing and workshop information of the studied enterprise. In this ontology, the information regarding tools, workstations, manufacturing cells, and manufacturing processes are structured to aid the process planning and control (Figure 28).

Figure 28 – Manufacturing Reference Ontology Structure



Source: The author.

5.3 FORMALIZED EXTERNAL KNOWLEDGE

During the Development Stage, many systems are used to support the product design, but as shown in Chapter 2 and 3, these systems must create information in their own language which generally cannot be understood by the other systems in the process, including the validation system presented in this Chapter.

The information gathered from these systems must be structured and formalised into a common structure. For this reason, a features taxonomy is applied and translates the gathered specialised information into common information that can be used. This formalised structure uses the Product Design Features Reference Ontology and the Product Design Reference Ontology.

In this experimental case, the information is gathered from three different sources: i) SolidWorks – Mechanical CAD environment; ii) Altium – Electronic CAD environment; iii) Tests Checklists and tools. In consequence, there was a need to develop tools that could efficiently and automatically translate the information from these sources.

For the mechanical CAD environment, a tool was developed in Microsoft Excel environment, where the information is automatically translated into the design features taxonomy and exported as a Comma-Separated Values (CSV) file, as it is a file format that can be read by the proposed system in the later stages of the experimental case.

The first step for the tool use is to export the information list from the CAD environment and input it into the computational tool, which will automatically translate the information into features. After that, using a visual basic application, the information is structured as a CSV file and exported to a specific folder inside the Company's server, where the SRIPDM system can access it.

For the electronic CAD environment, another tool was developed in a Microsoft Excel environment to extract the information and formalise it in the design features taxonomy and in the product manufacturing taxonomy. The information from the electronic CAD environment is extracted from a GERBER file because it is an open file format and, thus, can be read by the machines used in the manufacturing process. It is also the Company "X" procedure to export the electronic information as GERBER files. The Gerber file is composed of information regarding the tools required to print the circuit board and the tool path. The toolpath is translated into design features, and the tool is formalised into the manufacturing process taxonomy.

The Gerber file (Figure 29) is composed of a header and a body. The header contains information as the width of the electric path, the corner radius and which type of operation the electric path requires to be produced, while the body contains the coordinates for each of the segments that compose the electric path. These segments are broken into 2 sets of three coordinates (x,y,z), where the first three are the starting point and the last three the endpoint. In this way, the header of the file can be used to aid in the tool selection process, while the body is translated into primary electric design and transition features.

The computational tool developed for the electronic CAD environment operates like the mechanical CAD tool, automatically translating the information and exporting it as a CSV file to a specific folder inside the Company`s server.

The tests information translation uses another computational tool, also developed in a Microsoft Excel environment. The computational tool developed divides the tests and checklists into segments, such as mechanical, main circuit board, among others and presents each set according to the tests the design teams are running. The computational tool sets the test sequence inside each test set and standardises the test procedures in order to assure test repeatability. The test results are inputted into the computational tool, which, then structures the checklists and a CSV file that is exported into a specific folder of Company X's server (Figure 30).

Figure 29 – Example of a Gerber File.

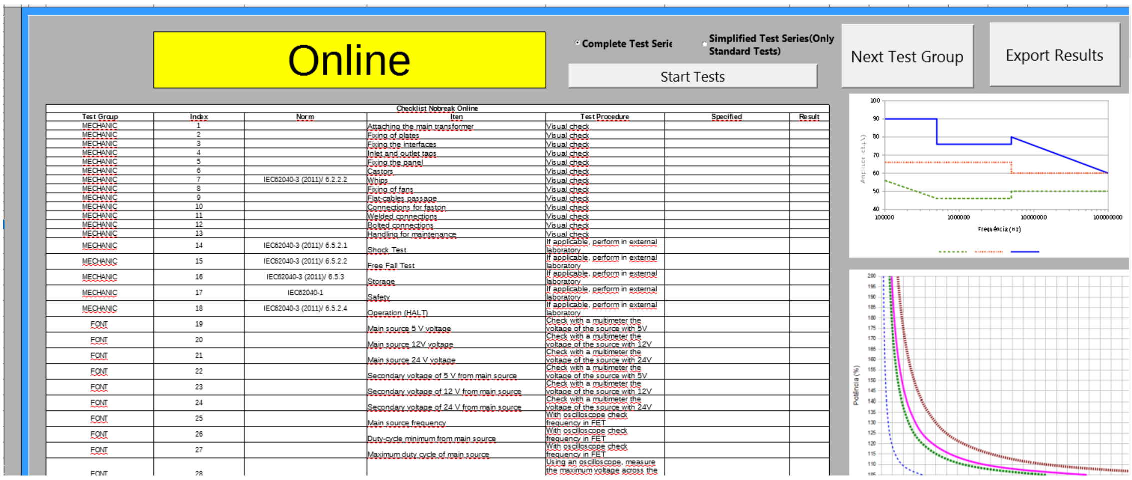
```
%ADD52ROUNDEDRECTD52*%
%ADD53R,0.05000X0.04000*%
G04:AMPARAMS|DCode=54|XSize=80mil|YSize=50mil|CornerRadius=7.5mil|HoleSize=0mil|Usage=FLASHONLY|Rot
%AMROUNDEDRECTD54*
21,1,0.08000,0.03500,0,0,180.0*
21,1,0.06500,0.05000,0,0,180.0*
1,1,0.01500,-0.03250,0.01750*
1,1,0.01500,0.03250,0.01750*
1,1,0.01500,0.03250,-0.01750*
1,1,0.01500,-0.03250,-0.01750*
%
%ADD54ROUNDEDRECTD54*%
%ADD55R,0.08000X0.07000*%
%ADD56R,0.06000X0.05000*%
G04:AMPARAMS|DCode=57|XSize=85mil|YSize=130mil|CornerRadius=8.5mil|HoleSize=0mil|Usage=FLASHONLY|Ro
%AMROUNDEDRECTD57*
21,1,0.08500,0.11300,0,0,180.0*
21,1,0.06800,0.13000,0,0,180.0*
1,1,0.01700,-0.03400,0.05650*
1,1,0.01700,0.03400,0.05650*
1,1,0.01700,0.03400,-0.05650*
1,1,0.01700,-0.03400,-0.05650*
%
```

Source: The author.

The developed tool reduces the test time since it automatically fills in the checklists used by Company “X”. It also creates a standard in which these checklists are filled in and, consequently, avoids ambiguities in the information when it is shared with the other activities and domains of the product development.

The computational tool was developed to aid the test process that can be used to fill the checklist, that is, it can do all the tests that the Company demands or complete only the necessary tests required by national and international standards. This functionality gives more flexibility to the research and development department, because when developing a “quick project”, the team can focus only on the relevant tests and deliver the product sooner without compromising its quality.

Figure 30 – Test Interface Application



Source: The author.

5.4 SEMANTIC RULES

Semantic rules, as discussed in Section 2.3, allows the construction of more complex relations and can be used to define more accurately the concepts in the ontology. So that, for the SRIPDM to be able to translate the design information into manufacturing information effectively, there is the need to insert complex relationship in the form of semantic rules.

However, these rules change according to the product that is being developed and as the product requirements are different, the rules used by each interaction of the product may not be the same and must be inserted into the specialised model for every single interaction. The SRIPDM must automatically make the process of taking the information gathered in the early stages of product development and choose the rules accordingly.

The semantic rules were modelled for each of the Company`s “X” product families and will be selected and inserted into the specialised model following each project requirements. Table 10 presents some of the rules developed and used in the experimental case.

Table 10 – Example of the Developed Semantic Rules.

Index	Rule Name	Syntax
1	Tool	Product(?x), HasProcess(?x,?y), HasTool(?y,?z) → HasTool(?x,?z)
2	Workshop/Tool	Workshop(?x), HasProcess(?x,?y), HasTool(?yz) → HasTool (?x,?z)
3	Product Family	Product (?x) ProductFamily (?y) HasPower (?x,?z) hasDimension (?x,?w) hasPower (?y, ?a) has Dimension (?y,?b) swrlb: lessThanOrEqual (?z, ?a) swrlb: lessThanOrEqual (?w,?b) → HasFamily (?x,?y)
4	Product Cost	Product(?x) HasCost(?x, ?y) HasFamíly(?x, ?z) HasCost(?z, ?w) swrlb:lessThanOrEqual(?y, ?w) → IsViableProduct(?x, “Yes”)
5	Process Cost	Product (?x) HasProcess(?x, ?y) Process(?y) HasCost (?y, ?z) HasCost (?x, ?w) swrlb:multiply(?a,?w, 0.30),swrlb:lessThan(?z,?a) - > IsViableProcess(?y,”Yes”)
6	Component Cost	Product (?x) HasComponent (?x, ?y) Component (?y) HasCost (?y, ?z) HasCost (?x, ?w) swrlb:multiply(?a,?w,

Index	Rule Name	Syntax
		0.50),swrlb:lessThan(?z,?a) - > IsViableComponent(?y,"Yes")
7	Power of Component	Product (?x) HasOutPower (?x, ?y) Component (?z) HasOutPower(?z, ?a) swrlb:lessThanOrEqual (?a, ?y) → IsViableComponent(?z, "Yes")
8	Battery/Product Autonomy	Product (?x) BatteryModule (?y) HasAutonomy (?y, ?z) → HasAutonomy(?x, ?z)
9	Power/Product Autonomy	Product (?x) HasOutPower(?x, ?y) BatteryModule (?z) HasAutonomy (?z, ?w) → HasAutonomy (?y, ?w)
10	Manufacturing Cell/Tool	ManufacturingCell (?x) HasWorkshop (?x, ?y) HasProcess (?y, ?z) HasTool (?z, ?w) → HasTool (?x, ?w)
11	Workshop/Component	Product (?a) HasComponent (?a, ?b) HasManufacturingCell (?a, ?c) HasWorkshop (?c, ?x)Workshop (?x) HasProcess(?x, ?y) HasProcess (?b, ?y)→ HasWorkshop (?b, ?x)
12	ElectricPath/Current	CircuitBoard (?a) hasElectricPath (?a, ?b)HasTension (?b, ?c) HasResistance (?b, ?d) swrlb:divide (?e, ?c, ?d)→HasCurrent(?b, ?e)
13	Consumer Requirements/Product Family	Product (?a) HasRequestedDimension (?a, ?b) HasRequestedPower (?a, ?c) ProductFamily (?x) HasDimension (?x, ?y) HasPower (?x, ?z) swrlb:lessThanOrEqual (?b, ?y) swrlb:lessThanOrEqual (?c, ?z) → HasFamily (?a, ?x)

Source: The author.

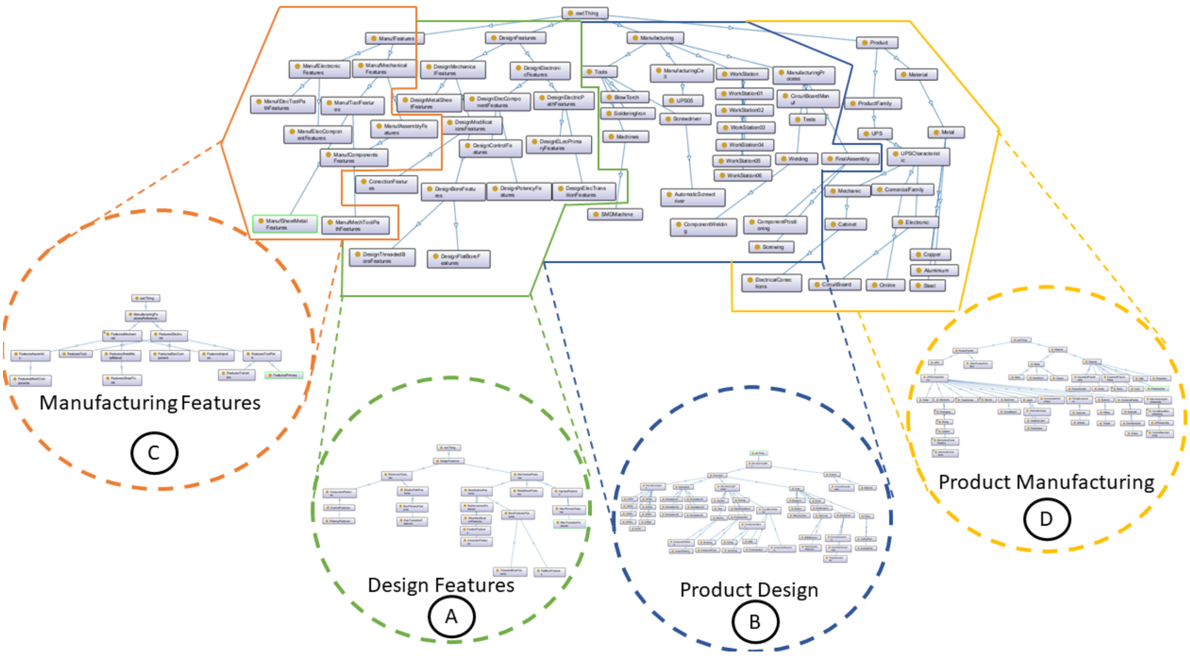
The developed rules address one or more of the domains represented by the reference ontologies, creating the relationships required for the creation of new knowledge, translate the information into the necessary domains and assure that the requirements of all the stages of the product development are respected during the conceptual stage of the product development.

5.5 ONTOLOGY MAPPING AND KNOWLEDGE TRANSLATION

In this step, the structure and company information formalised in the reference view is specialised in order to create an application ontology that will aid the product development process. Ontology mapping processes were made in the four reference ontologies for an optimised product development model. As shown in Section 4.3.1, the ontology alignment was the mapping process chosen, as it concatenates the relevant information and knowledge excluding the unnecessary information. Figure 31 shows the information and structures were taken from the reference ontologies and used to create the application ontology. Detail “A” shows the structure from the design features reference ontology used to create the application ontology, while Detail “B” demonstrated the knowledge extracted from the product design reference ontology. Detail “C” presents the features from the manufacturing features reference ontology and detail “D” the manufacturing information necessary for the product that is developed.

As can be seen in Figure 31, the injection features and related information (plastic materials, injection machines) were excluded from the creation of the application ontology. It occurs because the studied product has a metal cabinet and, therefore, plastic and related information are not relevant to the development of the product. Thus, to avoid ambiguities or misinformation across the product design and manufacturing, this information was left out of this application.

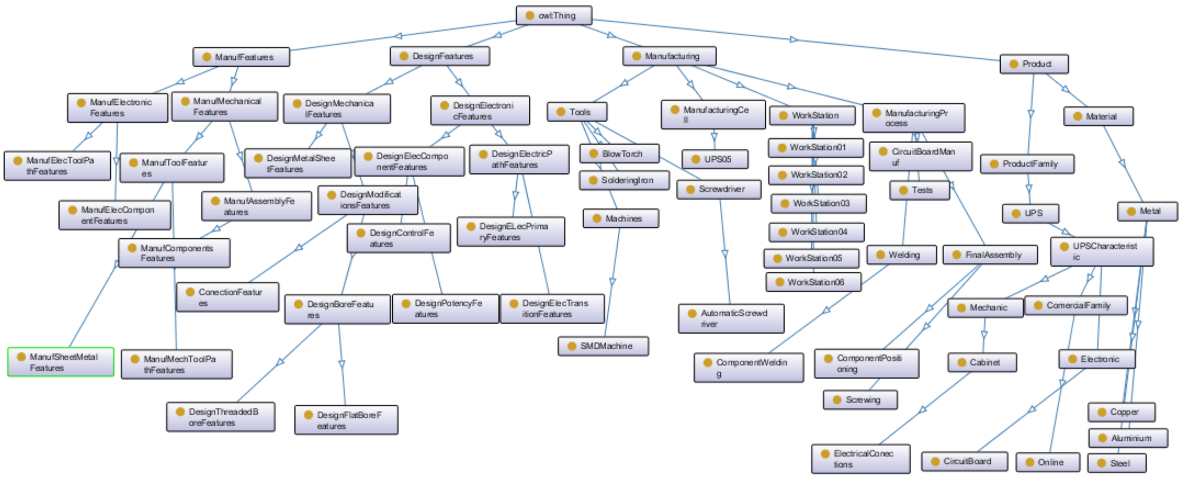
Figure 31 – Selection of the reference structures to create the application ontology.



Source: The author.

After the selection, a new ontology is developed by the system through an alignment process which structures the knowledge from the reference ontologies together, as shown in Figure 32. This new model is the application ontology that will aid in the product development process.

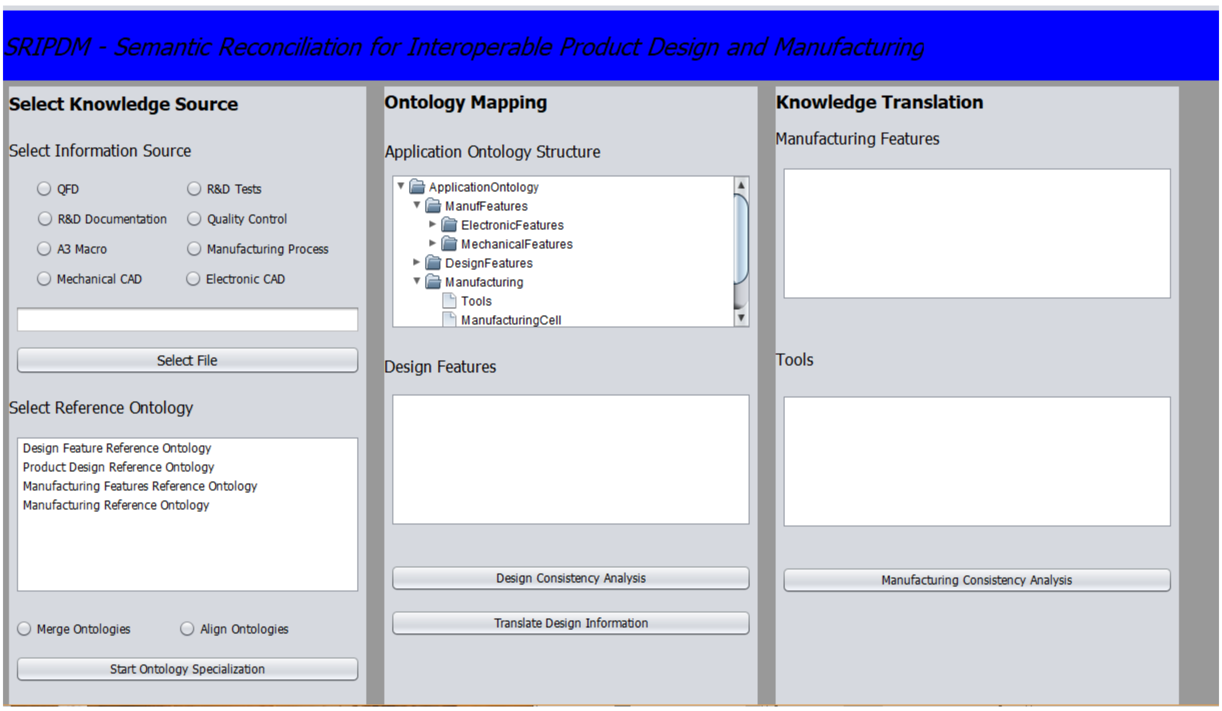
Figure 32 – Application Ontology Structure created for the 20kVAtriphase UPS.



Source: The author.

This ontology alignment is done in the backend of the experimental system. The user can decide which reference ontology will be used to create the application ontology and, in the sequence, the ontology mapping process is performed and, afterwards, the application ontology structure is shown to the user so he can check if the structure is coherent with the reference ontologies (Figure 33).

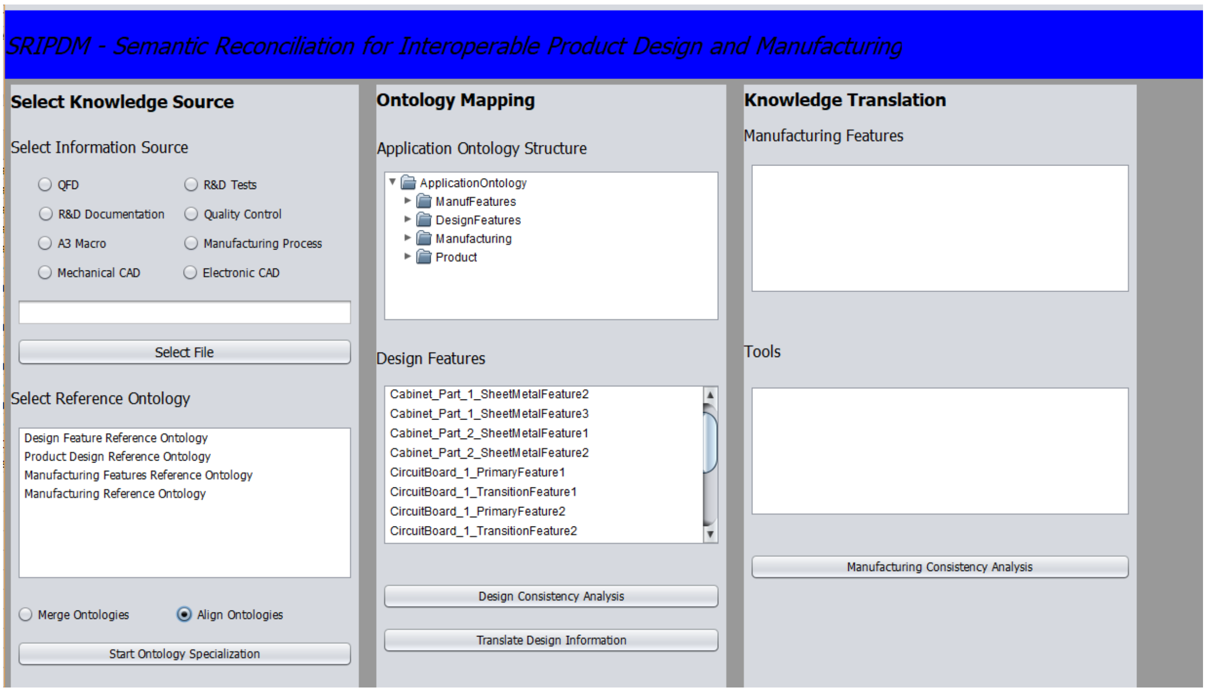
Figure 33 – The Experimental system's interface showing the application ontology structure.



Source: The author.

At this point, the application ontology does not contain the information of the product design yet. Therefore, the information gathered in Section 5.3 (Formalised External Knowledge) is inserted into the system which reads the data and formalises it into the application ontology. Figure 34 shows the experimental system with the design information inserted into the ontology.

Figure 34 - Experimental system with the design information inserted into the ontology.



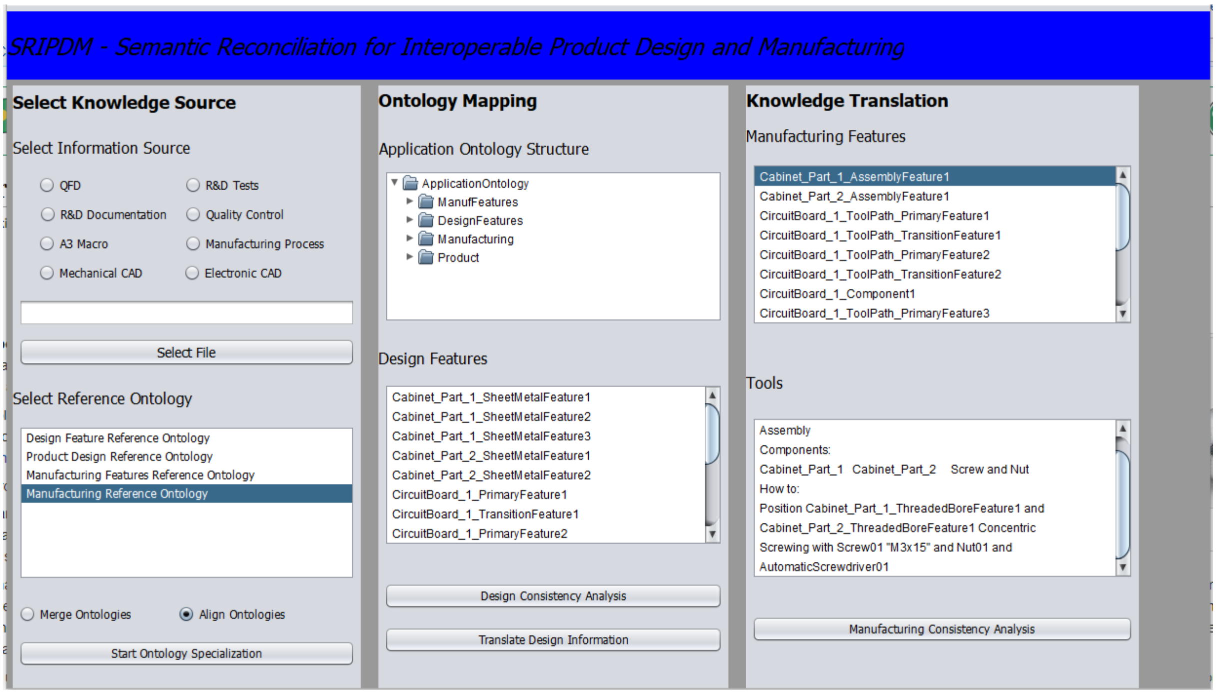
Source: The author.

The next step is divided into three activities that are simultaneously executed unless there is an error in one of these activities. It happens because these three stages are executed through the inference engine used. The first stage is a consistency analysis of the design information; that is, the proposed system checks if the design of the product, its components and structure are by Company`s “X” directives. The second stage translates the coherent design knowledge into manufacturing knowledge while the last stage checks if the manufacturing knowledge is consistent with Company X’s manufacturing capacity. Figure 35 presents how the SRIPDM shows the translated knowledge in its user interface.

A consistency check is run after the data insertion in the specialised model and the information translation into manufacturing features, and if there is inconsistency with the information, it must be corrected before going into the next stages of the product development. In the experimental case, there were no inconsistencies which lead product design to the next stage of development.

After the design is validated, a prototype is built according to the proposed manufacturing processes, and the tests needed can be carried out to validate the product under the Brazilian Government and the Company's standards. Afterwards, the information obtained from the test is inserted in the SRIPDM which shares the information with the quality control and the manufacturing information with the factory floor in order to assure that the test and manufacturing parameters are similar to guarantee the products' quality. With the correct information on the factory floor and quality control, the product`s mass production begins.

Figure 35 – Experimental System with translated design to manufacturing information.



Source: The author.

This Chapter explored the application of the Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM) approach that was conceptually proposed and developed in Chapter 4. The approach's application results and discussion will be present in the next Chapter.

6 RESULTS AND DISCUSSION

6.1 LITERATURE REVIEW RESULTS AND DISCUSSION

The Conceptual Background research made viable the identification of the relevant concepts and the problems of information and knowledge sharing in the product development process. Furthermore, the technologies used to aid in the solution, its applications, and limitations at the same time that indicated the need for greater understanding of them and led to the Systematic Literature Review and Content Analysis.

The Systematic Literature Review followed a careful methodology, depict in Chapter 3. The survey made in the Scientific Databases resulted in 1429 scientific articles, based on inclusion criteria such as keywords, abstract, and published period. Applying further exclusion criteria such as subject analysis and non-English written papers provided 182 articles that were closer to the research subject. These articles were examined and categorised according to defined criteria and resulted in 28 researches that were submitted to further investigation, on the Content Analysis.

The Systematic Literature overview showed that only 19% of the articles approach knowledge translation and share throughout several domains in a general matter or have the ability to have a generalist approach to these issues. These findings demonstrated that there were semantic reconciliation lacks across PDP and needs to be adequately addressed by the scientific academy to ensure the correct information and knowledge translation to reduce the misinterpretation and mistakes that happen during the PDP stages.

The 28 selected articles resulted from the Systematic Literature Review were submitted to a Regression Analysis and had a mathematical adherence of (adjusted r^2) 87% to the data. After ensuring the robustness of the selection for the research problem, a thorough investigation of the full content of each selected article was performed, pointing out the research contribution and limitation to the studied topics. This analysis answered the two questions of the 3.1.1 Section. The answer to the question 1- "*What are the recent relevant researches regarding the conceptual structure of information from multiple domains and its formalisation across PDP to support the decision-making process?*" were the research of Ahmad, Wynn and Clarkson (2013), Bruun et al. (2015), Caetano et al. (2017), Cardoso and Bussler

(2011), Chungoora and Young (2011), Goel et al. (2012), Imran and Young (2015), Jiang, Peng and Liu (2010), Monticolo et al. (2014), Peng et al. (2017), Ruiz et al. (2017), Witherell et al. (2013) and Zhang et al. (2017).

The researches conducted by Ahmad, Wynn and Clarkson (2013), Bruun et al. (2015), Caetano et al. (2017), Cardoso and Bussler (2011), Goel et al. (2012), Huang and Huang (2013), Jiang, Peng and Liu (2010), Jiao et al. (2009), Li et al. (2017), Monticolo et al. (2015), Pasqual and de Weck (2012), Peng et al. (2017), Rahmani and Thomson (2012), Ruiz et al. (2017), Tchoffa et al. (2016), Tessier and Wang (2013), Tian and Voskuijl (2015), Witherell et al. (2013), Xie and Ma (2015) and Zhang et al. (2017) were the answer to the question 2 of the 3.1.1 Section – " *What are the recent relevant researches regarding the semantic reconciliation process across PDP to support the decision-making process?*".

The Systematic Literature Review and Content Analysis provided a solid theoretical foundation, showing that mistakes have been identified in product requirements across the product development process due to the knowledge translation process. Moreover, there is a necessity for more research on information translation and sharing across different stages of the product development process and their domains without any loss of meaning and intent.

Although there is an increase in research concerning the use of computational tools aligned with ontological approaches to translate the information between the relevant domains, the semantic reconciliation across multiple domains and the product development process still has very little development since the majority researches focused on specific domains and specific activities of the PDP.

Unquestionably, systematic literature review and content analysis provided a comprehensive perspective about the issues to be addressed in the research field regarding knowledge translation and semantic reconciliation across general multiple domains and encompassing the entire product development process. Additionally, both of them supported substantially with the creation of the proposed approach of Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM).

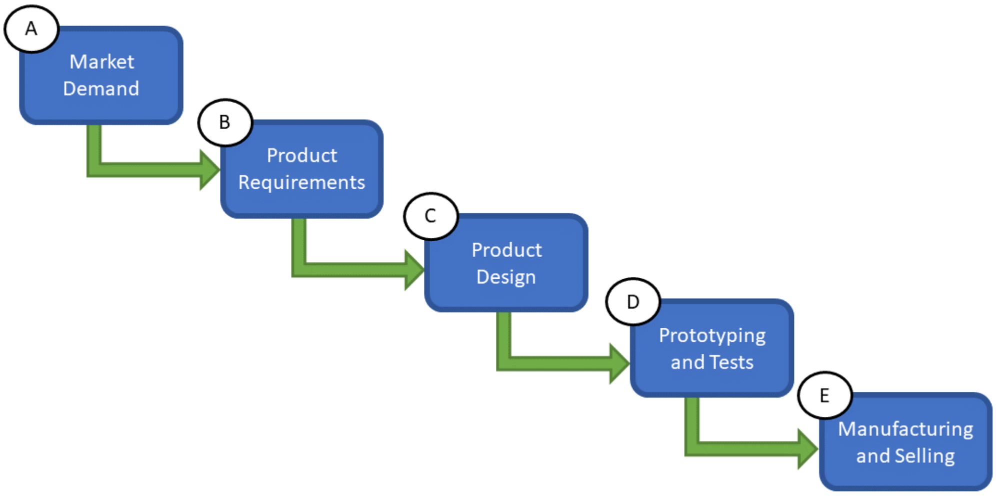
6.2 APPROACH AND EXPERIMENTAL CASE RESULTS AND DISCUSSION

This research has focused on the development of an approach for interoperable product design and manufacturing, which can effectively gather, translate and share information across the different domains and stages of the product development and manufacturing and, also, aid in the quality and productivity control of the production processes. The proposed conceptual approach of Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM) was structured in three main Stages and explored the semantic reconciliation approach to integrate the product development process using computational tools to translate and share information across its stages. Its application confirms that it creates a truly integrated environment where the information and knowledge generated in each stage of the product development process are shared with the later stages. The use of the DFMA approach in the design of the product allows the manufacturing requirements to be considered as restrictions, assuring that the product that is being developed will have a feasible production but do not sacrifice its quality.

The SRIPDM was developing using Protégé 5.2.0 to develop the reference view ontologies. Coolbeans 8.2.0 was used in association with Apache JENA to develop the user interface and main functionalities of the system. A GERBER file was used to export information from the electronic CAD environment because it is the file used in the Company X and in this way, it could be read by the machines used in the manufacturing process of the company. The mechanical structure was exported in a text file (.txt), and the test information was exported as a CSV file. The formalisation processes were made in a Microsoft Excel environment that structured the information from these sources and converted them into CSV files and saved them in a folder inside Company's X server that the SRIPDM could access and input into the specialised ontology

The application of the proposed approach changed the linear way that Company X used to perform the product development and manufacturing process to an integrated environment. In the previous linear approach, the marketing team would identify the market demands for new solutions and products (Figure 36 – Detail A), and then these demands were translated into product requirements by the research and development department (Figure 36 – Detail B). Next, these requirements were used to design a product (Figure 36 – Detail C), and in the sequence, a prototype was built and validated through tests (Figure 36 – Detail D) and finally, after the validation process the product would be manufactured and released to the market (Figure 36 – Detail E).

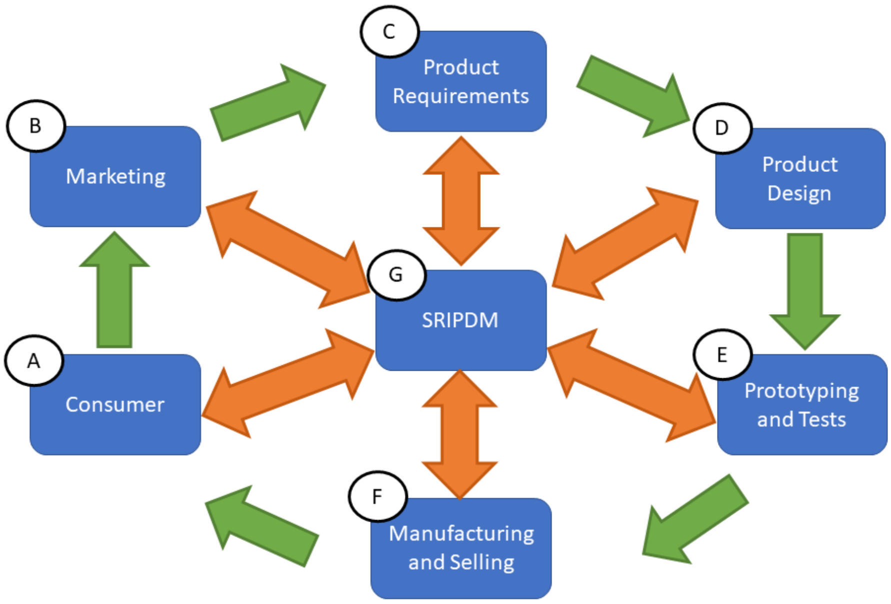
Figure 36 – Previous Product Development Process for Company X



Source: The Author.

The proposed approach of Semantic Reconciliation for Interoperable Product Design and Manufacturing (SRIPDM) uses a cyclical approach, as illustrating in Figure 37. In the SRIPDM (Figure 37 - Detail G), all the information and activities (represented by the orange arrows) from one development process stage are used as input to the next one (represented by the green arrows), that is, all information is an input, from early stages to further down of the development process.

Figure 37 – New approach to product development for Company "X".



Source: The Author.

This new approach begins with the continuous interaction from the Marketing Department (Figure 37 - Detail B) with the Consumer (Figure 37 - Detail A) in order to have continuous feedback about demands for new products and/or solutions for one that is already on the market. The information acquired in these interactions is inserted in the SRIPDM and aids the Marketing Department (Detail B) to analyse the relevant information about the market demands and compare with the Company's design and manufacturing capabilities to provide a market demand compatible with the Company's production reality. The information resulted from this phase is available in the SRIPDM (Detail G) for sharing with the other phases.

The Research and Development Department is responsible for the next three stages. Firstly, they create the Product Requirements (Figure 37 – Detail C) using the knowledge about the market demands from the Marketing shared through the SRIPDM (Detail G) alongside the information pertinent to this phase. The product strategies and costs are also defined in this phase as well as they are validated with the aid of the SRIPDM. The information produced in this stage can be shared with both previous and next ones. Next, the SRPIDM (Detail G) will share the product requirements defined in the previous stage and will provide the manufacturing restrictions that will be used as input to the new Product Design (Figure 37 – Detail D), which optimises the manufacturing processes and consequently reduces the product cost. These restrictions and requirements are processed in the SRIPDM (Detail G), which verifies the information and send warnings to the Design Team if there is any incoherency about the requirements and manufacturing processes. The information gathered in this phase is also available in the SRIPMD (Detail G) for sharing. In the next stage of prototyping and testing of the design, the SRIPDM (Detail G) shares all the information gathered in the market and the knowledge of the factory floor, which in turn aids in generating more realistic results and increasing the products' quality (Figure 37 – Detail E).

The processes have more agility and are faster performed in the manufacturing and assembly stage because the early stages used the SRIPDM shared information and took in account the restrictions of the processes into the product design (Figure 37 – Detail F). Finally, the proposed SRIPDM has the task of controlling the production processes. It uses the analysis of processes issues and quality control feedback allied with consumer demands to aid the development of new and better products, closing and starting the development cycle again.

This change in approach improved significantly the product' quality while reducing development time and cost, as shown in Table 11. The total development time has decreased from 18 to 12 months, that is, a reduction of 1/3 in the development time, possibly due to the reduction of 3 to 0 the number of reworks. The application of the SRIPMD saved about US$ 11.000,00 (eleven thousand American Dollars) in the product total cost.

Another value that demonstrates the improvement in the product design and manufacturing is the return rate of the 20 kVA triphase UPS in warranty time has a significant decrease, from 25% to 10%, after the SRIPDM implementation. Moreover, there is a rate of problems due to the manufacturing errors that decreased from 10% to 5%.

Table 11 – Comparison between the development of the product without the support of the experimental system and with the support of the experimental system

	First Version	Current Version
Total Development Time	18 months	12 months
Total Development Cost (R$)	131,360.00	87,574.00
Quantity of Reworks	3	0
Return in Warranty	25%	10%
Product Problems due to Manufacturing Errors	10%	<5%

Source: The Author.

The experimental case showed that the proposed SRIPD has limitations, for example, the ontology mapping process could be done automatically, respecting each project and product family characteristics but had to be manually done as there was not enough information and data to apply an artificial intelligence

As the development stage compromises circa 80% of the cost of a product, it is the most critical stage of the product design and manufacture, and the experimental case approaches it. However, the other two stages ought to be topics for future research.

The application of the proposed approach through an experimental case in a technology-based company provided a useful understanding of its potentials and limitations, contributing to the detection of new perspectives for its improvements in future works.

6.3 ACADEMIC RESEARCH RESULTS

This research published six articles, which are:

I. SZEJKA, A. L.; LEITE, A. F. C. S. M.; CANCIGLIERI, M. B.; CANCIGLIERI JUNIOR, O. Structuring a Foundation Basis for Semantic Interoperability in Product Development Process. In: Borsato, M., Wognum, N., Peruzzini, M., Stjepandić, J., Verhagen, W.J.C. (Org.). **Transdisciplinary Engineering: Crossing Boundaries**. 1ed.Amsterdam: IOS Press BV, 2016, v. 4, p. 957-966.

This article encompassed the creation of PDP ontologies that offers semantic capabilities from which new ontology-based models can be specialised; This paper aided this research by presenting a structure of product development information that would be used as a basis for the Reference ontologies used in the validation case

II. LEITE, A. F. C. S. M.; CANCIGLIERI, M. B.; SZEJKA, A. L.; CANCIGLIERI Jr., O. The Reference View for Semantic Interoperability in the Integrated Product Development Process: The Conceptual Structure for Injecting Thin-Walled Plastic Products. **Journal of Industrial Information Integration**, 2017.

This article explores the structuring of Core Ontologies, which can be used as a knowledge base and aid product development. This paper dwelled further in the creation of the reference ontologies and, as the previous paper, aided this research by structuring the information of the product development and manufacturing that would be the basis for the reference ontologies of the validation case.

III. LEITE, A. F. C. S. M.; CANCIGLIERI, M.B.; SZEJKA, A. L.; CANCIGLIERI JR, O.; ANNUNZIATTO, R. A Discussion on Current Issues for Semantic Interoperability in an Integrated Product Development Process; **IFIP Advances in Information and Communication Technology**. 2018.

This article encompasses a study of the current issues regarding the application of ontology-driven interoperability for Product Development and Manufacturing. It provides sustenance to a proposal of an ontology-driven semantic reconciliation approach and aims to use ontology mapping techniques to aid the product design and manufacture processes knowledge share;

IV. CANCIGLIERI, M. B.; LEITE, A. F. C. S. M.; SZEJKA, A. L.; CANCIGLIERI JR, O; ANNUNZIATTO, R. An Approach to Semantic Interoperability for Product Development through Automatic Requirement Extraction and Semantic Reconciliation. **IFIP PLM Conference 2019**. 2019

This article proposes to apply semantic interoperability concepts and tools to develop an interoperable environment that can efficiently represent and translate knowledge between different stages of the product development process and analyse the consistency of the created knowledge;

V. LEITE, A. F. C. S. M.; CANCIGLIERI, M. B.; SZEJKA, A. L.; CANCIGLIERI JR, O. A Knowledge Extraction Model for Semantic Interoperability in an Integrated Product Development Process. **ISPE Conference on Transdisciplinary Engineering**. 2019.

This article encompasses the automatic knowledge and information extraction, formalisation and the translation process they are submitted so they can be understood by the design teams without ambiguities;

VI. CANCIGLIERI, M. B.; LEITE, A. F. C. S. M.; SZEJKA, A. L.; CANCIGLIERI JR, O; An approach for Dental Prosthesis Design and Manufacturing through Rapid

Manufacturing Technologies. **International Journal of Computer Integrated Manufacturing**. 2019.

This article encompassed the design and manufacturing process to develop a dental prosthesis and the information conversion between activities alongside the formalisation of the product requirements and its sources. Although the application area is different from this research, the paper aided in the identification and formalisation of product requirements in order to share them across the stages of product development and manufacturing without ambiguities and errors.

7 CONCLUSION AND FUTURE RESEARCH

The approach proposed and developed in this research, the Semantic Reconciliation Approach for Interoperable Product Design and Manufacturing (SRIPDM), creates an interoperable product design and manufacturing environment In this interoperable environment, the knowledge from each domain and stage of the design and manufacturing processes is translated, converted and shared without ambiguities throughout the whole processes and which in turn increases the products quality and reduces its development time and costs.

A thorough theoretical foundation made evident that in the product development exist a wide range of information that must be effectively translated and shared across different stages of the product development process and their domains. The translation and sharing must be without any loss of meaning and intent and misinterpretation. The mistakes in product requirements across the PDP occur, in the majority of the cases, because of the unclearness in the knowledge translation process.

The systematic literature review and content analysis provided a comprehensive understand view of the scientific subject addressed on each studied paper to identify the potential contributions and limitations to support semantic reconciliation. The whole process of the literature analyses led to the key scientific topics explored in this research field that was the mapping, via sets of semantic mechanisms, of heterogeneous information relationships from multiple domains concerning Product Design and Manufacturing to translate the knowledge of the product development process and its knowledge domains. The analyses substantially supported the creation and development of the proposed approach of an interoperable environment during the three stages of the product development process, through the information translation, conversion, and sharing.

The conceptual of the SRIPDM proposed in this research brings a holistic view to all the stages of the product development as it automatically gives insights and restrictions from the later activities to the early stages of the PDP. It, also, assures the consistency of the knowledge and information created during the product development since it uses the ontologies relationships and hierarchical structures to verify the information created, warning the design teams if any error occurs.

The proposed SRIPDM approach acts in the three main stages of the product development process. In the Pre-Development stage, the proposed approach enhances the market information, gathering process, translating and sharing this information with the design, marketing, and manufacturing teams. Also, in this stage, it aids in the creation of the product strategy that will guide the further stages of the process. In the Development stage, the proposed approach aids in the product design by supplying the design team with information and restrictions from the manufacturing process. Consequently, the design of the product has assured its feasible manufacturing. Additionally, the translation of design information in manufacturing information allows for an optimised process planning, which reduces costs and time without sacrificing the product`s quality. In the last stage, the Post Development, the proposed approach aids in the control of the critical variables of the process ensuring the quality of the process and the product and saves user feedback to aid in the development of new products.

The proposed SRIPMD used ontology mapping methods to aid the creation of a single ontology project that brings together all the knowledge, information and data used and generated during the products development and manufacturing. It assures that restrictions and requirements from latter stages of the development are used in the proper activities, reducing reworks on the product design and, consequently, reduces costs and development time. It also aids in creating an optimised product design which increases product quality. Another vantage of the proposed approach is that the information can be accessed by everyone involved in the processed, and the information is automatically translated and consequently eliminates understanding errors that can thwart the product development process.

The application of the SRIPDM through an experimental case in a Technological Base Company validated the research because the change from the linear approach used by the Company to a cyclical one proposed by the author reduced in 1/3 of the development time. Furthermore, it provided an economy of US$11.000,00 in the product’ total cost and reduced in at least 50% the error in the manufacturing process.

The application confirmed the potential of the SRIPMD to improve product quality and reduce the cost and time of design and manufacturing, even though it required several steps to extract and formalise the information increasing, in the short term, the complexity of the activities and processes. It has also confirmed that besides the data limitations that required manual interactions within experimental SRIPDM it is able to implement an interoperable environment in the Company that is capable of efficiently translated and shared the information and knowledge across product design and manufacturing processes in a real world.

The research question - **“*Is it possible to develop an approach that allows for the semantic reconciliation of information which can efficiently translate, convert and share the information across the Integrated Product Development and Manufacturing and its domains?*”** has been explored through the application of concepts from integrated product development and semantic interoperability in the development of the proposed the Semantic Reconciliation System for Interoperable Product Design and Manufacturing (SRIPDM) approach that through the use of computational tools for the extraction, translation and share of information and knowledge can aid in the product development and manufacturing planning, integrating activities and reducing development time and costs.

Therefore, the answer to the question is Yes; it can be affirmed that it is possible to develop an approach that allows for semantic reconciliation of information since the developed SRIPMD approach assured the translation, conversion and sharing of the information across the product development and manufacturing alongside its domains, improving the product quality and significantly reducing the cost and time of its design and manufacturing. Thus, even if the preliminary results have shown promise, the author believes that it is essential to continue developing this approach so that it should be applied and tested on more complex product development and this will be the object of future exploration.

7.1 FUTURE RESEARCH

For future research, the author suggests:

- the application of artificial intelligence algorithms to support the mapping process in order to automatize it as it was shown as a limitation of this research in Section 6.2. As it was presented in Chapter 5 and Section 6.2, most mapping methods applied in this research had to be done manually, due to program limitations and the lack of data to program an artificial intelligence algorithm, for example, neural networks, and decision tree. etc., to obtain a precise application ontology. Thus, it is suggested as future research to dwell deeper in this limitation in order to create a truly automatized interoperable environment.

- to evaluate the efficiency of the approach in the other two stages that were not studied in this research (pre-development and post-development); As presented in Chapter 5, the validation case approached only the development stages and did not evaluate the efficiency of the proposed approach in the other two stages of the product development process. Thus, it is suggested as future research, the application of the proposed approach on the pre and post-development stage and evaluate its capability to support the product development process in its entirety.
- Apply the proposed approach in the development of the different kind of products or family of the products. The validation case approached only a technology enterprise, more specifically, a UPS manufacturer. Thus, it is suggested as future research the application in enterprises of different segments or products of the same segment in order to evaluate the efficiency of the proposed approach in different contexts.

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APPENDIX A - TABLE OF CLASSIFICATION OF THE 172 SELECTED ARTICLES

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
1	Abdul-Ghafour et al. (2014)	x			x		
2	Abele et al. (2017)	x	x	x	x		
3	Adagha; Levy and Carpendale (2017)	x			x		
4	Afshari and Peng (2015)	x	x		x		
5	Ahmad; Wynn and Clarkson (2013)	x	x			x	
6	Ahmed-Kristensen and Storga (2009)	x	x		x		
7	Ai et al. (2011)	x	x		x		
8	Aksulu and Wade (2011)	x			x		
9	Al Presher (2012)	x			x		
10	Al-Zaher; ElMaraghy and Pasek (2013)	x			x		
11	Albers et al. (2007)	x	x	x	x		

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
12	Barbieri et al. (2008)	x			x		
13	Baxter et al. (2007)	x			x		
14	Belardinelli et al. (2008)	x				x	
15	Belaud et al. (2014)	x	x		x		
16	Berkovich et al. (2014)	x	x		x		
17	Berkovich; Leimeister and Krcmar (2011)	x	x	x	x		
18	Bertolino et al. (2017)	x	x		x		
19	Bonesso; Comacchio and Pizzi (2011)	x			x		
20	Bragge; Tuunanen and Marttiin (2009)	x			x		
21	Brunsmann et al. (2012)	x			x		
22	Bruun et al. (2015)	x	x			x	
23	Cabrera et al. (2010)	x			x		
24	Cabrera; Woestenenk and Tomiyama (2011)	x				x	
25	Caetano et al. (2017)	x	x			x	

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
26	Caldwell et al. (2010)	x	x		x		
27	Cao; Li and Ramani (2011)	x	x		x		
28	Cardoso and Bussler (2011)	x	x			x	
29	Chandrasegaran et al. (2013)	x	x	x	x		
30	Chen (2010)	x	x			x	
31	Chen et al. (2016)	x	x	x	x		
32	Chen; Chen and Chu (2009)	x	x	x			x
33	Chen; Wang and Huang (2014)	x			x		
34	Chong et al. (2011)	x				x	
35	Chu et al. (2013)	x			x		
36	Chungoora and Young (2011)	x	x	x			x
37	Crilly (2015)	x	x		x		
38	Crilly and Cardoso (2017)	x			x		
39	Cui et al. (2008)	x	x		x		
40	Curtis; Hancock and Mattson (2013)	x	x		x		
41	Danilovic and Browning (2007)	x	x	x	x		
42	Dartigues-Pallez et al. (2007)	x	x	x			x

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
43	Dayan; Ozer and Almazrouei (2017)	x	x		x		
44	Demoly and Roth (2017)	x				x	
45	Demoly et al. (2011)	x	x		x		
46	Demoly; Matsokis and Kiritsis (2012)	x	x			x	
47	Dentsoras (2009)	x				x	
48	Di Guardo and Harrigan (2016)	x	x		x		
49	Edmunds et al. (2011)	x				x	
50	ElMaraghy et al. (2012)	x	x		x		
51	ElMaraghy et al. (2013)	x	x		x		
52	Fan et al. (2008)	x	x	x	x		
53	Fernandes et al. (2011)	x			x		
54	Fu et al. (2013)	x			x		
55	Fu et al. (2015)	x	x	x	x		
56	Gao et al. (2015)	x	x	x	x		
57	Gao et al. (2013)	x	x		x		
58	George (2013)	x			x		
59	Gerow; Grover and Thatcher (2016)	x			x		

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
60	Ghobadi and D'Ambra (2012)	x	x	x	x		
61	Goel et al. (2012)	x	x			x	
62	Grimshaw and Burgess (2014)	x	x		x		
63	Ducellier; Yvars and Eynard (2014)	x			x		
64	Hallstedt and Isaksson (2017)	x			x		
65	Hamraz et al. (2015)	x			x		
66	Harris; Collins and Hevner (2009)	x			x		
67	He; Hou and Song (2015)	x				x	
68	Hehenberger et al. (2013)	x			x		
69	Hehenberger et al. (2010)	x				x	
70	Helo et al. (2010)	x				x	
71	Hincapié et al. (2014)	x	x	x	x		
72	Hirunyawipada; Paswan and Blankson (2015)	x			x		
73	Hisarciklilar and Boujut (2009)	x			x		
74	Holley; Jankovic and Yannou (2014)	x	x	x	x		
75	Horváth and Vroom (2015)	x			x		

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
76	Huang and Huang (2013)	x	X	x		x	
77	Ihme et al. (2014)	x	X		x		
78	Imran and Young (2015)	x	X			x	
89	Jia et al. (2012)	x			x		
80	Jiang; Peng and Liu (2010)	x	X			x	
81	Jiao et al. (2009)	x	X			x	
82	Kamuriwo and Baden-Fuller (2016)	x	X		x		
83	Karlsson and Taylor (2010)	x			x		
84	Kettunen (2009)	x	X		x		
85	Kim and Gil (2015)	x	X		x		
86	Knudsen and Srikanth (2014)	x	X	x	x		
87	Komoto and Masui (2014)	x	X		x		
88	Kortelainen and Mikkola (2015)	x	X	x	x		
89	Koufteros; Vickery and Dröge (2012)	x				x	
90	Kung et al. (2015)	x	X	x	x		
91	La Rocca and Van Tooren (2012)	x	X	x		x	

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
92	Le Duigou et al. (2016)	x	X	x	x		
93	Lee and Suh (2009)	x			x		
94	Leithold et al. (2015)	x			x		
95	Li et al. (2017)	x	X			x	
96	Li; Zhao and Tong (2017)	x	X	x			x
97	Lina and Harding (2007)	x			x		
98	Linsey; Wood and Markman (2008)	x	X	x	x		
99	Liu; Wang and He (2016)	x	X		x		
100	Lu and Xu (2017)	x			x		
101	Lu and Xu (2017)	x			x		
102	Lyu; Chu and Xue (2017)	x	X		x		
103	Ma et al. (2007)	x				x	
104	Macher et al. (2015)	x			x		
105	Mak and Shu (2008)	x			x		
106	Mark; Lyytinen and Bergman (2007)	x			x		
107	Mirtalaie et al. (2017)	x	X		x		
108	Mohan; Jain and Ramesh (2007)	x	X	x	x		

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
109	Mokhtarian; Coatanéa and Paris (2017)	x			x		
110	Monticolo et al. (2015)	x	X	x		x	
111	Monticolo et al. (2014)	x	X			x	
112	Nagel et al. (2010)	x	X		x		
113	Neghab et al. (2015)	x			x		
114	Nowacki (2010)	x			x		
115	Pasqual and de Weck (2012)	x	X			x	
116	Pee; Kankanhalli and Kim (2010)	x	X		x		
117	Penciuc et al. (2016)	x				x	
118	Peng et al. (2017)	x	X	x		x	
119	Primus (2017)	x			x		
120	Purday (2012)	x	X	x	x		
121	Qamar; Wikander and During (2015)	x	X		x		
122	Qin et al. (2016)	x			x		
123	Raghupathi et al. (2015)	x	X		x		
124	Rahmani and Thomson (2012)	x	X	x			x

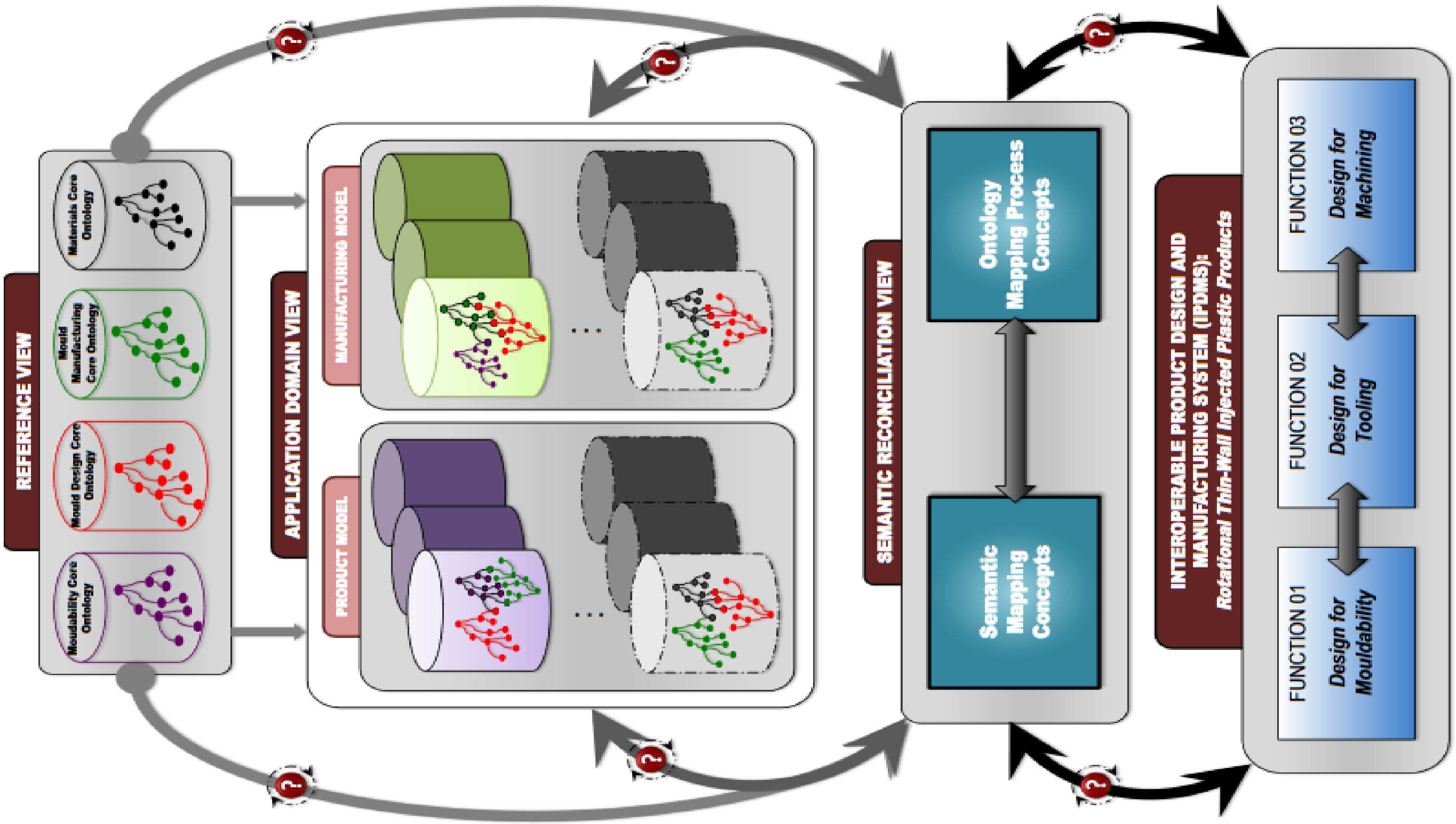
Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
125	Rayyaan; Wang and Kennon (2014)	x	X		x		
126	Revilla and Rodríguez (2011)	x	X	x	x		
127	Rio; Reyes and Roucoules (2013)	x				x	
128	Riou and Mascle (2009)	x	X		x		
129	Rodríguez et al. (2017)	x			x		
130	Ruiz et al. (2017)	x	X	x		x	
131	Rusák; Horváth and Mandorli (2013)	x	X	x			x
132	Salgueiredo and Hatchuel (2016)	x	X		x		
133	Sartori; Pal and Chakrabarti (2010)	x				x	
134	Sen et al. (2010)	x			x		
135	Shao; Liu and Li (2015)	x	X		x		
136	Shu (2010)	x	X		x		
137	Sommer et al. (2014)	x			x		
138	Sommer; Rao and Koh (2017)	x	X		x		
139	Stark et al. (2010)	x			x		
140	Suter (2013)	x			x		
141	Tamr; Lehtl and Rosi (2008)	x			x		

Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
142	Tang et al. (2010)	x	X	x	x		
143	Tchoffa et al. (2016)	x	X				x
144	Tessier and Wang (2013)	x	X	x			x
145	Thune and Gulbrandsen (2017)	x				x	
146	Tian and Voskuijl (2015)	x	X	x		x	
147	Trifunovic et al. (2015)	x	X		x		
148	Uddin et al. (2016)	x	X		x		
149	Umeda et al. (2012)	x	X	x	x		
150	van Beek and Tomiyama (2012)	x			x		
151	Van der Auweraer; Anthonis and Leuridan (2013)	x			x		
152	Vandevenne et al. (2015)	x			x		
153	Vandevenne; Pieters and Duflou (2016)	x	X		x		
154	Wang; Guo and Lee (2014)	x	X		x		
155	Witherell et al. (2013)	x	X	x			x
156	Wu et al. (2013)	x			x		

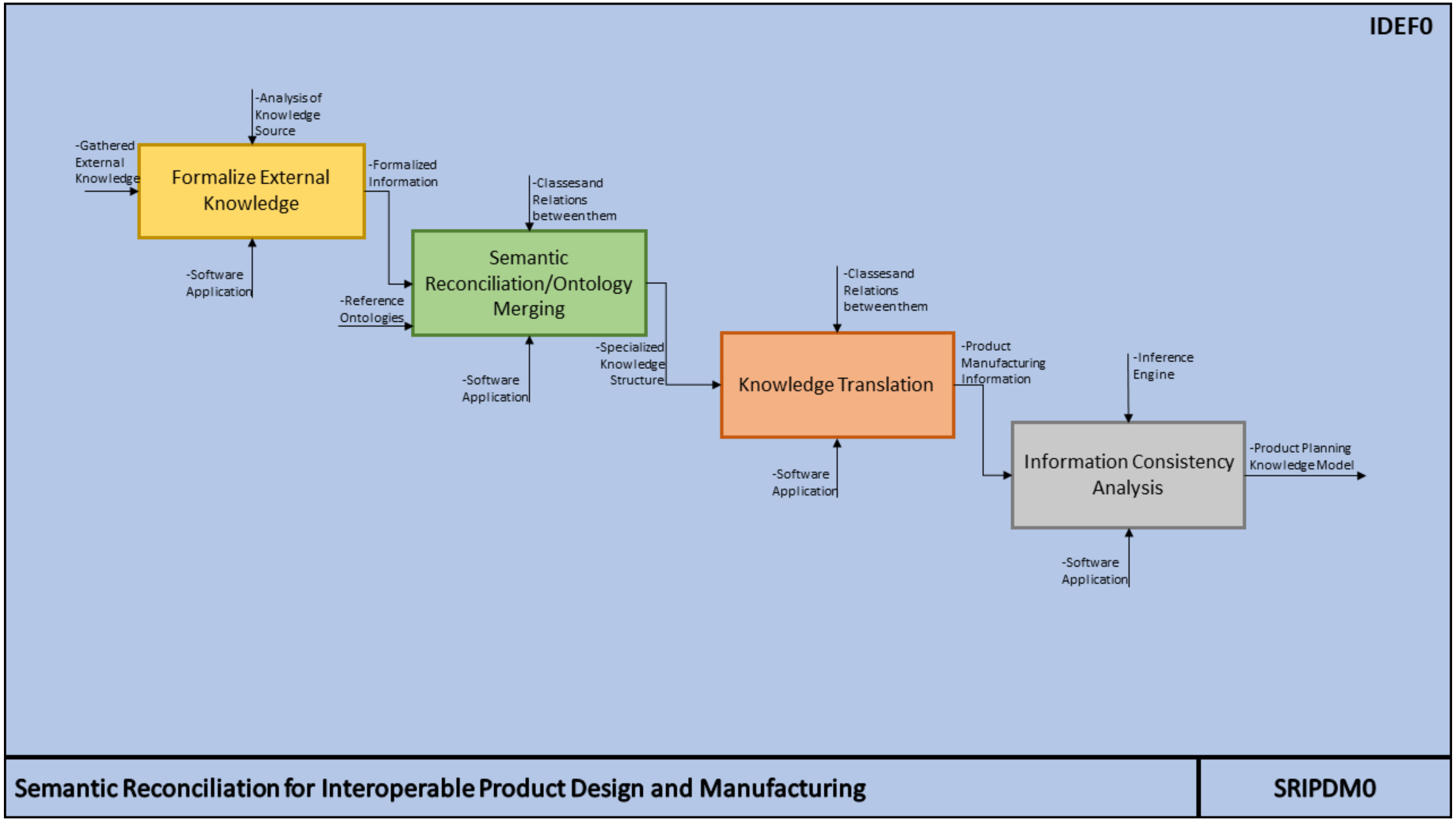
Authors and Year		Multiple Domains Issues			Semantic Reconciliation Issues		
		D1	D2	D3	SR1	SR2	SR3
157	Wu et al. (2015)	x			x		
158	Wu; Leu and Liu (2010)	x				x	
159	Xie and Ma (2015)	x	X			x	
160	Xu and Musicant (2016)	x	X		x		
161	Yan et al. (2010)	x	X		x		
162	Yang et al. (2015)	x	X	x	x		
163	Yang et al. (2015)	x			x		
164	Yassine; Chidiac and Osman (2013)	x	X			x	
165	Yin et al. (2015)	x	X		x		
166	Yoon et al. (2017)	x			x		
167	Zhang et al. (2017)	x	X	x		x	
168	Zhang et al. (2017)	x			x		
169	Zhang et al. (2012)	x			x		
170	Zhang et al. (2014)	x	X		x		
171	Zhang et al. (2010)	x	X		x		
172	Zhu; Jayaram and Kim (2011)	x	X			x	

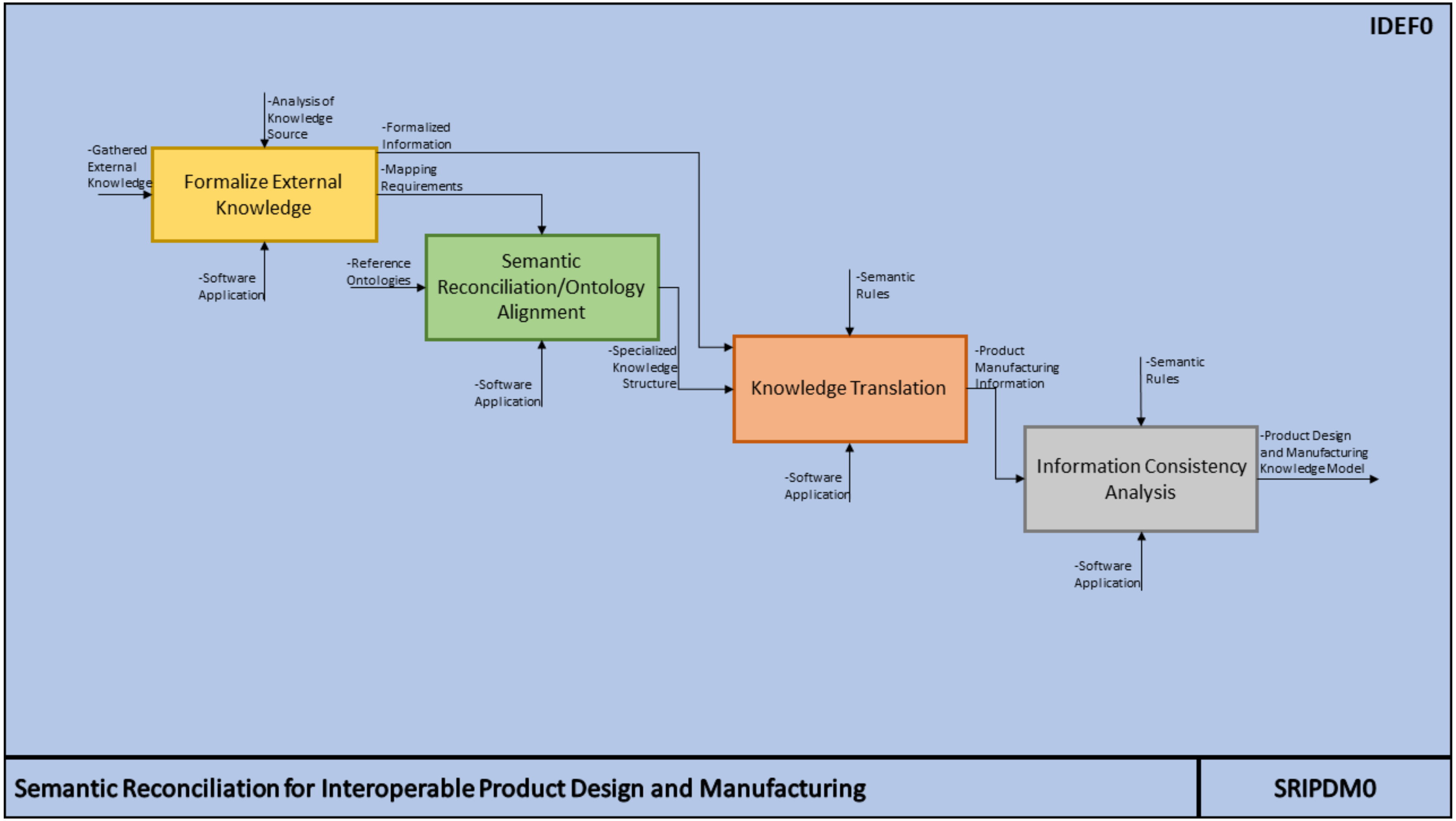
Source: The author.

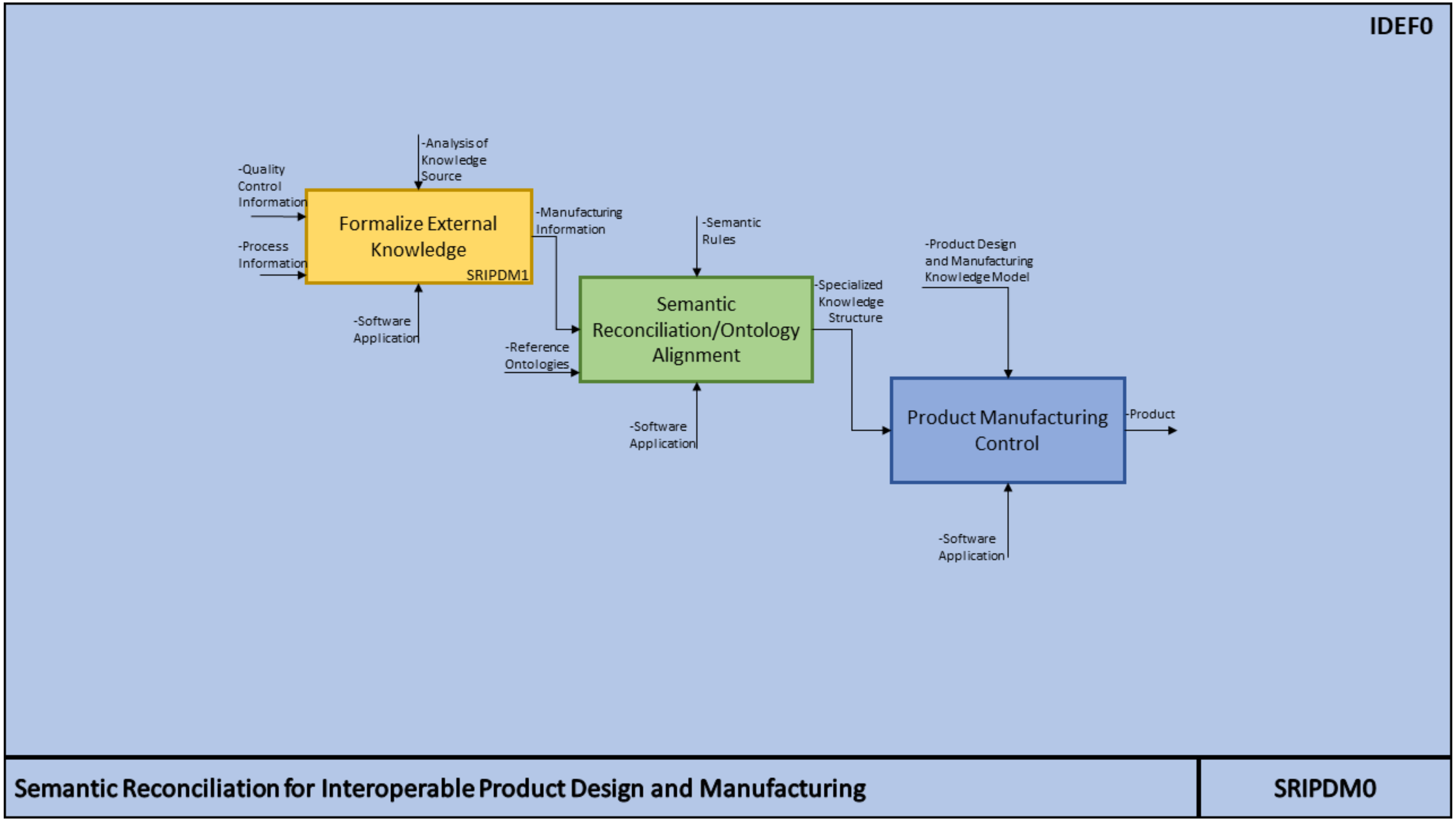
APPENDIX B – CONCEPTUAL FRAMEWORK FOR SEMANTIC INFORMATION INTEROPERABILITY IN PRODUCT DESIGN AND MANUFACTURING



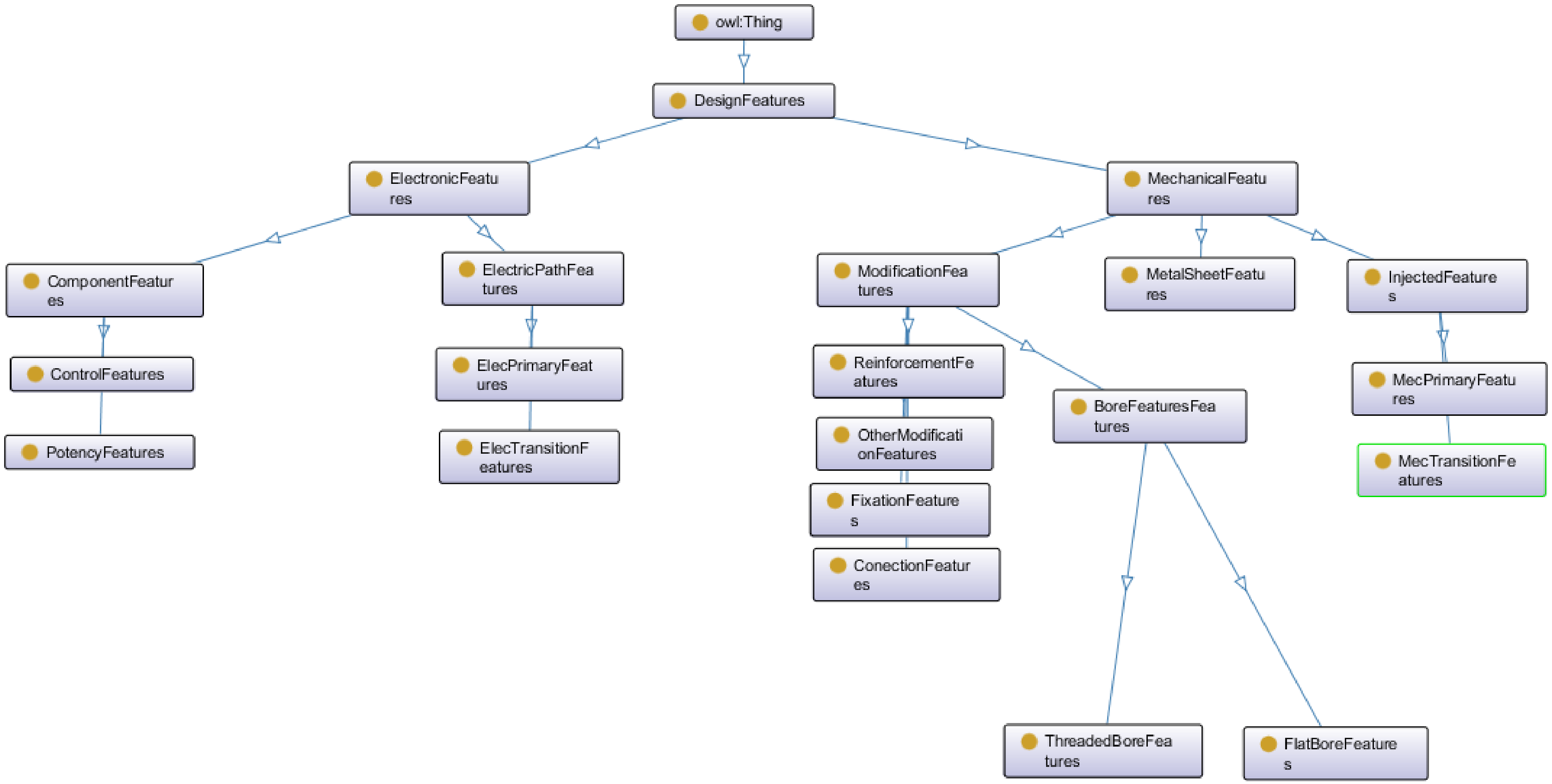
APPENDIX C – IDEF0 DIAGRAMS OF THE PRE-DEVELOPMENT, DEVELOPMENT AND POST-DEVELOPMENT PROCESSES

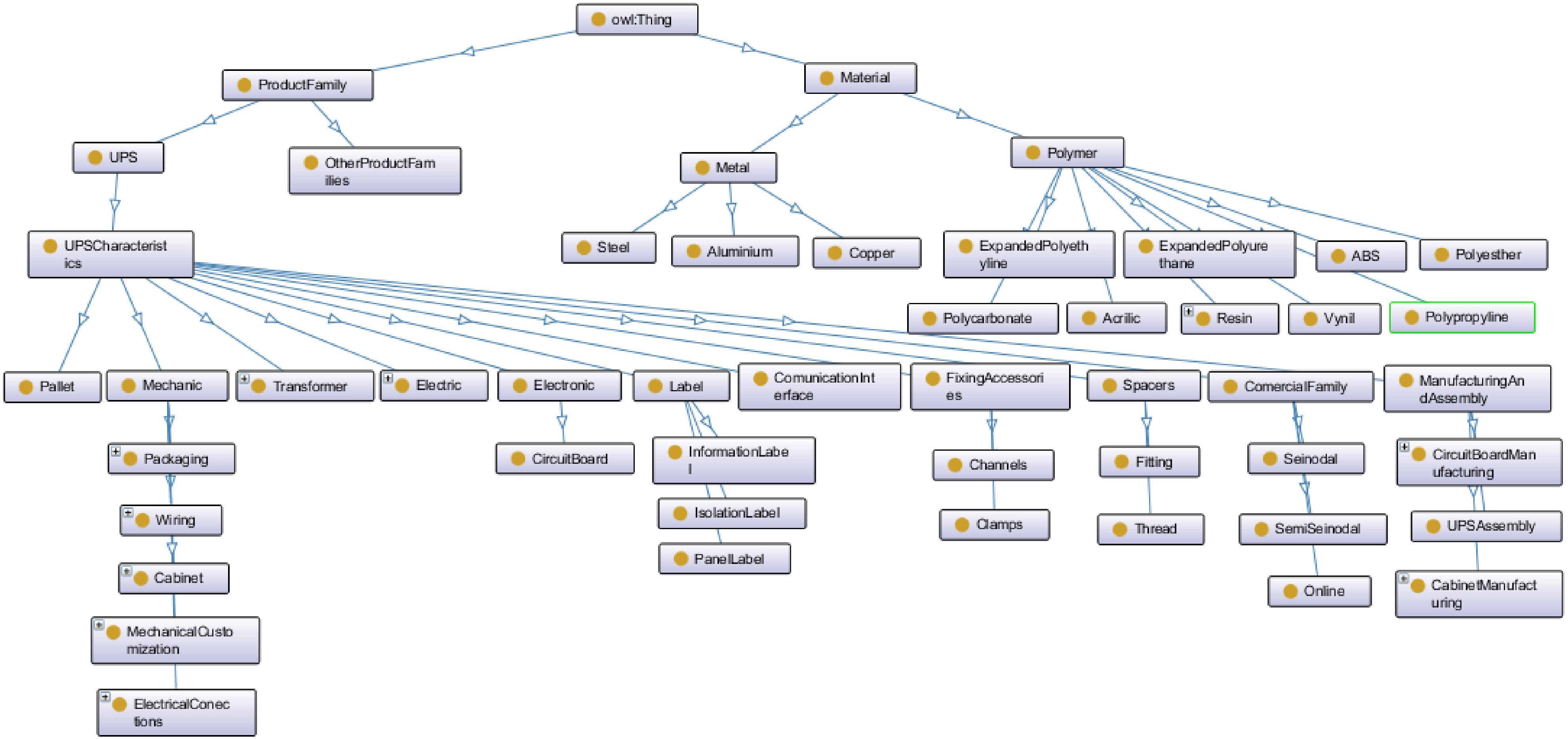



IDEF0
-Analysis of Knowledge Source
-Gathered External Knowledge
Formalize External Knowledge
-Formalized Information
-Mapping Requirements
-Software Application
-Reference Ontologies
Semantic Reconciliation/Ontology Alignment
-Software Application
-Specialized Knowledge Structure
-Semantic Rules
Knowledge Translation
-Software Application
-Product Manufacturing Information
-Semantic Rules
Information Consistency Analysis
-Product Design and Manufacturing Knowledge Model
-Software Application
Semantic Reconciliation for Interoperable Product Design and Manufacturing
SRIPDM0


IDEF0
-Analysis of Knowledge Source
-Quality Control Information
-Process Information
Formalize External Knowledge
SRIPDM1
-Software Application
-Manufacturing Information
-Semantic Rules
-Reference Ontologies
Semantic Reconciliation/Ontology Alignment
-Software Application
-Specialized Knowledge Structure
-Product Design and Manufacturing Knowledge Model
Product Manufacturing Control
-Product
-Software Application
Semantic Reconciliation for Interoperable Product Design and Manufacturing
SRIPDM0

APPENDIX D – CASE ONTOLOGIES

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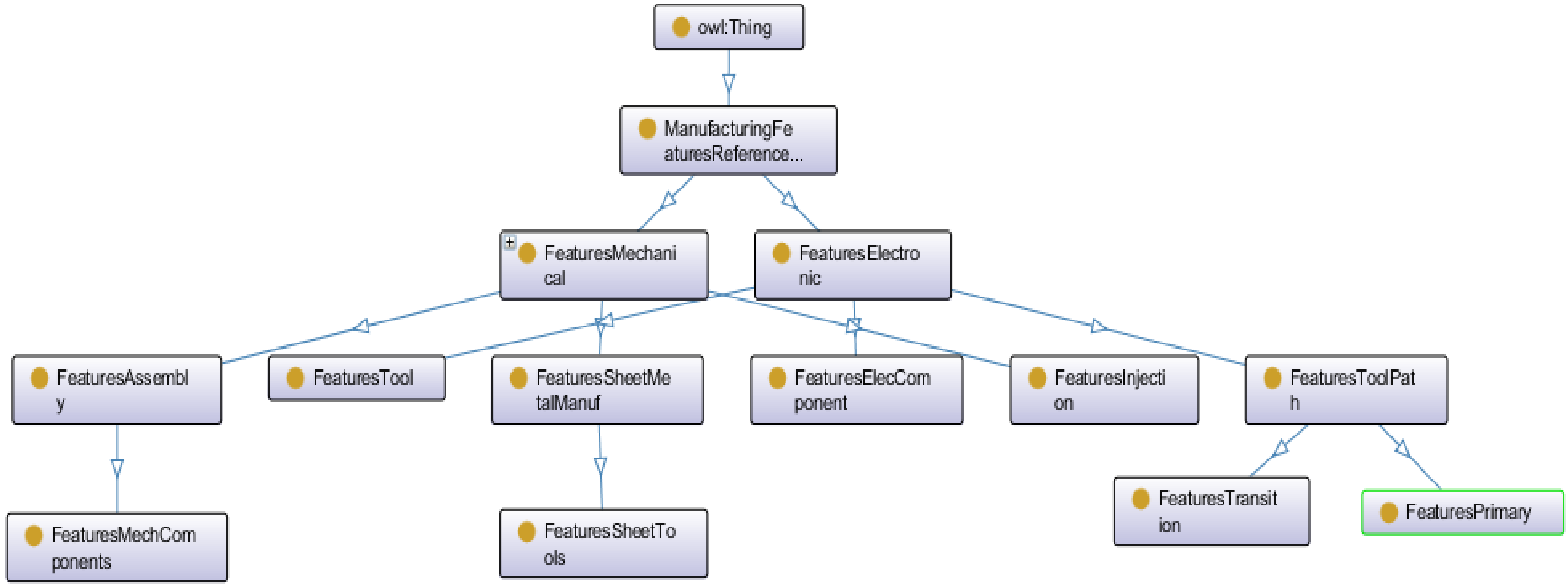
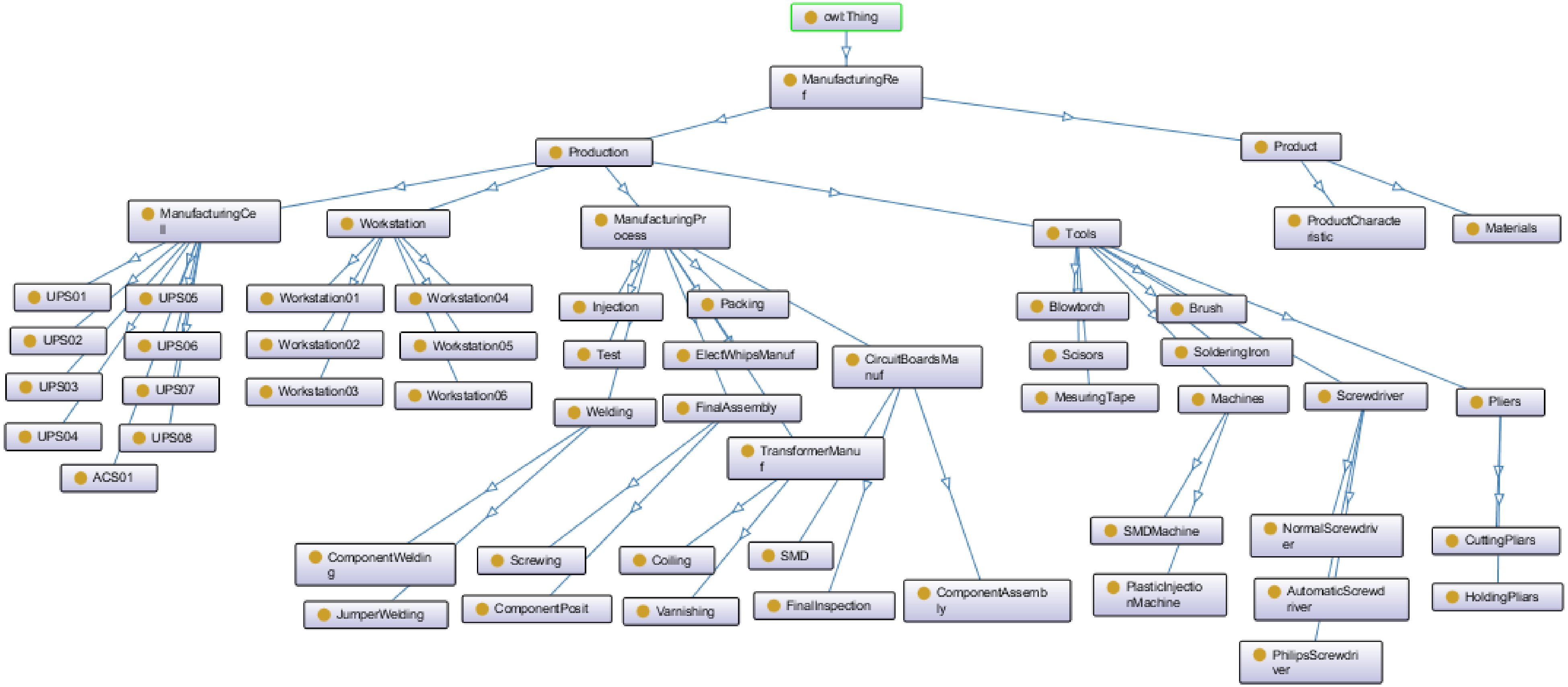
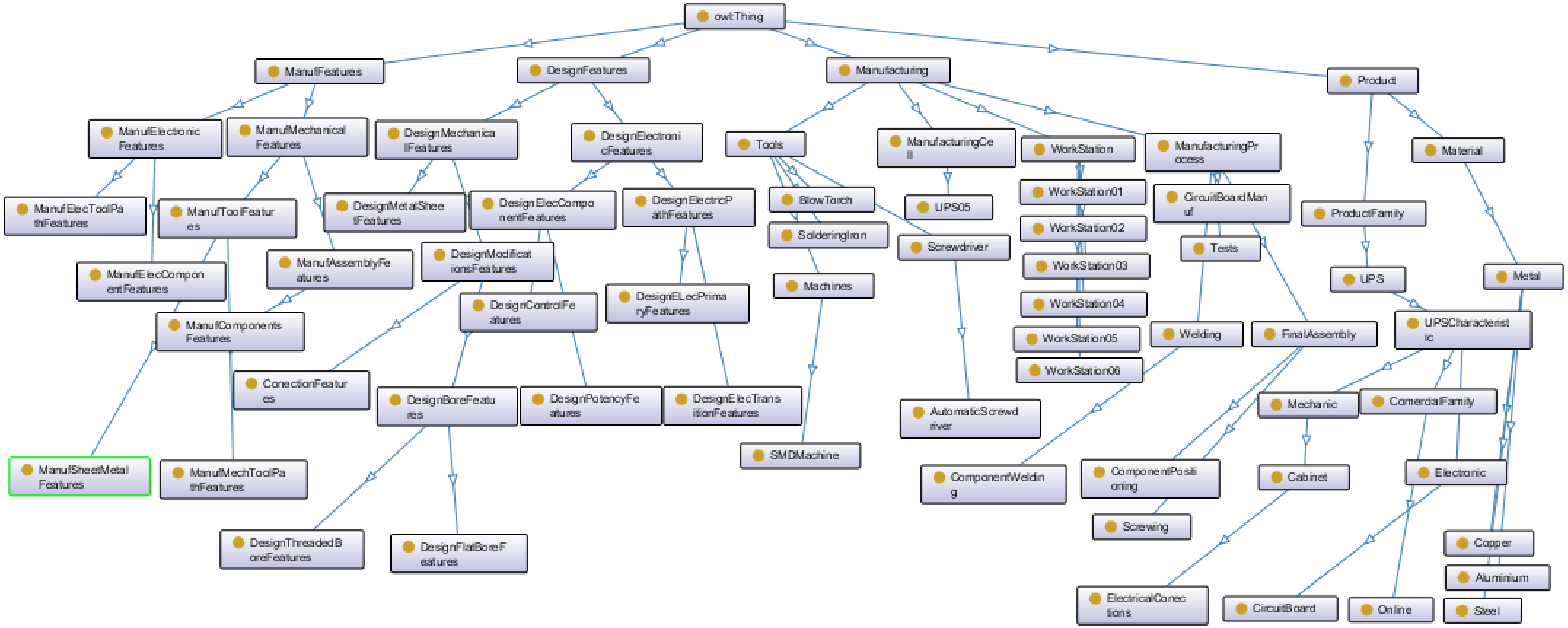
ProductFamily
Material
UPS
OtherProductFamilies
Metal
Polymer
UPSCharacteristics
Steel
Aluminium
Copper
ExpandedPolyethyline
ExpandedPolyurethane
ABS
Polyesther
Polycarbonate
Acrilic
Resin
Vynil
Polypropyline
Pallet
Mechanic
Transformer
Electric
Electronic
Label
ComunicationInterface
FixingAccessories
Spacers
ComercialFamily
ManufacturingAndAssembly
Packaging
CircuitBoard
InformationLabel
Channels
Fitting
Seinodal
CircuitBoardManufacturing
Wiring
IsolationLabel
Clamps
Thread
SemiSeinodal
UPSAssembly
PanelLabel
Cabinet
Online
CabinetManufacturing
MechanicalCustomization
ElectricalConections


owl:Thing
ManufacturingFe
aturesReference...
FeaturesMechani
cal
FeaturesElectro
nic
FeaturesAssembl
y
FeaturesTool
FeaturesSheetMe
talManuf
FeaturesElecCom
ponent
FeaturesInjecti
on
FeaturesToolPat
h
FeaturesMechCom
ponents
FeaturesSheetTo
ols
FeaturesTransit
ion
FeaturesPrimary


owl:Thing
ManufacturingRef
Production
Product
ManufacturingCell
Workstation
ManufacturingProcess
Tools
ProductCharacteristic
Materials
UPS01
UPS05
Workstation01
Workstation04
Injection
Packing
Blowtorch
Brush
UPS02
UPS06
Workstation02
Workstation05
Test
ElectWhipsManuf
CircuitBoardsManuf
Scisors
SolderingIron
UPS03
UPS07
Workstation03
Workstation06
Welding
FinalAssembly
MesuringTape
Machines
Screwdriver
Pliers
UPS04
UPS08
ACS01
TransformerManuf
SMDMachine
NormalScrewdriver
CuttingPliars
ComponentWelding
Screwing
Coiling
SMD
PlasticInjectionMachine
AutomaticScrewdriver
HoldingPliars
JumperWelding
ComponentPosit
Varnishing
FinalInspection
ComponentAssembly
PhilipsScrewdriver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ManufFeatures
DesignFeatures
Manufacturing
Product
ManufElectronic Features
ManufMechanical Features
DesignMechanicalFeatures
DesignElectronicFeatures
Tools
ManufacturingCell
WorkStation
ManufacturingProcess
Material
ManufElecToolPathFeatures
ManufToolFeatures
DesignMetalSheetFeatures
DesignElecComponentFeatures
DesignElectricPathFeatures
BlowTorch
UPS05
WorkStation01
CircuitBoardManuf
ProductFamily
SolderingIron
Screwdriver
WorkStation02
Tests
ManufElecComponentFeatures
ManufAssemblyFeatures
DesignModificationsFeatures
Machines
WorkStation03
UPS
Metal
DesignControlFeatures
DesignELecPrimaryFeatures
WorkStation04
ManufComponents Features
WorkStation05
Welding
FinalAssembly
UPSCharacteristic
WorkStation06
ConectionFeatures
DesignBoreFeatures
DesignPotencyFeatures
DesignElecTransitionFeatures
AutomaticScrewdriver
Mechanic
ComercialFamily
SMDMachine
ManufSheetMetal Features
ManufMechToolPathFeatures
ComponentWelding
ComponentPositioning
Cabinet
Electronic
Screwing
DesignThreadedBoreFeatures
DesignFlatBoreFeatures
Copper
Aluminium
ElectricalConections
CircuitBoard
Online
Steel