製品ライフサイクルマネージメントへの持続可能性の導入：意味論的アプローチ

Bringing Sustainability to Product Lifecycle Management: a Semantic Approach

by

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Abstract

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Abstract: The global manufacturing industry has faced continuing challenges over recent years to improve manufacturing performance and sustainability. Markets, as well as regulations and self-consciousness, have driven enterprise-wide initiatives that favour environment-friendly activities. Yet, the challenge to harmonize current manufacturing practices with on-going sustainability efforts remains. In order to be effective, manufacturing systems, in the context of the Integrated Enterprise (IE), require semantic representations of engineering information that are machine-readable, as opposed to the tradition of engineering drawings and textual documents still dominant throughout a product's lifecycle. One way for implementing the concept of IE is through intensive and extensive application of models in the corporate environment. An alternative way of representing enterprise models is through the use of formal ontologies. Ontologies are rather adequate structures for the representation of business models because through their well-defined semantics they are able to define attributes and relationships with differing levels of formality. The main goal of the present research is three-fold: (i) to develop an ontology that can ensure knowledge capture and sharing, so that information can be exchanged amongst distinct people and systems during a product's life-cycle; (ii) to develop a reference ontology that may ultimately be used to overcome interoperability issues between engineering and business applications and facilitate the use of sustainability data throughout a product's lifecycle; and (iii) to develop an ontology to be applied for obtaining energy efficiency indicators related to designed products that use commonly used manufacturing processes. For that purpose, the present research was conducted as a sequence of three phases. In the first phase, an ontology that captures knowledge of the various domains that compose the product lifecycle context was built. In the second phase, PLM concepts previously captured in the first step were extended and connected to sustainability-related concepts, extracted from numerous sources, from ISO standards to sustainable design practices, to produce an ontology that can be used as interlingua, for communicating relevant information between heterogeneous environments. In the third phase, based on the previous ontologies, the determination of energy efficiency built upon product and process data was demonstrated by means an instantiating a proposed ontology.

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Chapter 1: Introduction

Motivation

The global manufacturing industry has faced continuing challenges over recent years to improve manufacturing performance and sustainability. There are a number of reasons for this, including the deep-rooted approaches of traditional engineering, the changing landscape of global manufacturing, and the relatively slow adoption of IT innovations in the production environment [1].

In a continuous effort to adapt, survive and thrive, a third industrial revolution, proclaimed by the Economist magazine in April 2012, is taking place the form of digitization in manufacturing. It follows the first industrial revolution, which began in Britain in the late 18th century with the mechanization of the textile industry, and the second industrial revolution, when Henry Ford introduced mass production in the early 20th century [1].

In Europe, Germany has launched what it proclaims to be the fourth industrial revolution (or *Industry 4.0*), following the use of mechanization, electricity, and information technology. It promises to transform industrial production by the creation of "Smart Factories" and turn manufactured goods into "Smart Products" based on the broad adoption of cyber-physical systems (CPS). *Industry 4.0* is expected to emerge by the use of technological innovations in information technology, analytics, automation engineering, and other emerging technologies [2].

Industry 4.0 assumes that industrial production in the future will be characterized by a high degree of customization of products, supported by highly flexible, reconfigurable and agile manufacturing operations, easily adaptive to changes in market demands and customer requirements. It is also expected to work collaboratively with other factories and suppliers. Therefore, manufacturing transparency, in the form of seamlessly exchanging information and resources across and between Smart Factory networks, is a key concept [1].

Smart manufacturing systems require semantic representations of engineering information that are machine-readable. However, the tradition of engineering drawings and textual documents still dominate engineering practice throughout a product's lifecycle. Computer generated drawings (e.g. using computer-aided drafting systems) and rich-text files (e.g. using modern word processing systems with graphics) are still the means by which much of the information is communicated to through-life engineering services. This then requires human reading and interpretation, which are error prone and time consuming [2].

Smart manufacturing systems demand augmented, three-dimensional (3D), geometric models; and, rich-text files are to be replaced by information models of products and processes. These alternatives enable machine readability, which results in fast and error-free processing of engineering information from beginning to end of a product's lifecycle.

The vision of totally digitally-driven design, production, and product support environment became an important driver of manufacturing enterprise strategies in the 1990s as extensions of Concurrent Engineering, integrated product and process development, and other emerging disciplines. Integrated product realization emerged as an all-encompassing concept that went beyond basic integration of product and process activities to call for a new toolset supporting a totally digital product lifecycle management system.

On the other hand, manufacturing companies throughout the world have gradually turned their attention to sustainability matters, as a strategy for competitiveness. However, environmental regulations, such as RoHS, REACH and EuP have enforced new specific requirements to be met. At the same time, customers are more aware of possible hazardous effects of manufacturing operations on the environment and consequently on their lives. Moreover, products that are environmentally benign have attracted more attention, for customers may prefer them amongst others. Therefore, markets, as well as regulations and self-consciousness, have driven enterprise-wide initiatives that favor environment-friendly activities. Yet, the challenge to harmonize current manufacturing practices with ongoing sustainability efforts remains. According to Srinivasan [3], there is a strong sense of dissatisfaction among business executives and engineers, as they do not fully understand the sustainability problem while they try to apply different approaches on a trial-and-error basis.

PREVIOUS WORKS

The concept of Integrated Enterprise (IE) assumes connection and collaboration between people, systems, processes and technologies to ensure that the right people and the right processes to have the right information and the right resources at the right time [4]. IE enables successful operations, in a world of continuous and largely unpredictable change, of a single manufacturing company or a set of distributed enterprises (extended or virtual), allowing decisions and adapting operations for quickly and accurately responding to threats and emerging opportunities. One way for implementing the concept of IE is through intensive and extensive application of models in the corporate environment. The Model-based enterprise (MBE) has therefore become the embodiment of this progressive approach [5].

Simply stated, MBE, in the context of manufacturing, is an organization that applies modeling and simulation technologies to substantially improve, seamlessly integrate, and strategically manage all of its technical and business processes related to design, manufacturing, and product support [5]. By using product and process models to define, execute, control, and manage all enterprise processes, and by applying science-based simulation and analysis tools to make the best decisions at every step of the product lifecycle, it is possible to radically reduce time and cost of product innovation, development, manufacture, and support.

According to NGMTI [5][1], a model has multifaceted definitions. It is a representation of a product. A product model is commonly referred to an electronic representation of all attributes of a product that enables its manufacture, use, and support. An effective product model contains all elements needed to define a product and can provide detailed information about that product. Furthermore, it provides information that is useful in applying the product as a piece of a whole, as in components, subassemblies, and assemblies.

A model is a representation of interactions and results as well. In manufacturing processes, a model mimics a process, including the interrelationships of entities and parameters. Hence, a model is able to determine the results of interactions based on changes in parameters of an entity or a process variable. In more scientific language, a process model is a mathematical description of a complex phenomenon or object useful in defining how products, processes, or systems respond to various inputs.

A model is also an enabler. It can enable many things that are not possible otherwise. A product model can provide information that enables downstream processes such as tooling design, fabrication of fixtures and molds, manufacturing of products and assemblies, and inspection operations. It also enables the exploration of options and quantification of expected results for each option. This capability is often referred to as virtual prototyping. Models allow evaluation of all parameters and their impacts on performance, costs, and other important attributes of a product or a process.

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[1] Next-Generation Manufacturing Technologies Initiative (NGMTI) is sponsored by the U.S. Office of the Secretary of Defense, for developing a national manufacturing technology investment strategy to accelerate the transformation of the U.S. industrial base. NGMTI is led by a coalition of the Advanced Technology Institute, the Integrated Manufacturing Technology Initiative, and the National Counsel for Advanced Manufacturing.

And finally, a model is an integrator. The ability to assemble collections of related models into metamodels that can define the results of complex interactions across products and processes – without losing any of the constituent values – can add remarkable value. The ability to integrate complex models offers the possibility of implementing radically new business processes and reengineering corporate cultures, based on an exceptional ability to accurately predict the results of options for change. Process models, integrated across an enterprise, enable enterprise-wide process management. Cost models, when fully populated across a full range of product and process functions, can enable cost estimating, tracking, and management to a level not achievable otherwise. Process and factory models that document the full range of capabilities can be configured in enterprise resource models to enable optimization of capacity and utilization.

While there is a tendency to interpret the MBE concept as simply all-digital processes, enterprise functions are modeled only to the level that it makes business sense to do so. The technical environment is data-, information-, and knowledge-rich, and provides analytical tools that understand the interactions and dependencies of the enterprise's systems and tools. This empowers a new level of technical understanding of products, processes, and resources – supporting radically improved decision making across the enterprise.

In an MBE, business functions are conceived to pull needed information from product and process models and linked knowledge sources, and apply that information together with business models. Product engineering, cost management, resource allocation, and other enterprise systems would interact with that model based on their own models and data in order to optimize plan for the best balance of results. In this manner, all business processes are integrated across the enterprise, using models to share and act on requirements, knowledge, and resource information.

As stated by Rospocher, et al. [6], a business model is a structured description of various aspects relevant to the company. Modeling of business processes is an essential task for a company in the context of the contemporary market, because it is through such models that organizational resources can be studied and optimized for achieving the strategic and operational objectives of a company. Modeling can significantly reduce inconsistencies and redundancies in business processes. Recently modeling other properties of a company such as goals, human resources, and rules, among others have also become important for building an enterprise-wise model.

The effects of enterprise modeling are enhanced when they exceed a company's own limits, as models of customers and suppliers, or other associated companies are integrated. That allows for a more comprehensive view of the entire environment in which a company operates.

One of the most important achievements of business modeling is to facilitate the integration and interaction with other business partners. However, connecting models of different contexts and organizations can be a more difficult and complex task than it appears. The integration process between different organizations can occur in various ways. According to Liu, et al. [7], much of this is due to the lack of standards in the modeling or the agreement of experts to create a common model, simply because a business process can be performed in different ways, yet reaching the same goals.

An alternative way of representing enterprise models is through the use of formal ontologies. Ontologies are rather adequate structures for the representation of business models because through their well-defined semantics they are able to define attributes and relationships with differing levels of formality. The use of formal ontologies provides a complete set of axioms that restrict interpretation ambiguities allowing more complex inferences on the model [8].

Ontologies consist of sets of vocabulary used in a particular field of knowledge, enriched by some specification of the meaning or semantics of terminology within the vocabulary. Therefore, ontologies can potentially be used to bridge the gap between heterogeneous information systems, including those extensively used in manufacturing, which manipulate product information models and lifecycle processes.

Bräscher, et al. [9] characterize the domain of lifecycle assessment (LCA) by means of an ontology, based on concepts extracted from the ISO 14040 standard. Information is organized in such a way that it covers environmental aspects and potential impacts during a product lifecycle in its materials use perspective, that is, from acquisition of raw material, to production, use and disposal. Nevertheless, terms and concepts from other environment related information sources are not fully integrated, and neither are their relationships with product information data.

Heravi, et al. [10] propose the use of ontologies as a basis for standardized development models, with an ontology for the ebXML Business Process Specification Schema (ebBP) in the context of B2B (Business-to-Business) capturing and sharing semantics allowing deduction, inference and reasoning on shared knowledge. For this the Ontology-based Standards Development methodology (OntoStanD) is used, which allows greater ability to capture and identify the semantics than automated methods developed in XML language. Furthermore, it demonstrates how semantic web technologies can be used as a basis for the development of standardized models for allowing interoperability between business partners.

Heravi, et al. [10] identify which XML-based standards, as well as ebBP, are widely used, but present limitations for their lack of semantic expressiveness, providing only syntactic representations, which is a problem when there is the need for integrating processes between different organizations. Their work presents the use of ontologies as appropriate means for data integration by providing forms for representing entities, and their relationships, therefore reducing ambiguities, allowing inferences and reasoning on the model, thus facilitating the transmission of shared knowledge.

PROBLEM STATEMENT

Given the perspective built upon previous works, i.e.:

(i) The importance of enterprise modeling for integration (i.e. IE, MBE);

(ii) The use of ontologies for non-ambiguous modeling of processes and related information; and

(iii) Ontologies' potential to facilitate and enable intelligent process integration and seamless information exchange in the context of product lifecycle management and sustainability.

The following problem statement can therefore be posed:

"*Is it possible to use ontologies to represent knowledge in product lifecycle operations, integrate sustainability-related concepts and semantically connect product and manufacturing process data, to ultimately promote interoperability between information systems in the context of the Integrated Enterprise?*"

RESEARCH GOAL

The main goal of the present research is three-fold: (i) to develop an ontology that can ensure knowledge capture and sharing, so that information can be exchanged amongst distinct people and systems during a product's life-cycle; (ii) to develop a reference ontology that may ultimately be used to overcome interoperability issues between engineering and business applications and facilitate the use of sustainability data throughout a product's lifecycle; and (iii) to develop an ontology to be applied for obtaining energy efficiency indicators related to designed products that use commonly used manufacturing processes.

An ontology for knowledge capturing and sharing would incorporate all different terms used throughout a product lifecycle. It would be the first step to overcome ambiguity, when it comes to bringing closer different perspectives to product planning, development, manufacturing, use and disposal. Next, reference ontologies aimed to allow seamless information exchange between information systems could mean a step further towards machine-readability of product related data. And finally, the application of ontologies for decision-making during a product lifecycle could close the loop and demonstrate the usefulness of semantic-rich information models, as opposed to commonly applied product structure data (e.g. bills of materials).

DISSERTATION OUTLINE

The remainder of this thesis is structured as follows. Chapter 2 provides a conceptual background on product lifecycle management, business process management, sustainability and discusses the importance of ontologies and Semantic Web technologies for interoperability in the IE context. Chapter 3 presents the research methodology employed for this work, for reaching each one of the previously mentioned objectives: ontology for knowledge capture and sharing in the product lifecycle context, reference ontology for interoperability in sustainable product development and ontology for decision making, also in the same context. Chapter 4 presents results and discussion, focusing on the challenges faced. And Chapter 5 concludes the dissertation, bringing possibilities for future works.

Chapter 2: Conceptual Background

This chapter presents fundamentals as building blocks used in the present research. First, the concept of Product Lifecycle Management is introduced, and so are its perspectives (materials, innovation and manufacturing). It is the backbone for understanding how product data should be semantically enriched for the purpose of interoperability and decision-making. Next, sustainability and sustainable product development are introduced, as needed concepts for achieving the three-fold objective of the present work. Similarly, exergy-based analysis for sustainability is presented, as such an approach is to be used in the last phase of the present research. Business process management (and modeling) is introduced next, as a means for binding manufacturing operations (such as welding) to product data. Ontologies, as previously stated, is a resourceful means to represent knowledge, and its fundamentals are necessary for all phases of this work. Finally, fundamentals and recent work on standards are introduced, as powerful tools to facilitate interoperability and potentially direct future work.

PRODUCT LIFECYCLE MANAGEMENT

Product Lifecycle Management (PLM) is a business strategy for creating and sustaining a product-centric knowledge environment. It is rooted not only in design tools and data warehouse systems, but also on product maintenance, repair and dismissal support systems. A PLM environment enables collaboration between various stakeholders of a product over its lifecycle [11].

The term 'lifecycle' generally indicates the whole set of phases, which could be recognized as independent stages to be passed/followed/performed by a product, from 'its cradle to its grave'. According to Kiritsis, et al. [12], product lifecycle can be defined by three main phases, as depicted in figure 2.1. In Beginning of life (BOL), design and manufacturing are included. Design is a multilevel phase since it comprises product, process and plant design. Generally speaking, design implies a recursive application of multiple sub-actions: identifying requirements, defining reference concepts, developing detailed design, building prototypes and performing tests. Manufacturing means developing production process, plan the production facilities and manage manufacture of products with diverse suppliers. During this phase, the product is in the hands of the company within the boundaries of the (extended) enterprise.

Middle-of-life (MOL) includes distribution (external logistic), use and support (in terms of repair and maintenance). In this phase, the product is in the hands of the final customer and/or some service providers. In the MOL phase, products are distributed, used and supported (repaired and maintained) by customers and/or service providers. The product history related to distribution routes, usage conditions, failures and maintenance are possibly collected to create up-to-date reports about the status of products.

In End-of-life (EOL) products are retired. They can be recollected in the company's hands (reverse logistic) in order to be recycled (disassembled, remanufactured, reused, etc.) or disposed. EOL is the phase where products are collected, disassembled, refurbished, recycled, reassembled, reused or disposed. EOL starts from the time when the product no longer satisfies its users. Information from EOL about 'valuable parts and materials' and other knowledge that facilitates material reuse should be routed to recyclers and reusers, who can obtain accurate information about product status and product content.

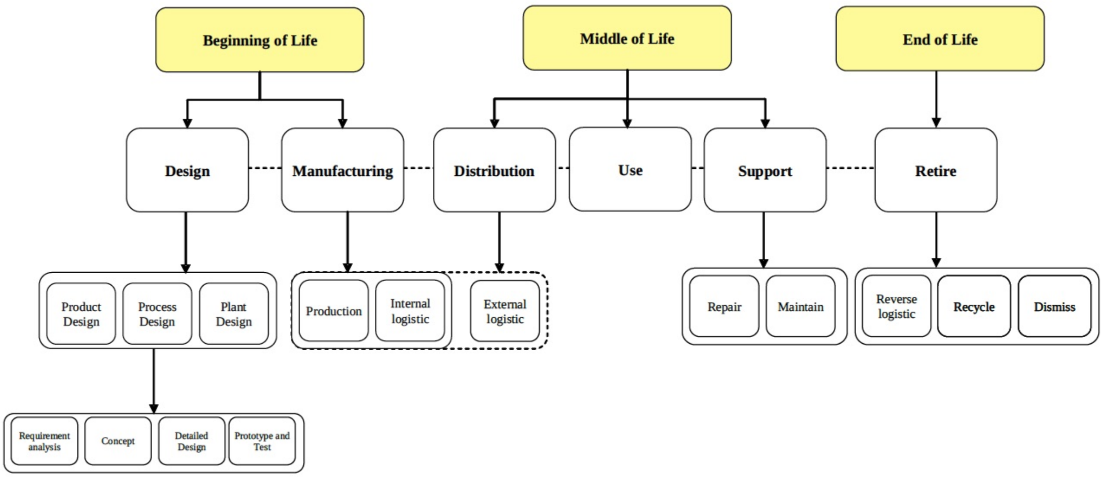

Figure 2.1 – Product lifecycle phases.
Source: Terzi, et al. [13].

PLM is considered to be the 21st century paradigm for product development. According to Stark [14], the management of a product from inception to disposal has strategic value for a given company in the networked economy. This has only been possible due to extensive use of IT infrastructure and technology to exchange information, which enables companies to explore external possibilities like partnering with suppliers and co-developers [15].

In the PLM paradigm, information flows occur through several different channels in a web-like pattern. Subrahmanian, et al. [15] have presented the metaphor of epicycles in a product's life cycle. In this representation, nodes on a circle stand for major phases in a lifecycle, and links and arrows across the circle stand for information flows. This metaphor aims at conveying the idea of interdependence among stages, as effective communication is needed to complete all tasks (figure 2.2).

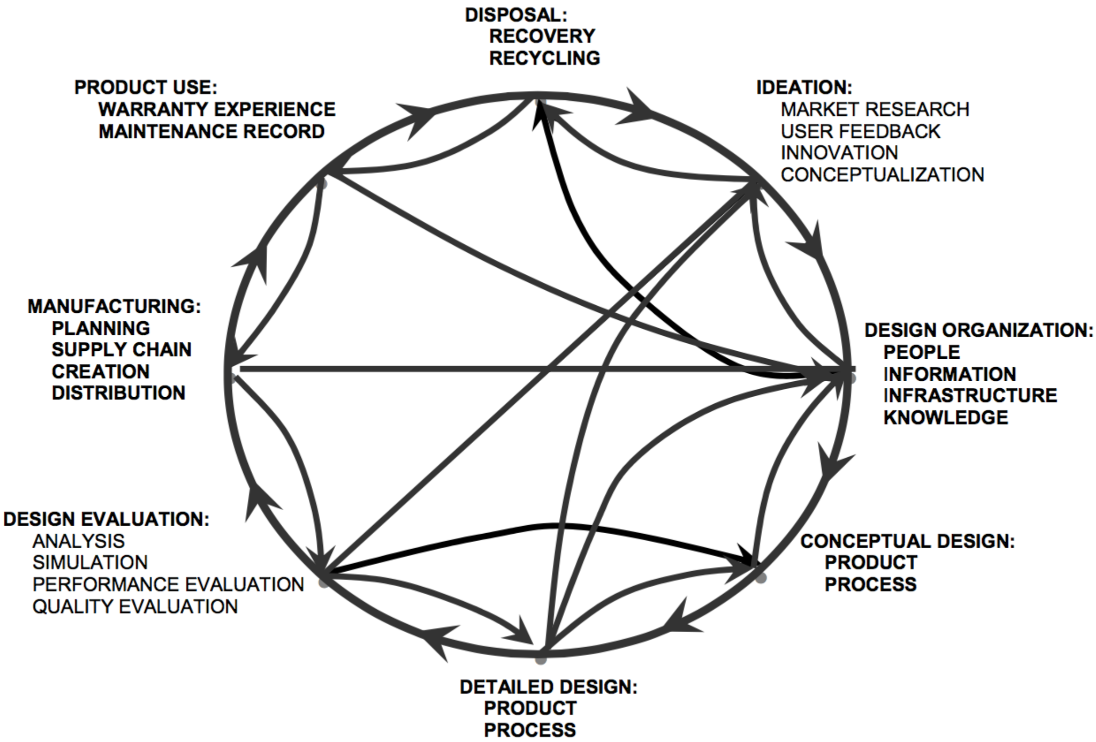

Figure 2.2 – Epicycles in product life cycle development.
Source: Subrahmanian, et al. [15].

On the other hand, the reference model for managing product development suggested by Seliger [16] offers a cross-vision of knowledge areas and their intensity throughout the product development phase, which illustrates the need for information exchange between functions, such as marketing, quality and engineering.

In an extended enterprise, distributed, multidisciplinary and cooperative teams design products design, in a knowledge-intensive product development environment that requires a computational framework that enables the capture, representation and reuse of product and process knowledge. In the manufacturing phase, all this product information has to be shared along the production and distribution chain and synchronized with future updates. Moreover, product data are to be put at disposal of the service chain during the use and support phase. During product use, input data on product behavior could be collected for design improvement. The recycling and dismissal activities could require and provide information on components, materials and other resources [11].

PLM is already well known in the market of information and communication technologies (ICT). As a technology solution, PLM is an integrator of tools and technologies that streamlines the flow of information through the various stages of the product lifecycle. Unlike other technologies, PLM is grounded in the philosophy of connectivity of knowledge and seeks to provide the right information at the right time and in the right context. It can be said that PLM enables the establishment of a sustainable, product-related, corporate strategy for competitiveness [11]. Currently, the PLM acronym is playing a 'holistic' role, bringing together products, services, activities, processes, people, skills, ICT systems, data, knowledge, techniques, practices, procedures and standards [14].

Establishing effective PLM implies enforcing coherent data flow, avoiding redundancies and gaps [17]. From the ICT point of view, PLM is an enterprise level application, yet not an exclusive ICT problem, for it also comprises business processes (where data flow among actors/resources with relative competences, inside and outside an organization) and methods (practice and techniques adopted along the business processes, using and generating product data). Therefore, methods, processes and ICT are the three fundamentals of PLM that are involved along the product lifecycle [11].

SUSTAINABILITY AND SUSTAINABLE PRODUCT DEVELOPMENT

The traditional quality-cost-time paradigm, in which manufacturing companies operate, has gradually shifted towards considering sustainability aspects. The Integrated Manufacturing Technology Initiative has defined Environmental Sustainability as one of the 'Grand Challenges' for manufacturing success in the 21st century [18]. Environment-friendly products are more popular than ever, since consumers are more aware of future scenarios of scarce resources shared by an increasing world population

[19]. In this scenario, companies have set strategies to both seize market opportunities and reduce production cost [20, 21].

Efforts for a more sustainable society still find many barriers. Ljungberg [21] define four major problems left with no solution: excess of consumption, resource depletion, air pollution and population growth. These problems can be directly linked with the standing global economical development model, which sets a highly accelerated consumption pattern and high competition levels between enterprises, causing deep environmental damages, resource scarcity and many other undesirable side effects.

It is important to establish a product lifecycle vision that encompasses new insights, such as those related to sustainability issues, with consolidated interpretations, as they cannot be considered obsolete in any sense. This can be obtained through the combination of three perspectives, namely an innovation perspective, a production perspective and a materials perspective, as presented in figure 2.3, in business process modelling notation (BPMN). Each perspective is modelled as a BPMN **pool** (coloured rectangle).

The **innovation perspective** has its focus on the product as the result of a conceptualization process and preparation for production. The obsolescence of its concept terminates this process and gives way to a new instance of the innovation process. On the other hand, the **production perspective** has its focus on the product as an artifact and embraces not only its assembly, but also its disassembly and possible reuse. Finally, the **materials perspective** focuses on the product as a combination of materials, encompassing the extraction of raw materials and future disposal or recycling. Labels BOL (beginning-of-life), MOL (middle-of-life) and EOL (end-of-life) have been added to group activities according to their chronology, as suggested by Kiritsis, et al. [12]. A given task in each perspective may provide information to another task in other perspectives (dashed lines), thus demonstrating how the integration between perspectives can be accomplished.

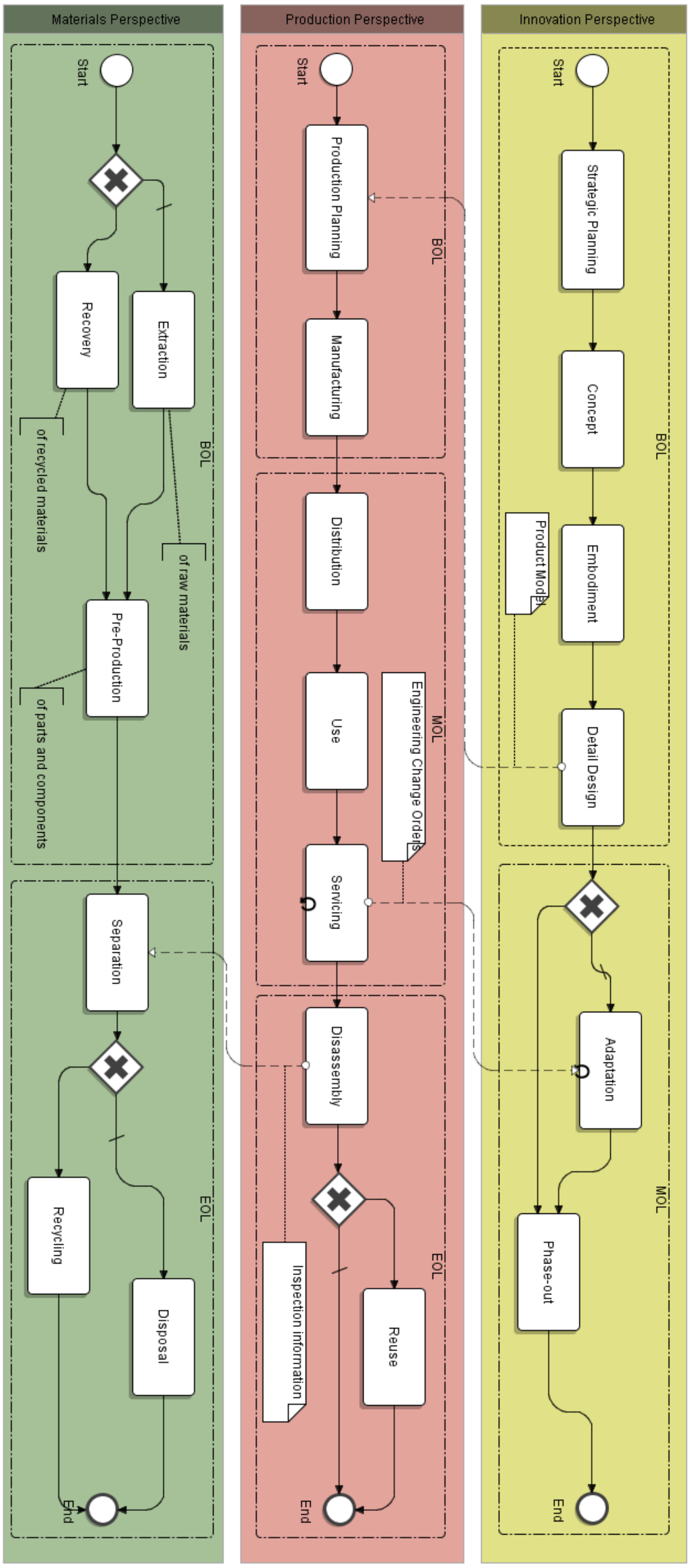

Figure 2.3 – Innovation, production and materials perspectives of a product’s lifecycle.

Source: Author.

EXERGY-BASED ENERGY EFFICIENCY ANALYSIS FOR SUSTAINABILITY

Companies are looking at their manufacturing processes to find ways to cause less impact on the environment [22]. Comprehensive examination of manufacturing processes as to their energy efficiency have led to the fact that state-of-the-art fabrication methods may be more precise or reliable, but on the other hand use enormous amounts of energy per weight of processed material [23].

Manufacturing processes encompass operations that take material inputs, including working materials and auxiliary materials, and transform them into products and waste. Similarly, the energy inputs into these processes are transformed into useful work, some of which is embodied into the form and composition of the products and waste, and waste heat. In addition, the energy inputs usually require fuel and produce emissions [24].

According to Gutowski, et al. [23], "Exergy represents the maximum amount of work that could be extracted from a system as it is reversibly brought to equilibrium with a well-defined environmental reference state". The concept of exergy analysis can be used to characterize and accumulate work, heat and material streams entering and leaving manufacturing systems and can greatly simplify the problem [25].

An exergy balance can be formulated for a given manufacturing system [23] as follows:

$$\dot{B}_{in} + \dot{B}_{W,in} + \dot{B}_{Q,in} = \dot{B}_{out} + \dot{B}_{W,out} + \dot{B}_{Q,out} + \dot{B}_{loss} \quad (1)$$

In equation (1), $\dot{B}$ denotes exergy rate. $\dot{B}_{in/out}$ is the exergy rate of the aggregated materials entering and leaving the system. $\dot{B}_{in/out} = \dot{W}_{in/out}$ (where $\dot{W}$ denotes work rate) and $\dot{B}_{Q,in/out} = (1 - T_0/T).\dot{Q}_{in/out}$ (where $\dot{Q}$ denotes heat rate) show the exergy rates accompanied with work and heat, respectively. Work rate required beyond the minimum requirement is lost and expressed by $\dot{B}_{loss}$. For this analysis, all exergies are calculated with respect to the reference state $T_0 = 298.15\,K$ and $p_0 = 101.3\,kPa$. Figure 2.4 represents the exergy balance of a given welding operation. $\dot{B}_{Fuel}$ denotes exergy rate related to fuel consumption; $\dot{B}_{Waste}$ expresses exergy rate related to waste; and the subsystems represented are the Parts Supply Thermodynamic System (PSTS), the Welding Operation Thermodynamic System (WOTS) and the Consumables Supply Thermodynamic System (CSTS). EC stands for Energy Conversion.

In the case of an exergy-based thermodynamic analysis, the efficiency measure is given by the 'degree of perfection' (η_p), which can be expressed as follows [23]:

$$\eta_p = \frac{\dot{B}_{useful\,products}}{\dot{B}_{in} + \dot{B}_{W,in} + \dot{B}_{Q,in}} = 1 - \frac{\dot{B}_{loss}}{\dot{B}_{in} + \dot{B}_{W,in} + \dot{B}_{Q,in}} \qquad (2)$$

In a welding process, the exergy rate of useful products is that embedded in the assembly. Exergy tables [26] can be used for obtaining specific exergy values, according to the materials of the parts. That data, multiplied by the weight of a given part gives the exergy rate in J/part and, consequently, per assembled unit.

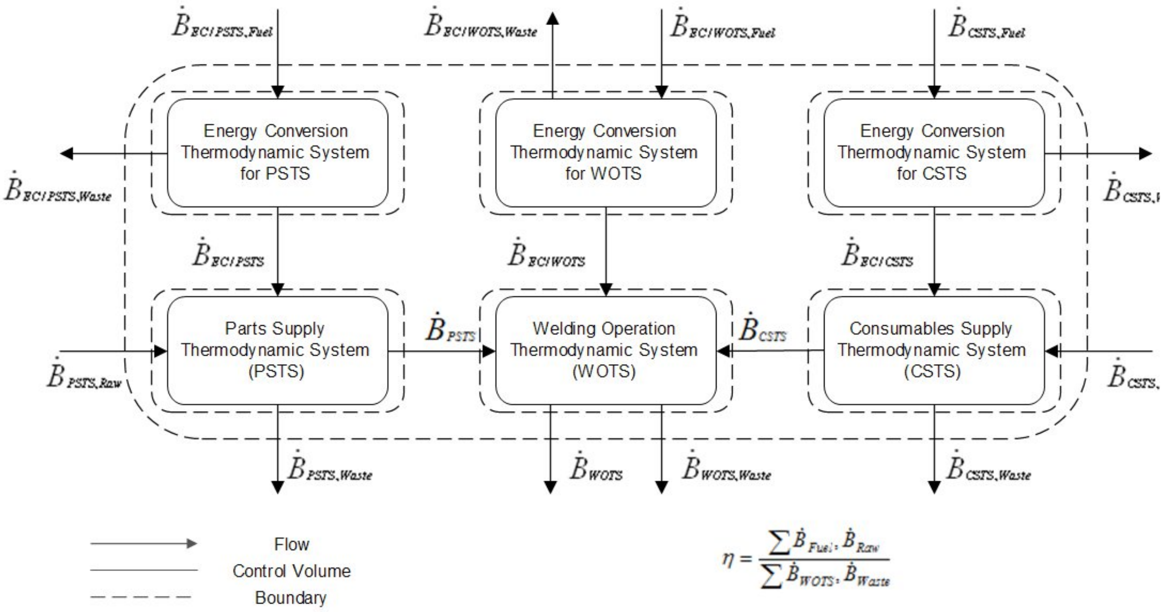

Figure 2.4 – Exergy balance of welding processes.

Source: Author.

Business Process Management

Business processes are chains of events and activities for delivering a service or a product to customers. The way processes are designed and performed affects both the quality of service that customers perceive and the efficiency with which services are delivered. Business Process Management (BPM) is therefore the art and science of overseeing how work is performed in an organization to ensure consistent outcomes and to take advantage of improvement opportunities [27].

An organization can outperform another organization offering similar kinds of service if it has better processes and executes them better. This is true not only of customer-facing processes, but also of internal processes such as a procure-to-pay process, which is performed for the purpose of fulfilling an internal need.

In the BPM jargon, business processes encompass a number of events and activities. Events correspond to things that happen atomically, meaning that they have no duration. This event may trigger the execution of a series of activities, named tasks when they can be seen as one single unit of work. In addition to events and activities, a typical process involves decision points, that is, points in time when a decision is made that affects the way the process is executed. A process also involves a number of actors (human actors, organizations, or software systems acting on behalf of human actors or organizations), physical objects (equipment, materials, products, paper documents) and immaterial objects (electronic documents and electronic records). Finally, the execution of a process leads to one or several outcomes, either negative or positive. Thus, a business process can be formally defined as a collection of inter-related events, activities and decision points that involve a number of actors and objects, and that collectively lead to an outcome that is of value to at least one customer.

Process models are meant to facilitate communication between stakeholders involved in a BPM initiative. It is common practice to use diagrams in order to model business processes. Diagrams allow easy comprehension of a given the process. Also, if a diagram is made using commonly standard notation, easily understood by all stakeholders, there is less room for any misunderstanding.

There are many languages for modeling business processes diagrammatically. Perhaps one of the oldest ones are flowcharts. In their most basic form, flowcharts consist of rectangles, representing activities, and diamonds, representing points in the process where a decision is made. Unified Modeling Language (UML) Activity Diagrams are cross-organizational flowcharts. However, UML Activity Diagrams go beyond cross-organizational flowcharts by providing symbols to capture data objects, signals and parallelism among other aspects. Yet another language for process modeling is Event-driven Process Chains (EPCs). EPCs have some similarities with flowcharts but they differ from flowcharts in that they treat events as first-class citizens. Other languages used for process modeling include data-flow diagrams and IDEF3, just to name a few.

Nowadays there is a widely used standard for process modeling, namely the Business Process Model and Notation (BPMN). The latest version of BPMN is BPMN 2.0 [28], which was released as a standard by the Object Management Group (OMG) in 2011. In BPMN, activities are represented as rounded rectangles. Control nodes (called gateways) are represented using diamond shapes. Activities and control nodes are connected by means of arcs (called flows) that determine the order in which the process is executed. Figure 2.5 brings an example of business process modeled in BPMN.

In some cases, however, the model needs more details for it to be useful. Which additional details should be included in a process model depends on the purpose. Oftentimes, process models are intended to serve as documentation of the way an organization works. In this case, the key characteristics of process models are simplicity and understandability. Accordingly, additional text annotations might be added to the process model to clarify the meaning of certain activities or events, but beyond such annotations, not much additional detail would be added. In other cases, process models are intended to be analyzed in detail, for example in order to measure process performance. In this case, further details may be required such as how much time each task takes (on average). Finally, in a few cases, process models are intended to be deployed into BPMS (Business Process Management Software) for the purpose of coordinating the execution of the process. In the latter case, the model needs to be extended with a significant amount of details regarding the inputs and outputs of the process and each its activities [27].

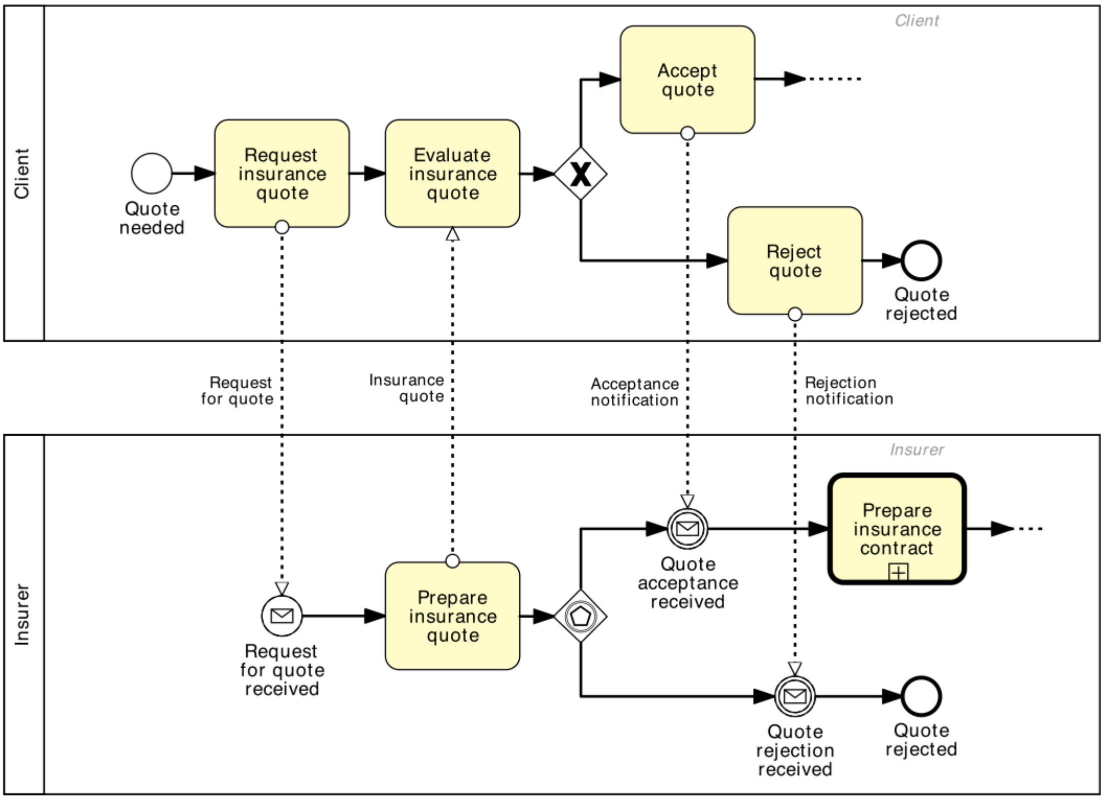

Figure 2.5 – Example of business process modeled in BPMN.

Source: Dumas, et al. [27].

ONTOLOGIES AND THE SEMANTIC WEB

An ontology is an explicit specification of a conceptualization [29]. For information systems, anything that exists (e.g. a physical item or knowledge) can be represented. The knowledge of a certain domain must be represented in a declarative formalism and have a set of axioms that constrain the possible interpretations for the defined terms. This set of objects, and the describable relationships among them, are reflected in the representational vocabulary with which a knowledge-based program represents knowledge [30].

Ontologies do not have to be limited to conservative definitions and can express the tacit knowledge from those agents involved. The advantages are: (i) has a vocabulary for representation of the knowledge; (ii) have the sharing of knowledge; and (iii) have an accurate description of the knowledge. One of the most promising approaches for developing ontologies is the one provided by the model proposed by Uschold and Gruninger [30], as seen in figure 2.6.

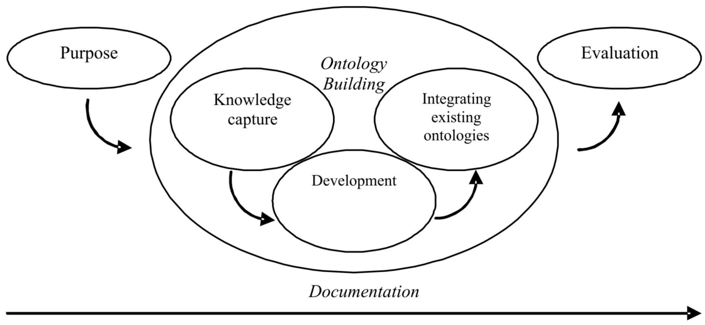

Figure 2.6 – Ontology building.
Source: Uschold and Gruninger [30].

According to this approach, once a specific purpose is identified, an ontology may be built in a three-stage effort: capturing existing knowledge, developing definitions and relations and integrating existing ontologies, such as upper level ones (e.g. SUMO[2]) and nearby domains. Next, an evaluation is performed based on well-established criteria, such as those used by evaluation tools like Chimaera [31].

For Chandrasekaran, et al. [32], ontologies are the core of any information representation system and in the absence of it, there would be no vocabulary that truly represents the knowledge of a certain reality. The generation of a common domain vocabulary may result in a more transparent and objective communication among users and can facilitate the search for knowledge in a given area.

Ontologies can help share knowledge between information systems. That occurs as one system is sharing the representation language with others that have similar demands in that domain, eliminating the need to replicate the process of knowledge

[2] The Suggested Upper Merged Ontology (SUMO) and its domain ontologies form the largest formal public ontology in existence today. They are being used for research and applications in search, linguistics and reasoning. SUMO is the only formal ontology that has been mapped to all of the WordNet lexicon.

analysis already performed. Furthermore, as information is described, codified, and understood by all those involved, the speed and efficiency of the sharing process are enhanced in the area.

When dealing with highly intensive knowledge environments, information structures become critical in order to capture, represent, retrieve and reuse knowledge associated with products [33]. Different terms, expressions and languages employed for the identification of subjects and components, as well as those different programming languages and environments, usually lead to inconsistencies, errors and losses of data. This can mean waste of time and scarce resources.

As Subrahmanian, et al. [15] have pointed out, today's networked organizations are still only partially integrated islands of information and tend to have a static view of the use of information, rather than viewing PLM as a holistic real-time control system that is continually adjusting and improving the underlying business and operational processes.

In this scenario, formal ontologies can provide mechanisms for structuring information and representing knowledge from a vocabulary set and its definitions, which may guarantee semantic interoperability between different information systems and knowledge sharing amongst different functional areas within a company.

Semantic interoperability is the ability of two or more computer systems to exchange information and have the meaning of that information accurately and automatically interpreted by the receiving system. It implies the existence of a common and shared understanding of the meaning underlying the information, i.e. being exchanged. To achieve perfect semantic interoperability, all communicating systems must use symbols and definitions that are identical or can be accurately translated. Thus, a common ontology is the ideal solution for semantic interoperability [34].

Ontology and its use in modeling knowledge have been studied extensively in the context of artificial intelligence and linguistics. In recent times, a big thrust came from research aimed at enhancing the web to what is referred as the Semantic Web. The Semantic Web is an evolving extension of the World Wide Web in which web content can be expressed not only in natural language, but also in a format that can be read and used by software agents, thus permitting them to find, share and integrate information more easily. Several ontology description languages have emerged that are now in the process of being standardized. Resource description format (RDF) along with its extension RDF Schema (RDF/S) was the initial standards [35, 36]. The web ontology language (OWL) extends RDF/S by providing additional vocabulary along with a formal semantics [37].

A semantic model is a set of information in the form of an ontology, which can be provided to an integrated application in the form of a metamodel. This metamodel sets standards of information for a particular market segment, providing resource settings integrated into business operations structures. An integrated semantic model enables focused applications based on real-world problems, supporting integration of operational data related to the business. The semantic information model provides an abstraction of the real world of business and assets in a graphical model. Through it, applications can access information from disparate systems with multiple access methods. The same can be consulted through services or based on the implementation of an interface with queries.

Integrated systems that use semantic models need adapters for integration with applications such as Web services and databases. A system based on semantic models has two views, the reference model composed of ontology where the classes are defined and the relationships between them and the model instantiated with the individuals that have a direct reference to the real world. Individuals are filled with a set of properties and relationships with other instantiated entities. Semantic models play a key role in the evolving architecture solutions, for support aimed at businesses that seek a more complete view of what is happening within the operations [38].

Ciocoiu, et al. [39] advocate the use of ontologies for modeling information in order to achieve these ideals through their expressive power, free from ambiguity and imprecision. However, it is necessary that this ontology to present a certain degree of formalism having axiomatic characterization capacity and thus provide a free model ambiguities, which can be read and interpreted automatically by a computer.

Ciocoiu, et al. [39] present two basic approaches to interoperability between business problem solution: the normalizing approach and interlingua. The normalizing approach concerns the construction of a standard ontological basis for the representation of information that will be shared between business entities and different systems. This approach is considered very effective when modeling systems that use have not been built, or when there is rather easily to changes in this modeling, in other words, it is important that the base ontology is set before the business models that use it.

The idea behind interlingua is to use a shared ontology between applications, serving as a translator for communnication between them. Its objective is to solve the problems that the normalizing approach brings, so that it can be used in systems which were not constructed for the purpose of interoperability. In practice, this implementation requires a point to point, i.e. a new translator must be written for each pair of systems, rules for defining the relationship of the terminology and behavior of both ends.

STANDARDS

According to Ivezic, et al. [2], recent developments in standards provide some of the necessary tools and technologies to move towards machine readability. As no single software vendor or organization can cover the entire extent of a product's lifecycle, standards have emerged as an alternative to link disparate software systems and services.

It is also important to understand the increasing relevance of open standards and source models. Open source models seem to address large scale distributed design of complex products. The major success of open source comes from the recognition of the scale and diversity of skills through modular design the minimizing of the costs of bad local decisions the ability to mobilize people of diverse skills.

Standards for other aspects such as traceability, validation, verification and other audit and archival functions will have to be considered in the support system for PLM. Terzi, et al. [40] suggest that standards tend to focus on a specific area of the product lifecycle, but none include all the information needed in the whole lifecycle chain. Figure 2.7 presents a classification of standards according to their main scope and content: product, process or enterprise service. The horizontal axis represents the product lifecycle with the major stages or phases identified. The vertical axis represents three complementary aspects of the information.

Ivezic, et al. [2], report recent developments for standards in the following categories: (a) model-based 3D engineering supporting standards; (b) business objects; (c) model-based systems engineering supporting standards; (d) product lifecycle support; and (e) MTconnect. Model-based 3D engineering support standards comprise the recently released ISO 10303-242 standard (also known as STEP AP 242), which belongs to the STEP family of standards, based on XML and EXPRESS. Its focus is on Product Manufacturing Information (PMI), which refers to Geometric Dimensioning and Tolerancing (GD&T), surface texture, finish requirements, process notes, material specifications, welding symbols, and other annotations commonly used in CAD/CAM-related activities. STEP AP 242 also offers a new capability known as the Business Object Model (BO Model), which represents much of the standardized meta-data associated with a product, such as the assembly structure of a complex product. These pieces of information are commonly stored in PDM (or PLM) systems that manage 3D CAD models [31].

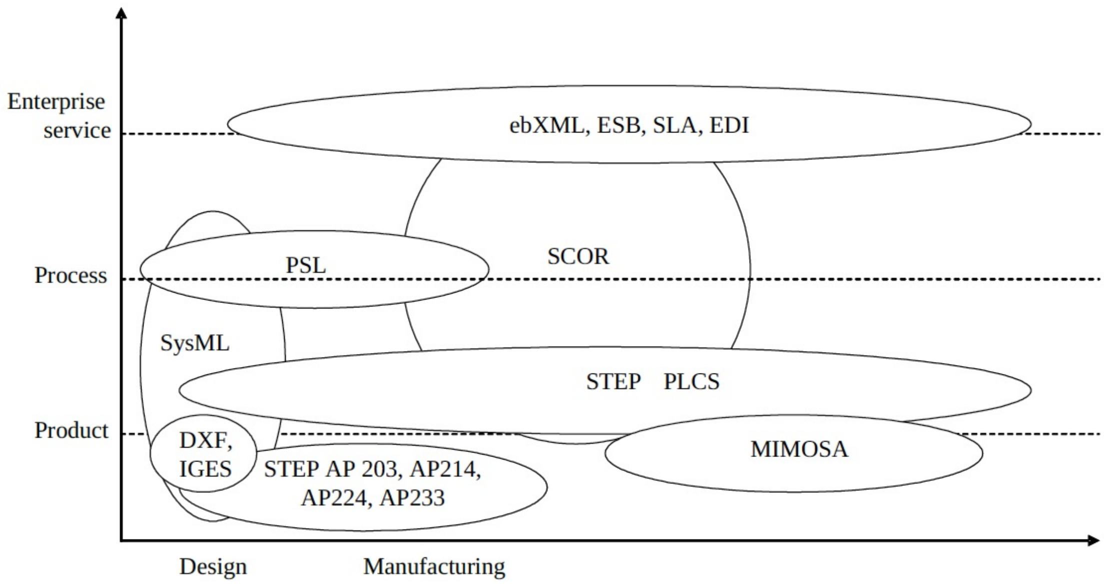

Figure 2.7 – Standards through product lifecycle phases.
Source: Terzi, et al. [40].

Non-geometric meta-data, which are equally important for through-life engineering operations are addresses by other standards, such as business objects, to be managed by Enterprise Resource Planning (ERP) systems. Business Object Documents (BODs) are standard engineering and business message specifications developed in XML by Open Application Group Inc. (OAGi). The entire suite of specifications is called Open Application Group Integration Specification (OAGIS) [41].

Model-based systems engineering (MBSE) standards are machine-readable models targeted to manage requirements, realization and maintenance of complex artifacts. One such standard is SysML, an extension of the Unified Modeling Language (UML), represented by a set of diagrams that enable engineers to represent complex requirements, and to link them to systems simulation and analysis programs [42].

Product LifeCycle Support (PLCS) is another standard in the STEP family, the ISO STEP AP 239. PLCS provides standardized representations (currently defined in UML/SysML) for product configurations during various phases of a product lifecycle (e.g. as-designed, as-built, and as-maintained) and other capabilities [43].

MTConnect, developed by the MTConnect Institute, is a standard for networking manufacturing devices and applications. It allows device data including subcomponents, measurements, and events to be uniformly communicated to manufacturing management, diagnosis and prognosis applications [44].

According to Heravi, et al. [10], ontologies, as an appropriate means for capturing knowledge in a domain, should be utilized in the process of standards development. Therefore, the conceptual model of standards and their restrictions and rules can be better modeled in an ontological manner. In addition, having an ontological model of a standard makes the semantics accessible to automated processing and to engineers not expert in a given knowledge domain.

Bock, et al. [45] have introduced a product modelling language for collaborative design that combines the benefits of ontology and conventional product modelling. The proposed approach focuses on combining, refining, and checking consistency of requirements and designs from multiple, disparate sources. Moreover, OntoSTEP has been developed to offer a version of STEP that allows logic reasoning and inference mechanisms and thus enhance semantic interoperability [46]. The development of OntoSTEP has required the conversion of EXPRESS schema to OWL-DL, and the classification of EXPRESS instances to OWL individuals. Further developments will be possible due to recent advances in ontology building languages, such as OWL and automatic reasoners, like Pellet [47].

The present work sets the fundamentals for introducing ontology-based standards for supporting product lifecycle operations. The following chapter presents its methodological aspects.

Chapter 3: Research Method

The present research can be understood as a sequence of three phases. In the first phase, an ontology that captures knowledge of the various domains that compose the product lifecycle context was built. In the second phase, PLM concepts previously captured in the first step were extended and connected to sustainability-related concepts, extracted from numerous sources, from ISO standards to sustainable design practices (e.g. LCA), to produce an ontology that can be used as interlingua, for communicating relevant information between heterogeneous environments. In the third phase, based on the previous ontologies, the determination of energy efficiency built upon product (i.e. features) and process (i.e. manufacturing) data is demonstrated by means an instantiating a proposed ontology. Figure 3.1 presents an overview of these phases.

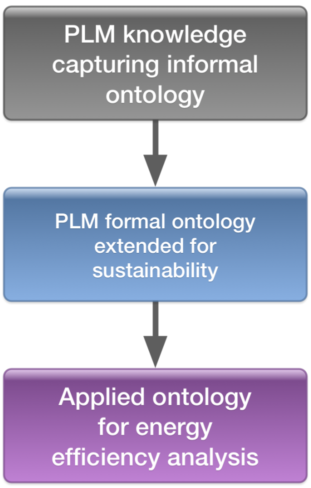

Figure 3.1 – Research phases.

Source: Author.

Uschold and Gruninger (1996) propose the approach for ontology building shown in figure 3.2, which corresponds to a detailed view of the development step shown previously in figure 2.6.

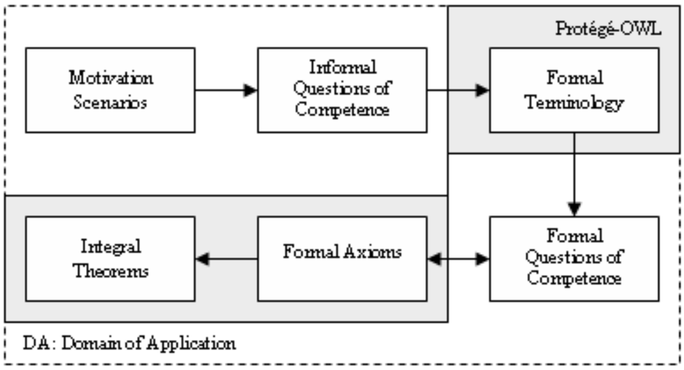

Figure 3.2 – Ontology building approach.
Source: Uschold and Gruninger [30].

The approach starts with a search for motivation scenarios, which are story problems or examples, which are not adequately addressed by existing ontologies. A motivating scenario also provides a set of intuitively possible solutions to the scenario problems. These solutions provide an informal intended semantics for the objects and relations that will later be included in the ontology.

Given the motivating scenario, a set of queries will arise, which place demands on an underlying ontology. These queries can be considered expressiveness requirements that are in the form of questions. An ontology must be able to represent these questions using its terminology, and be able to characterize the answers to these questions using the axioms and definitions. These are the informal competency questions, since they are not yet expressed in the formal language of the ontology. Given the informal competency questions, the set of terms used in expressing the question can be extracted; these will form the basis for the specification of the terminology in a formal language.

Once informal competency questions have been posed for the proposed new or extended ontology, the terminology of the ontology is specified using a logical formalism such as OWL [48]. A formal ontology is a formal description of objects, properties of objects, and relations among objects. This provides the language that will be used to express the definitions and constraints in the axioms. If a new ontology is to be designed, then for every informal competency question, there must be objects, attributes, or relations in the proposed ontology or proposed extension to an ontology, which are intuitively required to answer the question. Once the competency questions have been posed informally and the terminology of the ontology has been defined, the competency questions are defined formally as an entailment or consistency problem with respect to the axioms in the ontology.

The first phase of the present research was conducted in the following steps: (i) definition of customer needs (i.e. industry); (ii) search for existing/similar projects and relevant information; (iii) establishment of PLM application domains (knowledge or domain areas - DAs); (iv) capture of motivating scenarios (to build relevant vocabulary); (v) generation of competence questions (to establish a fundamental taxonomy); (vi) specification of formal terminology (to establish an extended taxonomy, properties and asserted definitions); (vii) generation of formal competence questions (to build assertions for defined terms); (viii) specification of axioms (to establish necessary and sufficient assertions to completely define terms); (ix) verification of axioms (against rationale-based algorithms, e.g. RacerPro); and (x) ontology proposal.

The second phase of the present work involved an extended search for reliable sources of information that can provide unbiased definitions for commonly used terms. These definitions can then serve not only as a clue to categorize a given term, but also as a first step towards formulating assertions, which are building blocks for more advanced semantic constructs. A controversial term may have its definition clarified by examining its original meaning, which often relate it to other terms. In the present work, several different sources of information, which could possibly contain terms related to the proposed scope, have been examined. Figure 3.3 brings a Venn diagram that illustrates the main relations of sets of entities used to build the taxonomy. Overlaps in this representation contain shared terms, whose definitions have had to be unified and harmonized with the rest of the taxonomy. Along with the sources if information mentioned in the previous section, OAGi's Business Objects (BODs) have been examined, as well as information provided by other initiatives and organisations, such as the GHG Protocol, ACLCA, PLCS, US EPA, IPC and ProSTEP.

Other sources of terms and definitions in the present work comprise specific areas of knowledge that often have well established terminology within their respective BoKs (bodies-of-knowledge), such as PMI's (Project Management Institute) PMBOK, Knowledge Management and CMMI (Capability Maturity Model Integration). For terms that are not explicitly provided by any information source, but still necessary to complete missing spots in the proposed taxonomy, conventional English lexical sources such as the Merriam-Webster or the American Heritage Dictionary were used.

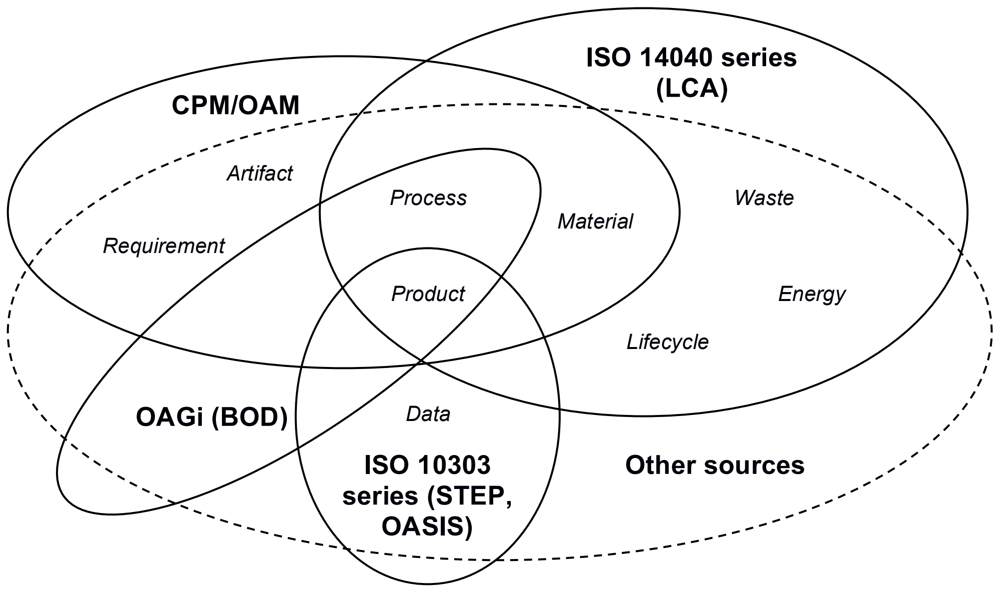

Figure 3.3 – Venn diagram of information sources for ontology building.
Source: Author.

A middle-top/middle-bottom approach has been used to structure the ontology, for most of the terms captured from the information sources previously mentioned form a bulk of middle-level or bottom-level terms. That means some upper level classes are needed to accommodate newly introduced terms. As a construction principle, the number of classes on the top-level part of the hierarchy has been kept minimal, as it provides a comprehensive, yet revealing structure that may seem surprisingly elegant. Also as a construction principle, slightly different interpretations for a given term have been set aside. In such cases, strict examination of lexicon-based definitions has been preferred over controversial, sometimes personal, interpretations.

The third phase of the present work has been carried out in five consecutive steps: (i) determine knowledge areas; (ii) build architectural ontology design pattern (ODP); (iii) build content ODPs; (iv) build integrated ontology; and (v) build test case scenario. Figure 3.4 presents a workflow that depicts the main activities. Ontology building has an intrinsic iterative nature, as the main loops reveal.

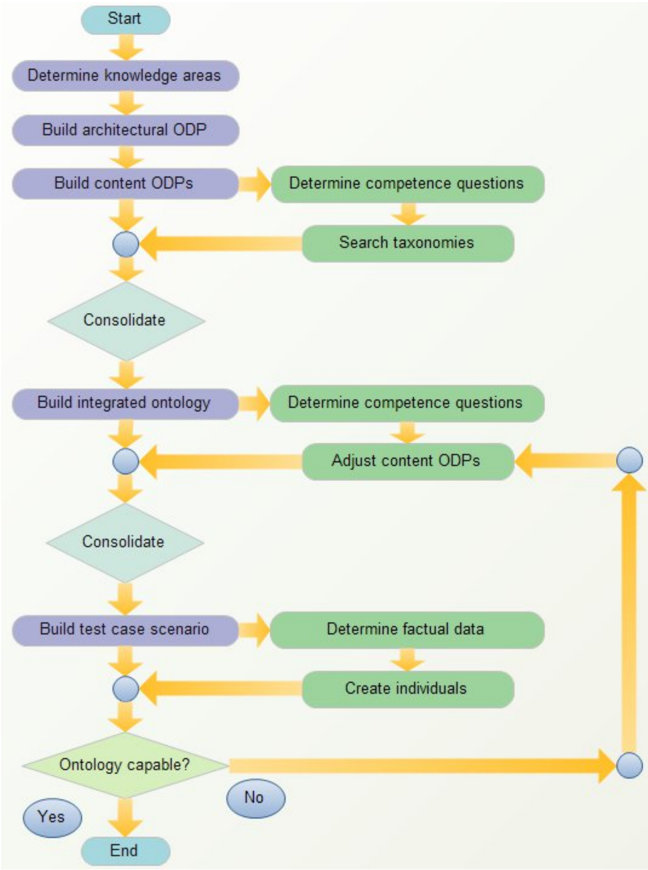

Figure 3.4 – Ontology creation workflow.
Source: Author.

In the first step, different knowledge areas that are related to the purpose of the resulting information model were determined. Those include areas such as business process modeling, manufacturing processes, exergy analysis, assembly topology and features, and welding technology. The purpose was to internalize specific vocabulary and basic relations between terms and concepts. Also, it provides flexibility to modify or enhance the integrated ontology. For example, other manufacturing processes may be detailed in the future or other energy analysis approaches may emerge. Figure 3.5 illustrates the main knowledge areas in the present work.

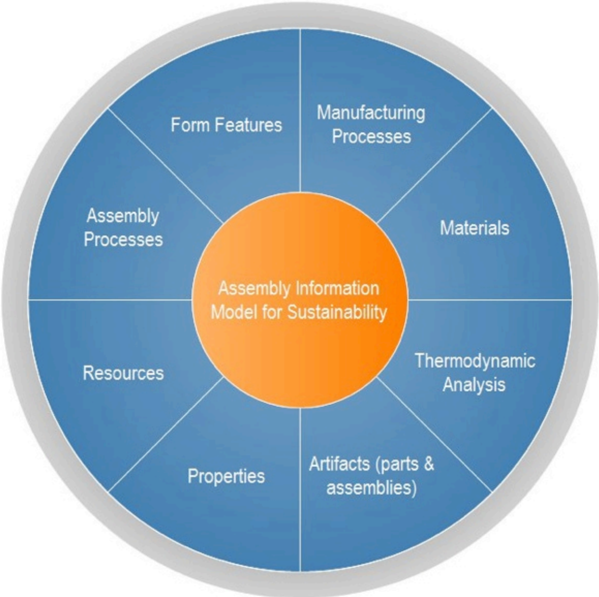

Figure 3.5 – Knowledge domain areas.
Source: Author.

The tools used for modeling were selected based on availability and background knowledge. Protégé version 4.3 [49] was used for ontology editing; RacerPro [50] and Fact++ were used for reasoning; and Bonita BPM Community Edition [51] for process modeling.

In the second step of the present research, a major architectural ODP was determined to set the overall structure of the composed ontology, regarding its classes, object properties and data properties. According to Gangemi and Pressutti [52], architectural ODPs affect the overall shape of the ontology. Their aim is to constrain how the ontology should look.

Most architectural ODPs present a taxonomy of root classes to accommodate further classes down in the taxonomy. In the present work, however, as only a few classes are present in the first level (eight), they have all been placed as siblings. On the other hand, object and data properties have been organized hierarchically for the purpose of clarity.

Object properties are commonly defined in a 'hasSomething-like' manner, such as `hasFeature`. Because the verb 'to have' may lead to several different meanings, such as 'to own', 'to contain' and 'to hold for use', several categories for accommodating each different sense of 'to have' should be created. Since ontologies are built to avoid any sort of semantic ambiguity, each specific meaning was grouped under a certain root object property, like `ownershipProperty` and `characterizationProperty`. The same was valid for data properties, as they may refer to types or values. In this case, `hasTypeProperty` and `hasValueProperty` were created. Figure 3.6 illustrates the tree structure of the architectural ODP.

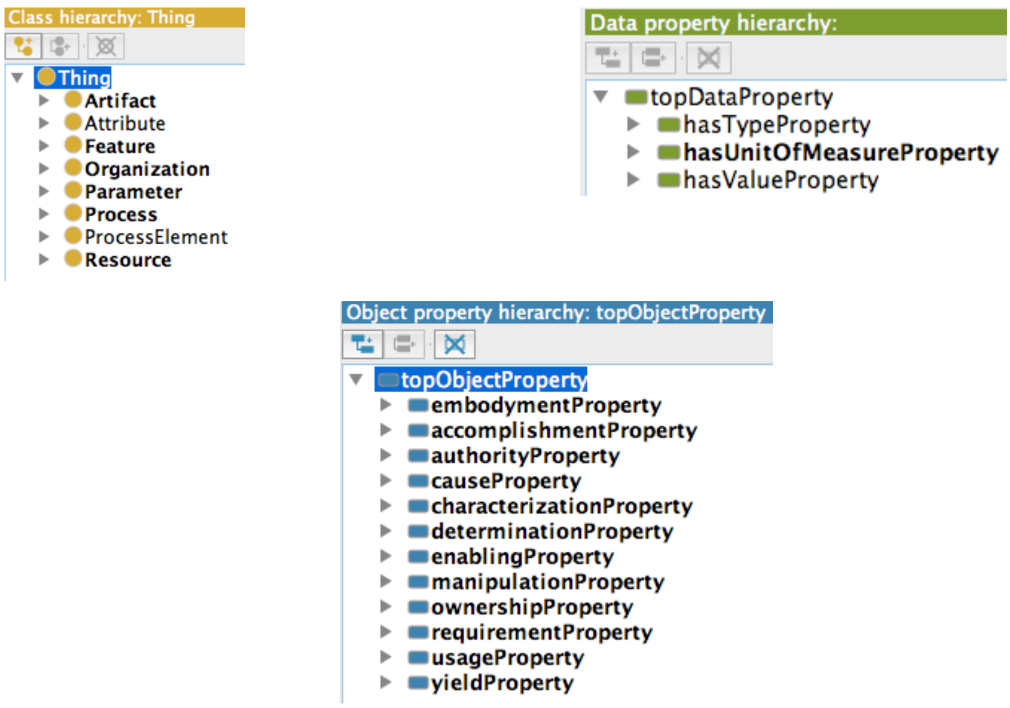

Figure 3.6 – Tree structure of the architectural ODP.
Source: Author.

Object properties and data properties in the various content ODPs were prepared to fit into the categories suggested by the architectural ODP. In addition, relationships with entities in other content ODPs were prepared partially, so that integration was facilitated. For example, object property isAccomplishedByManufacturingUnitProcess refers to class ManufacturingUnitProcess (i.e. range class). However, the definition of 'what' is accomplished by a manufacturing unit process (i.e. domain class) is left for the integration phase. Figure 3.7 depicts how properties in a given ODP were prepared for integration.

In the fourth step, the ODPs were integrated into an overall ontology. A basic structure was created to accommodate all top-level entities imported from ODPs. Some integration issues such as the correct positioning of classes within the overall hierarchy and duplication of terms were solved. In some cases the imported hierarchies were inserted in second or third levels of the hierarchy. In addition, disjoint axioms were built at this point.

Figure 3.7 – Preparation of properties for integration.
Source: Author.

In the last step, an example scenario was tested with the proposed ontology. The quality of a given ontology [53], i.e. regarding accuracy, adaptability, completeness, computational efficiency, conciseness and consistency could be further investigated at this point. An example scenario helped provide insights for many of these issues, as it reflected many situations that would be widely found. For the example scenario, a BPMN model was created to capture the corresponding assembly process. The application example was used to populate the ontology with individuals and assertions. Existing axioms were used to check for consistency. ODPs and the integrated ontology were adjusted accordingly.

***

The following chapter present results and discussion for each of the three phases conducted in the present research.

Chapter 4: Results and Discussion

PLM Knowledge-sharing Ontology

From the capture of motivating scenarios and corresponding knowledge definitions, it has been possible to establish a set of classes for each domain of application. For this task, a bottom-up/top-down approach has been used. A set of primary classes has been listed first. Using this list, teams in each domain of application have included their own classes and definitions. As the class tree started to grow, new terms had to be added in the upper part of the taxonomy, in order to support terms that were included down below.

Table 4.1 contains some examples of classes that have been defined for the proposed ontology. These were named according to a standard created internally by the team, to work both mnemonically and also as a help to trace back the terms origin. Additionally, for the formal definition of each class, team members have sought for a sound reference (either from literature or practice).

Table 4.1 - Example of classes and respective definitions for specific DAs.

DA	Class	Definition
DA1	`TotalQualityManagement`	A business improvement philosophy, which comprehensively and continuously involves all of an organization's functions in improvement activities.
DA5	`CapacityPlanning`	A forward-looking activity, which monitors the skill sets and effective resource capacity of the organization.
DA6	`ProductionNetwork`	A set of inter-firm relationships that bind a group of firms into a larger economic unit.

624 classes and corresponding definitions have been inserted into Protégé. The arrangement of each primary class and respective subclasses is an on-going work, as new terms may be added at any time. However, this preliminary distribution has already provided useful insights into the aimed ontology construction. Figure 4.1 presents an excerpt of the class tree as provided by the Protégé suite, highlighting class `StandardCost` of DA `Cost` (on the left), its lexicon meaning (on the top right) and

respective axioms (both exclusive and inherited) including properties `hasPartValue` and `hasMonetaryValue` (on the bottom right).

In the present work, object instances have not been proposed based on the suggested classes, as the main objective has been to build a common vocabulary for knowledge sharing and information exchange.

In many cases the project team has found out that terms may have been misapplied as time goes by, perhaps due to the absence of a consensual definition. This leads, for example, to misunderstandings and misuse of terms when it comes to describing new approaches or tools used during a product's lifecycle. Frequently, team members had to refer to standards in order to trace back each term's origin. And in some cases, even definitions found in standards are not based on a common understanding from the community in this knowledge area. The upper part of the taxonomy includes 20 terms, as follows: `Activity`, `Attribute`, `Data`, `Environment`, `Interface`, `Item`, `LifeCycle`, `Organization`, `Outcome`, `Person`, `Process`, `Product`, `Program`, `Project`, `Resource`, `Role`, `Stage`, `Strategy` and `Subject`.

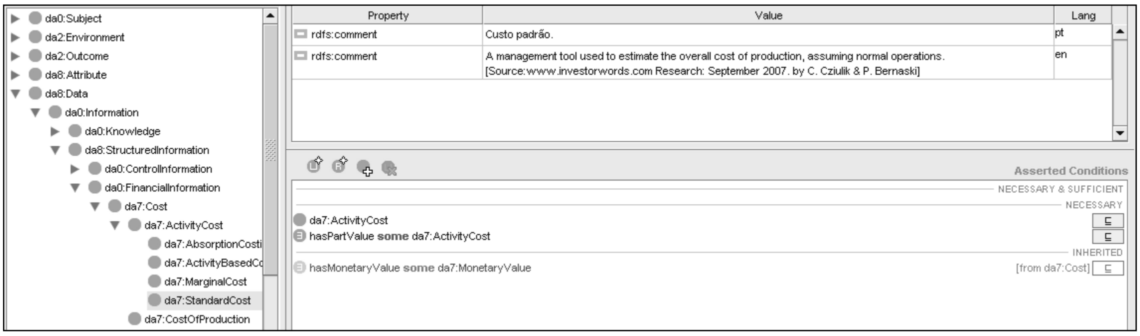

Figure 4.1 – Excerpt of the Protégé suite.
Source: Author.

On the other hand, some terms have been suggested by one DA to another, as better definitions should be found. As the taxonomy grew, terms have been grouped no matter what DA originated their entry. Conflicts were inevitable, and when they occurred, discussion opportunities were provided so that a common understanding could be brought about.

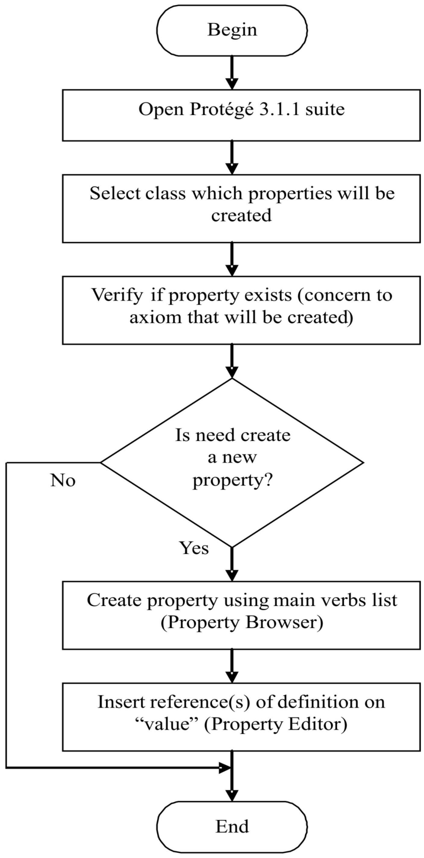

Figure 4.2 – Flowchart to aid property creation and validation.
Source: Author.

One of the greatest difficulties faced in the project, is related to the terminology formal specification that can be employed for the ontology construction. For instance, a conflict occurred when the terms `LifeCycleOfaProduct` and `ProductLifeCycle` were to be added. The first one relates to the consecutive and interlinked steps of a product system, from raw material acquisition or generation of natural resources to the final disposal. On the other hand, the latter describes a vision of product development management, consisting of phases that begin when a product is conceived until the product is no longer available for use. The solution adopted to address this difficulty was to create a discussion list and establish rules to insert such terms and others, which could be listed as synonymous. Workshops were organized with the purpose of unifying procedures, discussing conflicting terms and providing directions for future stages of the research.

Using the Protégé suite environment, properties were examined, created and validated using the flowchart as presented on Figure 4.2. In order to control the number of properties to be included, a restricted set of verbs was suggested as a starting point, as follows: be, have, use, follow, manage, execute, offer, need, occur, work, belong, compose, generate, start, exist, employ and contain. Properties that require any other verb have been evaluated according to the proposed flowchart. Next, 80 properties have been examined and validated by the project team. Figure 4.3 contains examples of properties that have been inserted and validated by the project members.

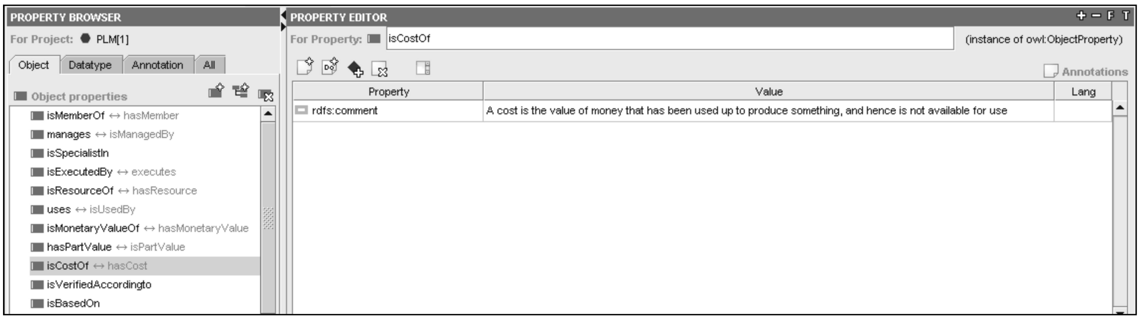

Figure 4.3 – Set of general properties defined for the proposed ontology.
Source: Author.

One of the most time consuming tasks in an ontology creation is the proposal of assertions (restrictions) that relate one class to another. That is because some assertions are automatically proposed based on the taxonomy. However, these are not enough to describe a given term. And even after a set of assertions is correctly applied, these may not completely define a term. This is considered to be an on-going task, as new properties will certainly be added and posted assertions may somehow be questioned in the future. Figure 4.4 presents class `Product` that has been proposed by DA0, with one restriction highlighted (e.g. it reads: *product is an output from the product development process*).

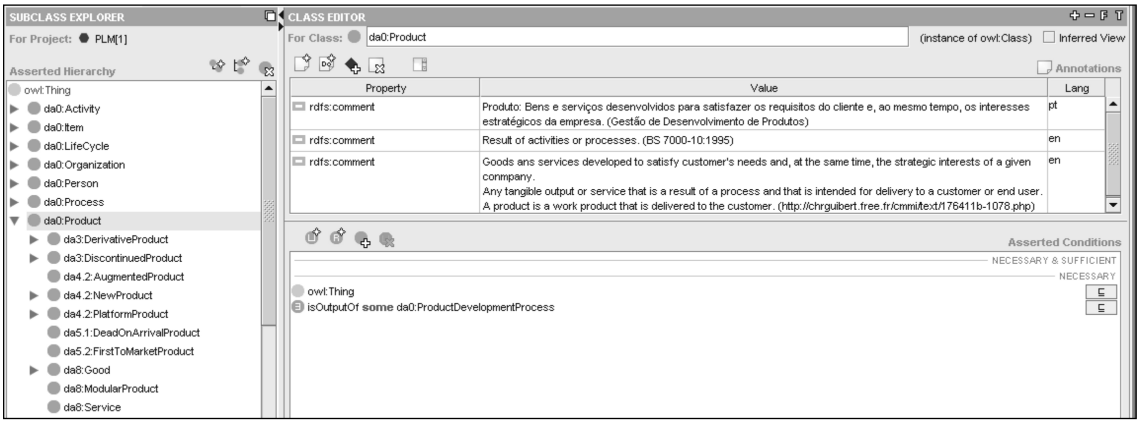

Figure 4.4 – Set of properties asserted for a specific class (in this case, the class: product). Source: Author.

SUSTAINABILITY FOCUSED ONTOLOGY FOR PRODUCT METADATA AND MANUFACTURING PROCESSES

In order to build a consistent, yet slim, taxonomy, eight fundamental classes have been placed in the `DomainConcept` partition, namely: `Activity`, `Data`, `Organization`, `Place`, `Process`, `Product`, `Property` and `Resource`. In the `ValuePartition` segment of the taxonomy, the following seven classes have been introduced: `Currency`, `Date`, `Direction`, `Scope`, `Status`, `Type` and `UnitOfMeasure`. Figure 4.5 presents the top-level hierarchy of terms in Protégé's OWLViz plug-in format. In fact, some of these entities were not placed on the top of the taxonomy at first. Many terms found in the information sources needed supporting classes to make sure a balanced structure could be created. Apparently, after some trial-and-error work was conducted, terms of equivalent abstraction level have let to this configuration.

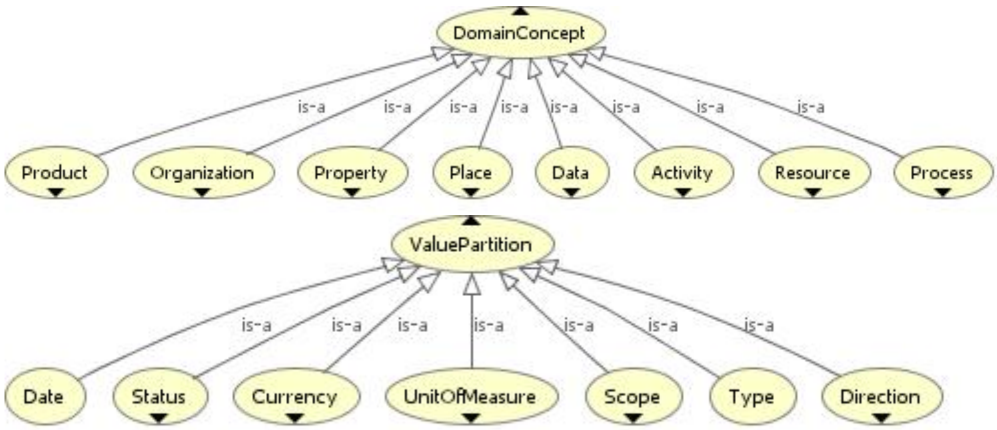

Figure 4.5 – Top-level hierarchy of terms.
Source: Author.

Some classes have presented challenging concepts and definitions, either for their intrinsic nature or because they have been categorized differently in referenced works. Notably, class `Property`, under class `DomainConcept`, has a special role in the suggested hierarchy, which is to join classes that are often referred to predicates of a given item, or "a quality or trait belonging and especially peculiar to an individual or thing". Yet, its subclasses do not fit under the `ValuePartition` category, for they do not lead to the enumeration concept previously mentioned. Figure 4.6 depicts class `Property` and its subclasses. The figure has bee split into two sections to facilitate visualization. Class `Material` is not listed as a subclass of `Property`, as described in the CPM[3] information model. Instead, `Material` has been considered to be a subclass of

[3] The Core Product Model (CPM) is a generic, abstract model with generic semantics. It is defined as a UML class diagram. It provides a base-level product model that is: not tied to any vendor software; open; non-proprietary; expandable; independent of any one product development process; capable of capturing the engineering context that is most commonly shared in product development activities. The core model focuses on artifact representation including function, form, behavior, material, physical and functional decompositions, and relationships among these concepts.

`Resource`, as suggested my several references in the sustainability domain. Moreover, `Feature`, which is also part of the CPM and OAM[4] models, has been considered a synonym for `Property`.

[4] The Open Assembly Model (OAM) defines an extension to CPM. The assembly model represents the function, form, and behavior of the assembly and defines both a system level conceptual model and associated hierarchical relationships.

Figure 4.6 – Class `Property` and its subclasses.

Source: Author.

Class `Product`, also has presented challenging issues when it comes for its hierarchy. Misleading definitions may be found throughout the references used in the present research. The adopted definition "Any goods or service" based on ISO 14040 has given the opportunity to create subclasses `Service`, `OperationalProduct` (defined in ISO 10303), `RelatedProduct` (defined in ISO 10303) and `CoProduct` (defined in ISO 14040). In addition, class `Artifact` (defined in CPM), under `OperationalProduct`, provides a desirable relationship to product information models. Figure 4.7 brings this section of the taxonomy. Many relationship associations suggested either by formalized definitions of terms or by information models such as CPM and OAM have been converted into object properties. For example, assertion "`Artifact` <u>`hasBehavior`</u> `Behavior`" has been created to express that a given individual of class `Artifact` has a certain behavior.

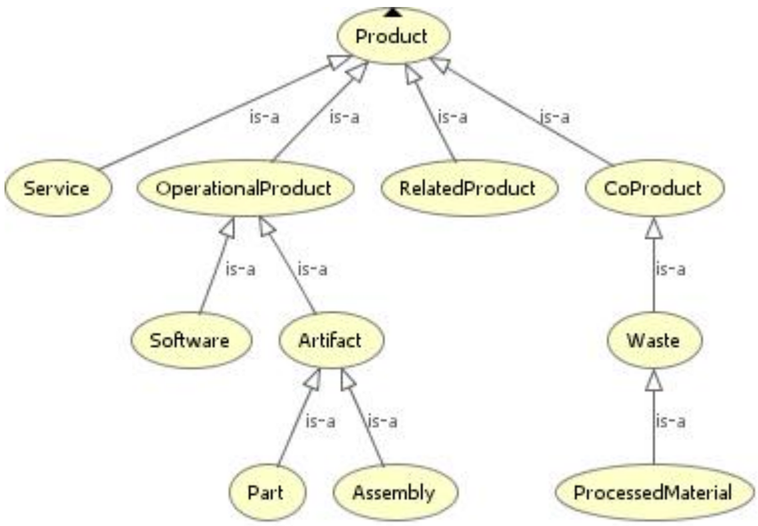

Figure 4.7 – Class `Product` and its subclasses.
Source: Author.

Further developments of class `Process` have also been revealing, for it may be used to comprise process phases and different methods used during a product's lifecycle. Phases of a given process have been linked through object property `isSubsequentOf`, to account for task chronology. Notably, unit processes have been included in this category, following a taxonomy adopted by NRC (1995). Figure 4.8 illustrates the hierarchy under class `Process`.

Figure 4.8 – Class `Process` and its subclasses.

Source: Author.

Typical sustainability related terms have been associated with traditional product and process terms by means of object properties and axioms that were formulated based upon formal definitions. Figure 4.9 depicts some of the object properties associated with class `Artifact`, with is central to the ontology, either in a domain or a range role. For example, a given artifact has an identification name and a number (i.e. part number). That is expressed in axioms[5] '`Artifact hasIdentificationName IdentificationName`' and '`Artifact hasIdentificationNumber IdentificationNumber`'.

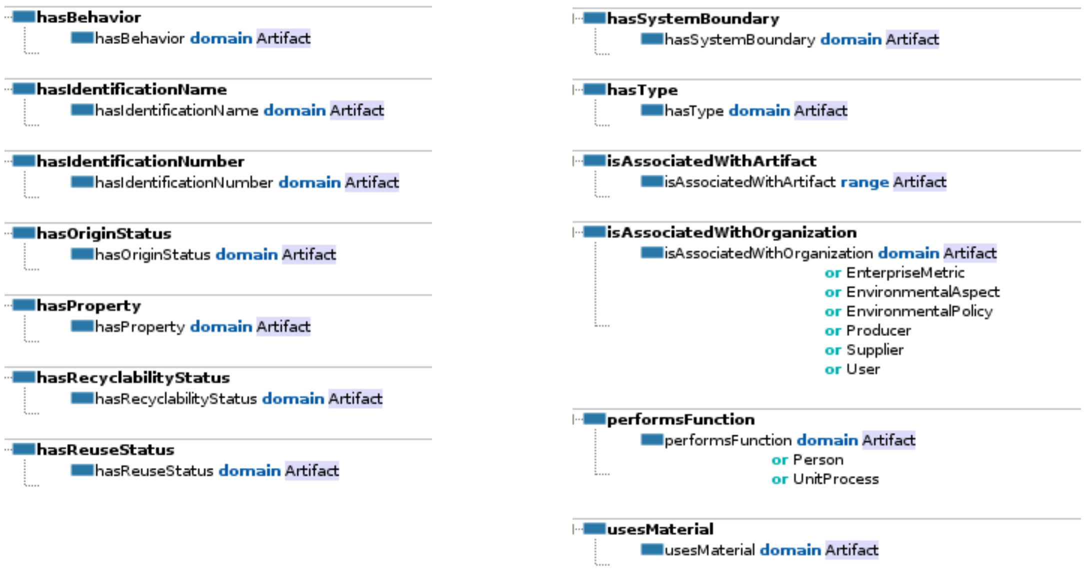

Figure 4.9 – Class `Artifact` and related object properties.
Source: Author.

The ontology proposed by the current research has grown to over 415 classes and 100 object properties. Reasoner **Pellet** has been used to check for *unsatisfiable* classes [54] and, as a result, the ontology is clear of inconsistencies. As ontology building may be considered by many as an evolving work, just like lexicons, the work is

[5] Range classes are not listed in the figure for the fact that the excerpt is taken from ODP `Artifact` before its integration to the overall ontology.

still far from being complete. However, the foundations have been launched upon which future enhancements can be attached.

As a form to evaluate the resulting ontology, an application scenario was conceived, with the purpose of verifying the feasibility of handling one of the most time consuming tasks at present times: relating information extracted from heterogeneous information systems, used in the sustainable manufacturing context. For this, a fictitious scenario has been created, in which a given person is assigned to perform a life cycle assessment (LCA) of a bicycle. Most of the information needed resides in information systems (e.g. PDM, PLM, ERP) that are not semantically connected to the LCA tool. In this particular, yet common situation, the detailed design step in the BOL phase of the innovation perspective has been examined (see figure 2.3). Needless to say, many similar situations may be thought of throughout a product's lifecycle.

The following issues have been raised in this scenario: (a) Which are the components of the artifact? (b) Which material have they been made of? (c) What is the mass of each component? (d) Which manufacturing process has been used for each component? (e) Which components can be recycled?

In order to answer such questions, some individuals (instances of classes) have been created in the proposed ontology (prefixed as "smo"). These instances have been inserted so that queries could be made, with the specific purpose of providing inferred information. The queries have been created using SPARQL [55] and the OWL2QUERY plugin [56] to Protégé. The Pellet reasoner has also been applied in this process. Table 4.2 presents the queries for each issue stated and respective results.

Table 4.2 - Queries used in the application scenario.

Issue	SPARQL queries	Results

(a) Which are the components of the product (bicycle: subassemblies; parts)?	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Bicycle>
	<smo:hasAssembly>?z.
	}
		smo:Break-system
		smo:Front-wheel
		smo:Transmission
		smo:Seat
		smo:Rear-wheel

	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Bicycle>
	<smo:hasPart>?z.
	}
		smo:Frame

	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Rear-wheel>
	<smo:hasPart>?z.
	}
		smo:Hub
		smo:Tire

(b) Which material is a part made of (frame; tire)?	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Frame>
	<smo:usesMaterial>?z.
	}
		smo:7075Alloy

	PREFIX smo: http://www.semanticweb.org/
	ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Tire>
	<smo:usesMaterial>?z.
	}
		smo: StyreneButadieneRubber

(c) What is the mass of a part (frame)?	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Frame>
	<smo:hasMassUnitOfMeasure>?z.
	}
		smo:Gram

	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Frame>
	<smo:massValue>?z.
	}
		"1500"xsd:double

(d) Which manufacturing processes have been used for manufacturing a part (frame; tire)?	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Frame>
	<smo:isAssociatedWithUnitProcess>?z.
	}
		smo:CuttingOperation
		smo:WeldingOperation
		smo:TubeDrawingOperation

	PREFIX smo: http://www.semanticweb.org/ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?z
	WHERE
	{
	<smo:Tire>
	<smo:isAssociatedWithUnitProcess>?z.
	}
		smo:VulcanizationOperation

(e) Which components can be recycled?	PREFIX smo: http://www.semanticweb.org/
	ontologies/2009/11/
	Ontology1261508321455.owl#
	
	SELECT?x
	WHERE
	{
	.x? <smo:hasRecyclabilityStatus>
	<smo:HighRecyclingPotential>.
	}
		smo:Frame
		smo:Tire

In issue (a), three queries are used to provide some of the sub-assemblies and parts of a bicycle. The first query elicits existing sub-assemblies in a bicycle. That produces ‘Break-system’, ‘Front-wheel’, ‘Transmission’, ‘Seat’ and ‘Rear-wheel’ as a set of results. The next query extracts existing parts in a bicycle. That results in ‘Frame’ as a single result. And finally, a query on sub-assembly ‘Rear-wheel’ produces ‘Hub’ and ‘Tire’ as a set of results.

In issue (b), the information about which materials the frame and the tires are made of is extracted from the ontology. That is done by relating class ‘Frame’ and property ‘usesMaterial’ in a query. That results in ‘7075Alloy’. Also, relating class ‘Tire’ and property ‘usesMaterial’ in a query results in class ‘StyreneButadieneRubber’.

In issue (c), the frame’s physical property mass is queried in terms of value and unit. The query results in class ‘Gram’. In addition, a query relating ‘Frame’ with property ‘massValue’ results in ‘1,500’ as a double precision figure. A combination of both queries yields the following meaning: “the frame has a mass of 1,500 grams”.

Issue (d) results in a list of unit processes used for manufacturing the frame and the tires. That is done by relating class ‘Frame’ and property ‘isAssociatedWithUnitProcess’, for producing a set of manufacturing unit processes: ‘CuttingOperation’, ‘WeldingOperation’ and ‘TubeDrawingOperation’.

Issue (e) allows one to retrieve information about the parts that have the highest potential for recycling. This is done by eliciting which part 'hasRecyclabilityPotential' 'HighRecyclingPotential' in a query, resulting in 'Frame' and 'Tire'.

SEMANTIC INFORMATION MODEL FOR SUSTAINABLE PRODUCT ASSEMBLIES

The following competence question is the driver for an ontology for product assemblies with focus on sustainability: 'How can energy efficiency indicators be obtained from assembly design and process data?' The answer is a set of classes and properties that can semantically describe concepts and their relationships.

There are eight top classes in the hierarchy: `Artifact`, `Attribute`, `Feature`, `Organization`, `Parameter`, `Process`, `ProcessElement` and `Resource`, as depicted in Figure 4.10. Various subclasses have been included in this taxonomy for facilitating its extension to account for other types of manufacturing processes and scenarios. For the application example used for validation, only a subset of classes has actually been used. The main developments of these classes are described as follows.

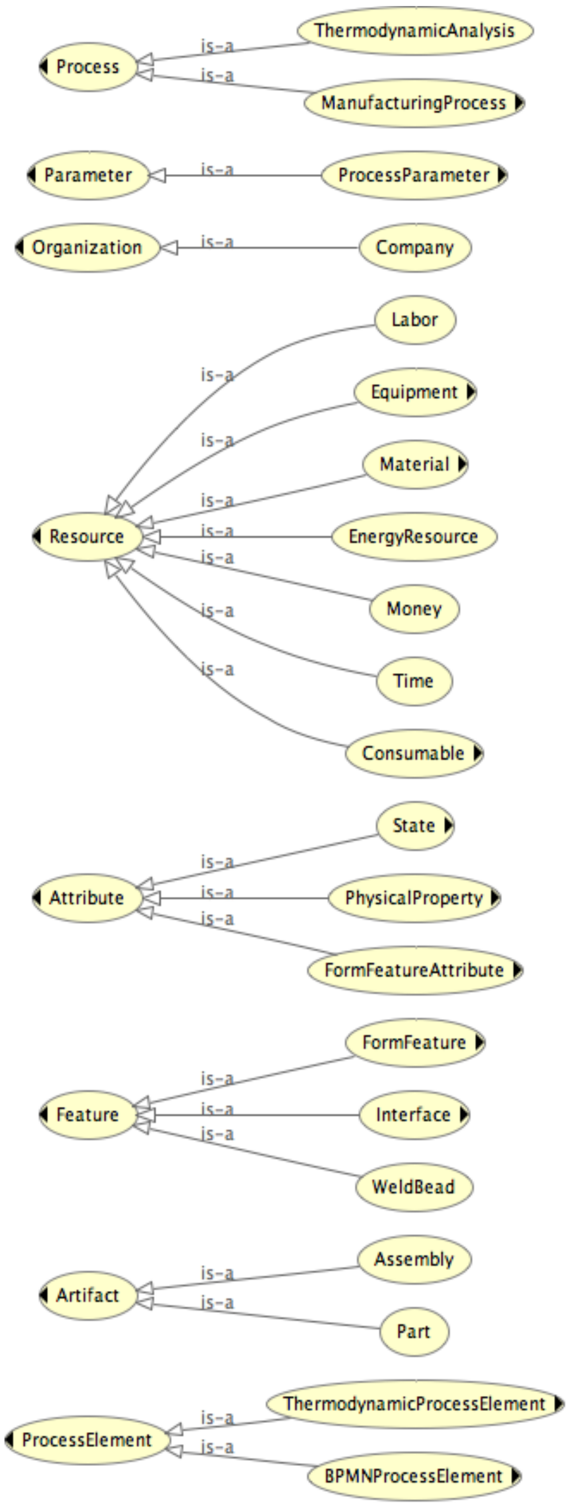

Figure 4.10 – Top class hierarchy.

Source: Author.

Class `Artifact` holds parts and assemblies. In the present ontology, subassemblies are considered assemblies that compose a final assembly. Therefore, an individual of class `Assembly` may embody (`embodiesAssembly`) another individual of class `Assembly` and subsequently, until a given assembly contains only single parts. A 'component' could be either a part or an assembly, depending on its reference to the whole, i.e. in the present work it is considered to be a synonym for artifact.

Class `ProcessElement` was created to hold two very distinct categories: BPMN process elements and thermodynamic process elements. BPMN elements are all entities described in the BPMN standard, such as events, flows and gateways. Thermodynamic process elements, on the other hand, encompass physics-related entities, such as energy balances and system boundaries. Process elements have been placed in a separate class (from class `Process`) because they do not represent processes themselves, but are building blocks for constructing processes.

Class `Process` embodies both manufacturing processes and thermodynamic analysis. Manufacturing processes, in turn, hold auxiliary manufacturing processes and manufacturing unit processes. Auxiliary manufacturing processes comprise 'supply chain operations' (e.g. delivering), which are classified into six different categories, as follows: `AssemblyProcess`, `ConsolidationProcess`, `DeformationProcess`, `MassChangeProcess`, `PhaseChangeProcess` and `StructureChangeProcess`. Important axioms for describing manufacturing unit processes use top classes (e.g. `ManufacturingProcess usesResource Resource`; `ManufacturingProcess manipulatesArtifact Artifact`). Figure 4.11 presents the subclasses of class `ManufacturingProcess`. Future modelling work may account for further describing each particular type of manufacturing process.

Figure 4.11 – Manufacturing processes.

Source: Author.

For the scope of the present work, most activities are either assembly processes (e.g. picking-up, positioning, moving, joining) or consolidating processes (e.g. arc welding). In fact, welding operations have been considered both 'joining' and 'welding', following the multiple inheritance concept of object-oriented programming.

Form features are embedded in class `Features`. This class presents a taxonomy that may be extended to describe several types of connections between parts, as needed for characterizing different manufacturing unit processes. As for welding, 'faces' characterize 'liaisons', and 'edges' are used to characterize 'weld beads'. Even though there is no standard classification of features that serves to all purposes, for the problem at hand the taxonomies proposed by [57-60] have been adapted and applied. Figure 4.12 shows the form feature taxonomy.

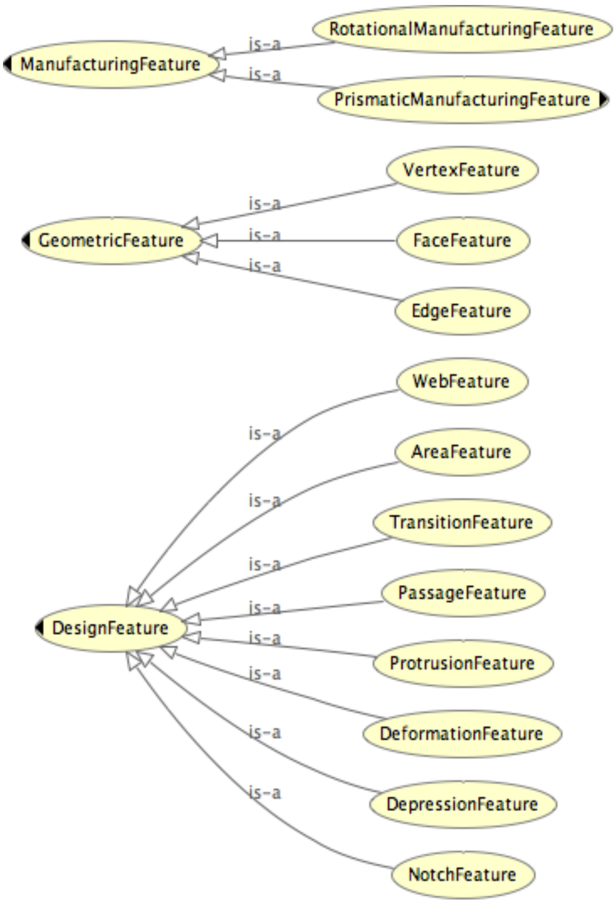

Figure 4.12 – Taxonomy of form features.
Source: Author.

Materials are considered a resource in the present ontology, although some other information models treat them as features [61]. In the case of carbon steel, for example, different types can be created as individuals of class `CarbonSteel`, which can be further characterized by properties such as stiffness (modulus of elasticity), composition and hardness. Specific mass and specific exergy, for example, are required for carrying out thermodynamic analyses. Figure 4.13 presents the general taxonomy of materials.

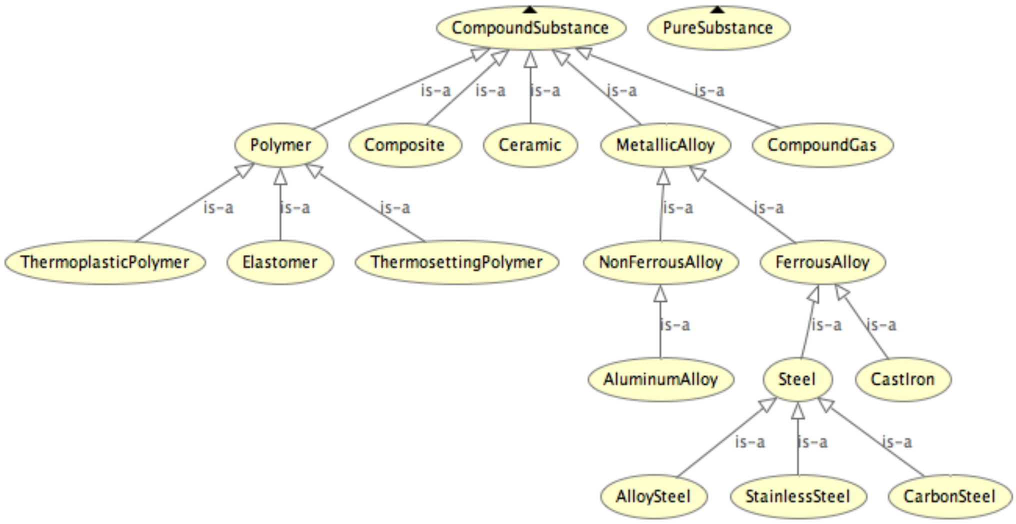

Figure 4.13 – Classification of materials.
Source: Author.

In this ontology, the word 'material' refers to abstract individuals from the point of view of its chemical composition (or other characteristics that distinguish them form other materials). Class `CarbonSteel`, for example, has individuals `ASTM_A131_Grade_AH36` and `E70C-6M_H4`, which have been added for the purpose of the application example. A `Part`, on the other hand, may be associated to weight, for example, by means of axioms `Part usesMaterial Material` and `Part isCharacterizedByVolume Volume`.

Class `Parameter` has process parameters that are to be used to thoroughly describe manufacturing processes. For example, class `TransportationParameter` contains classes such as `FuelConsumption`, `TravelDistance` and `TravelTime`. Parameters required for welding processes are `DepositionRate`, `ArcCurrent`, `WireSpeed` and others, as shown in Figure 4.14.

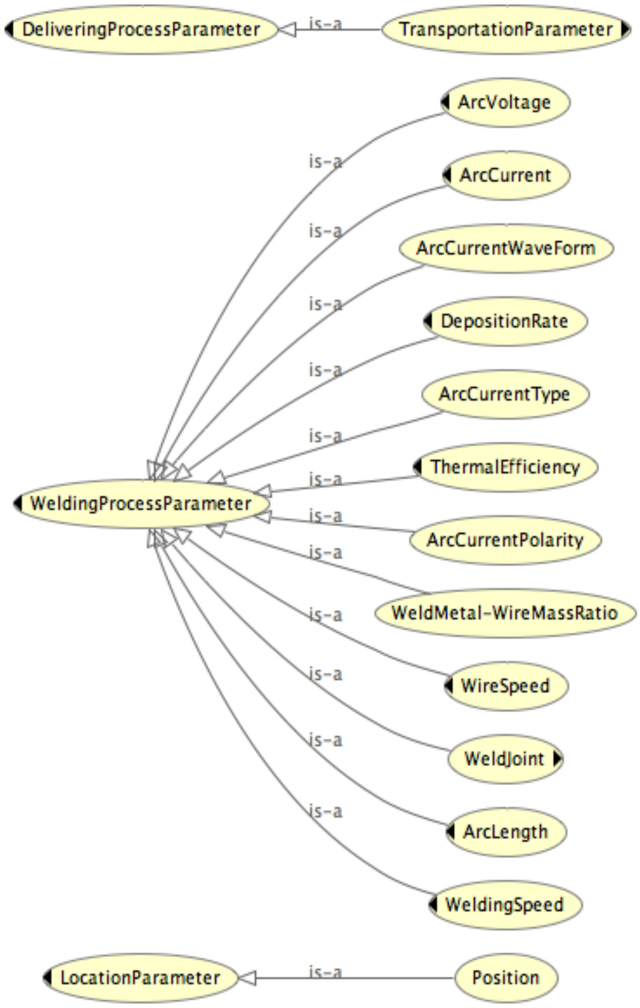

Figure 4.14 – Process parameters.

Source: Author.

Class `Attribute` contains several subclasses that are used for characterizing other terms in the ontology through various axioms. All physical properties are included in this category. Most of them are also related to data properties in such a way that a given physical property has at least a value and a unit of measure. `ArcLength`, for example, is both a subclass of `PhysicalProperty` (i.e. `Length`) and `WeldingProcessParameter`. As a physical property, it is entitled, by means of axioms, to a unit of measure (through data property `hasLengthUnitOfMeasure`) and value (through data property `hasLengthValue`).

Object properties have been organized hierarchically. Each major category has two subcategories, which are inverse. For example, properties in `accomplishedProperty` are inverse of properties in `isAccomplishedProperty`.

One of the most used categories is `isCharacterizedByProperty`, whose underlying properties are shown in Figure 4.15. All properties were created and given some characteristics that would indicate their uses.

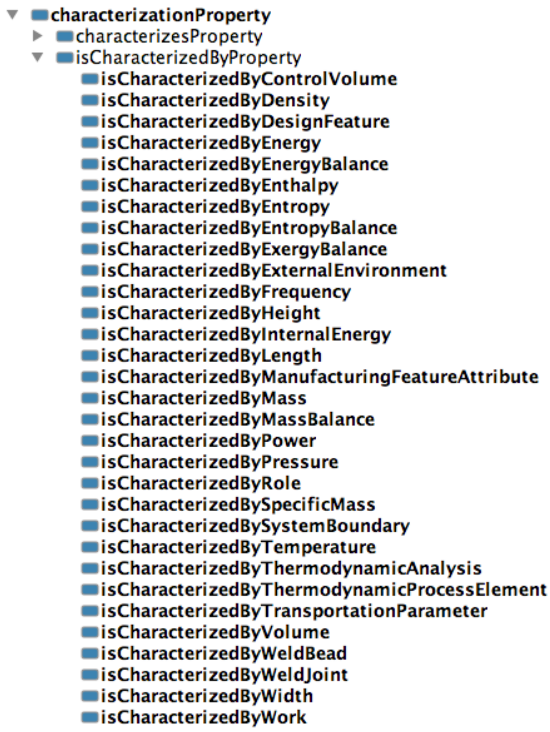

Figure 4.15 – Content of `CharacterizationProperty`.
Source: Author.

Property `isCharacterizedByExergyBalance`, for example, is functional, asymmetric and irreflexive. Its domain is class `ThermodynamicAnalysis` and its range is class `ExergyBalance`. From the previous assertion, it can be inferred that:

- an individual of class `ThermodynamicAnalysis` 'is characterized by' only one individual of class `ExergyBalance`;

- an individual of class `ExergyBalance` is <u>not</u> related to an individual of class `ThermodynamicAnalysis` by property `isCharacterizedByExergyBalance`; and
- individuals of classes `ThermodynamicAnalysis` and `ExergyBalance` are <u>not</u> the same.

Reasoners use this information to infer and provide feedback on the consistency of the ontology.

Data properties are applied in a similar way. They require a domain class as well, but in this case the range is a data type (e.g. float, integer, string). Category `hasTypeProperty` was added to the ones imported from the architectural ODP. An example of data property usage is the set of assertions that are related to an instance of arc current:

- an individual of class `Current hasUnitOfMeasure 'A'` (i.e. `Ampere`);
- an individual of class `Current hasCurrentValue 'double'` (i.e. double precision floating point number);
- an individual of class `ArcCurrent isCharacterizedBy` individuals of classes `ArcCurrentPolarity`, `ArcCurrentType` and `ArcCurrentWaveForm`;
- an individual of class `ArcCurrentPolarity hasCurrentPolarity 'reverse'` or `'straight'`;
- an individual of class `ArcCurrentType hasCurrentType 'AC'` or `'DC'`; and
- an individual of class `ArcCurrentWaveForm hasCurrentWaveForm 'sine wave'` or `'square wave'`.

An Application example has been used to demonstrate how the model developed in the present research can help capture the necessary information for determining energy performance of a given work piece. For this matter, a simplification of a hull panel, commonly used in shipbuilding was considered. Figure 4.16 brings a representation of such an assembly, which is composed of six welded parts of three different types: plate, stiffener beams and keel reinforcements.

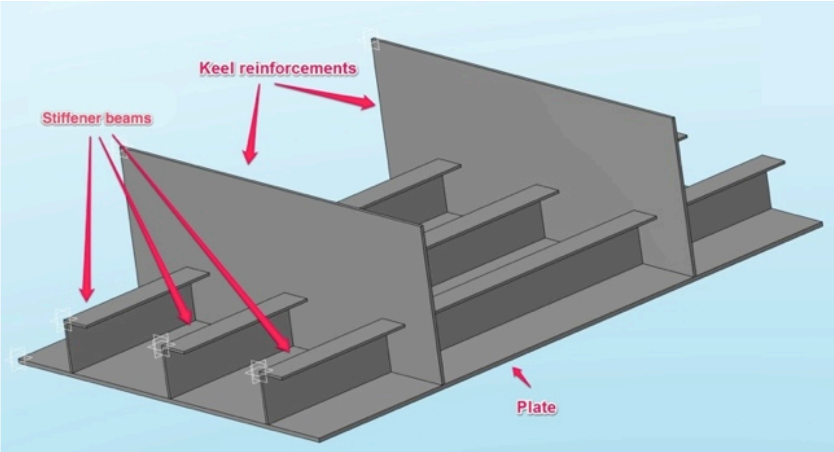

Figure 4.16 – Hull panel 3D model.
Source: Author.

The panel base (Plate) has an overall dimension of 2 m in width, 3 m in depth and 20 mm in steel plate thickness. All parts are shipped by truck from suppliers that are 100 km apart, ready for assembling (i.e. chamfers and other preparations as needed).

In order to account for the completeness of the information model, the application example was added to the ontology in the form of individuals, which were in turn related to each other by means of assertions. Reasoners were then used to check the consistency of the model. Figure 4.17 presents an overall flowchart that describes the major sequence of assertions applied to the ontology for withdrawing relevant information that leads to the determination of energy efficiency indicators (i.e degree of perfection).

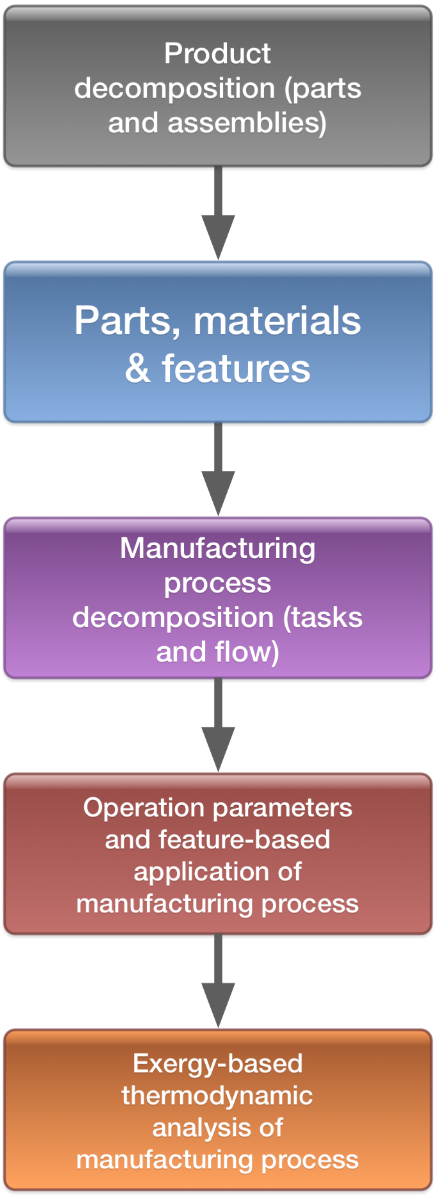

Figure 4.17 – Flowchart for model consistency checking.

Source: Author.

Figure 4.18 presents some assertions that involve assembly individuals and their relationships. The hull panel, in this case, is an assembly manufactured by company Blue Ocean Shipyard. It comprises a plate, 3 stiffener beams and 2 keel reinforcements.

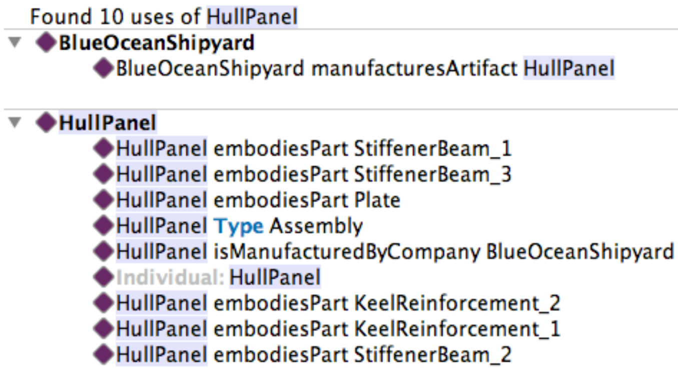

Figure 4.18 – Assertions involving parts and assembly.

Source: Author.

The parts are all made of ASTM A131 steel, grade AH36. In this case, the consumable wire to be used is AWS A5.18/A5.18M-01:E70C-6M H4. The shielding gas is M21 and it is supplied at the rate of 20 l/min. Other welding parameters are: [i] wire feed speed: 1,000 cm/min; [ii] DC current: 300 A; [iii] voltage: 30 V; [iv] deposition rate: 6 kg/h. Three GTAW welding machines, one semi-automatic overhead crane, three assembly operators and three welding operators are required during the assembly process.

The total length of the weld beads required in the hull panel assembly, considering each pass separately, is 106.8 m. Since each weld bead leg is 5 mm long, for each meter of welded joint, the added mass of metallic material is approximately 10.48 kg per pass. Figure 4.19 brings that information in the form of assertions related to material usage in the application example.

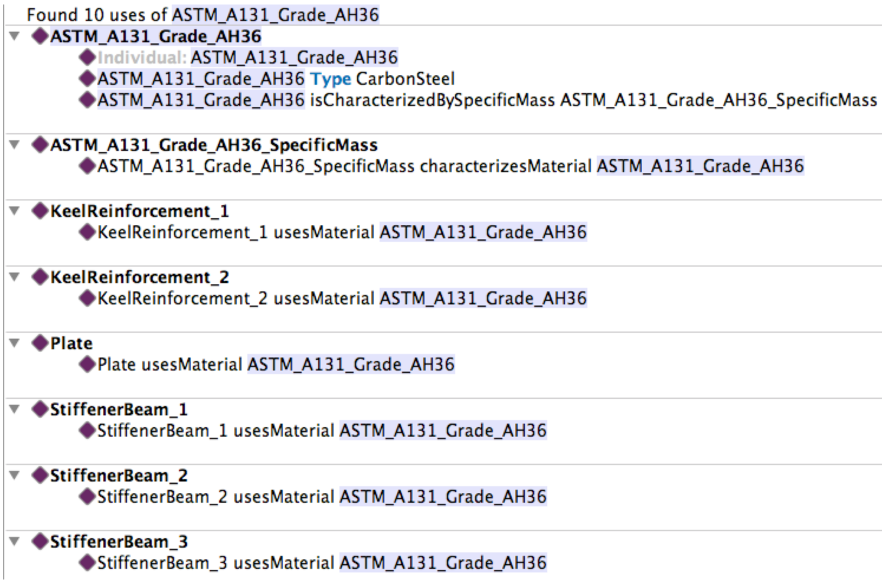

Figure 4.19 – Material assertions.

Source: Author.

The assembly process plan consists of four basic steps, as follows: [i] position keel reinforcements upside down; [ii] position and spot-weld stiffener beams on keel reinforcements forming an “egg box”; [iii] turn “egg box” upside down and position it on steel plate; and [iv] weld all elements. The welding operation in each joint is to be completed with 3 passes.

The manufacturing process plan was modelled in BPMN, and recursively decomposed into activities (i.e. sub processes) until elementary tasks were reached. This approach led to a four-level decomposition structure, as represented in Figure 4.20. A total of 80 elementary tasks were used to describe the entire process.

All BPMN entities (e.g. gateways, flows and tasks) have been mapped into the ontology, for assuring representativeness of the information model. Figure 4.21 shows assertions that relate different BPMN elements such as flows, tasks and activities. Activities (i.e. manufacturing steps) have been defined as a set of BPMN entities, such as tasks, gateways and flows (i.e. an activity “embodies” BPMN elements). BPMN elements (e.g. flows), on the other hand, may "require" other BPMN elements (e.g. destination task) to account for precedence.

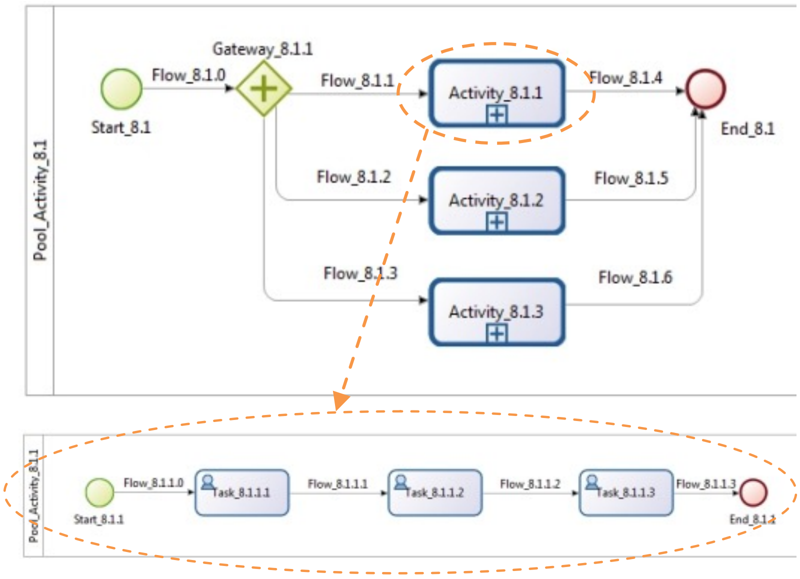

Figure 4.20 – Assembly process decomposition.
Source: Author.

All different types of tasks may compose an activity. For example, `Activity_1` is composed of assembly tasks "pick-up part" (`Task_1.1`), followed by "move part" (`Task_1.2`) and "position part" (`Task_1.3`).

Each task is accomplished by an operation, which in turn corresponds to a manufacturing unit process. A manufacturing unit process requires a set of parameters, manipulates artifacts and uses resources such as labour and equipment. In the case of a welding process, current, voltage, wire feed speed, deposition rate and other parameters are needed. Figure 4.22 shows all individuals connected to a given welding operation.

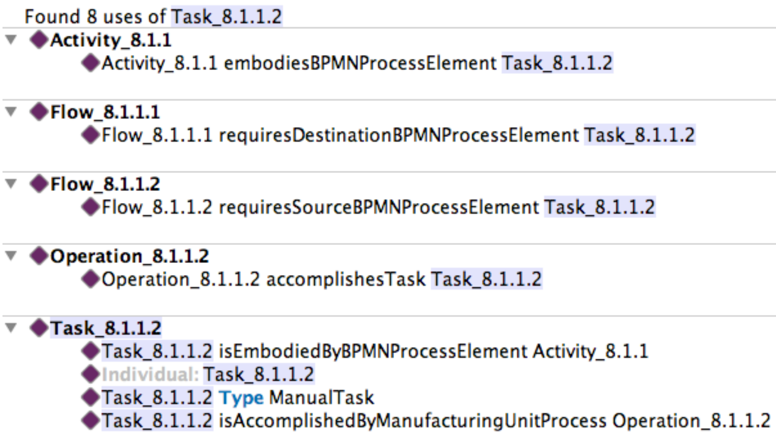

Figure 4.21 – Assertions between BPMN elements.

Source: Author.

Figure 4.22 – Assertions of manufacturing unit process individual.

Source: Author.

A parameter is further described by means of data properties. Therefore, a given parameter such as welding current is expressed by an amount, a measuring unit, type and polarity. Figure 4.23 brings data property assertions for a given individual of type `WeldingCurrent`

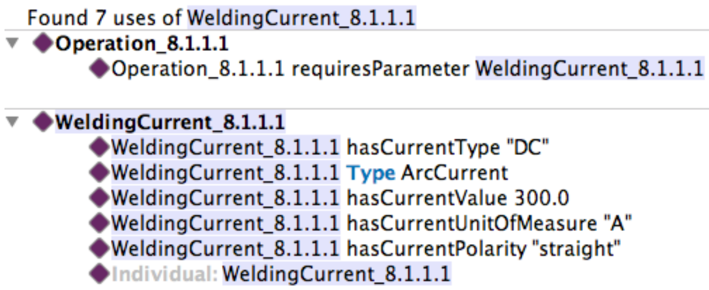

Figure 4.23 – Data property assertions for a welding current individual.

Source: Author.

In this application example, 35 liaisons (i.e. face-to-face contacts), 78 faces and 156 edges characterize the assembly. All features were instantiated, in such a way that each manufacturing operation is related to one or more features and liaisons, therefore allowing complete representation of the assembly, as it is actually built. One of the assertions in Figure 4.24 refers to which liaisons enable a given operation. In this case, `Liaison_1` is an individual of type `WeldConnectionLiaison`, which represents the contact between the top face of `Plate` and the bottom face of `StiffenerBeam_1`.

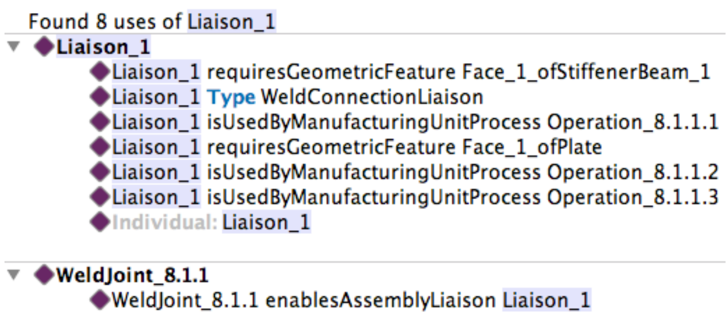

Figure 4.24 – Assertions for liaison elements.

Source: Author.

Once there is an individual for each manufacturing operation, information on resource usage and thermodynamic analysis can be integrated. A thermodynamic analysis is enabled by a thermodynamic system that, in turn, is characterized by control volume, system boundary, external environment and exergy balance. Figure 4.25 shows assertions for a given thermodynamic system individual and its exergy balance.

Figure 4.25 – Thermodynamic analysis assertions.

Source: Author.

A given manufacturing unit process requires individuals that carry information on physical, chemical, work and heat input and output exergies. Each exergy rate has a value, an orientation (in/out) and a unit of measure (MJ/part). Figure 4.26 shows data and object properties of an exergy balance component.

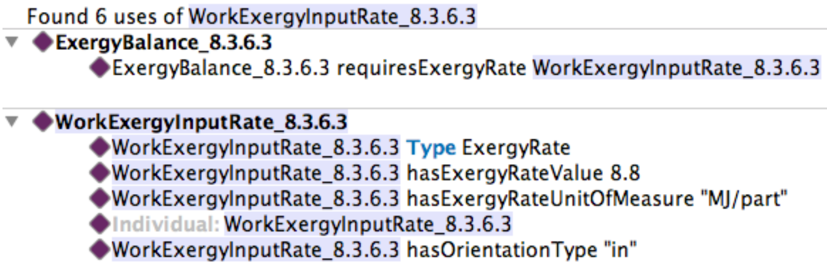

Figure 4.26 – Data and object property assertions for an exergy balance component.
Source: Author.

The overall thermodynamic system embodies all individual thermodynamic systems, including those that characterize supply chain operations, such as delivering parts. In this case, different parameters are required such as fuel consumption, distance and travel time. Figure 4.27 shows an example of a transportation operation.

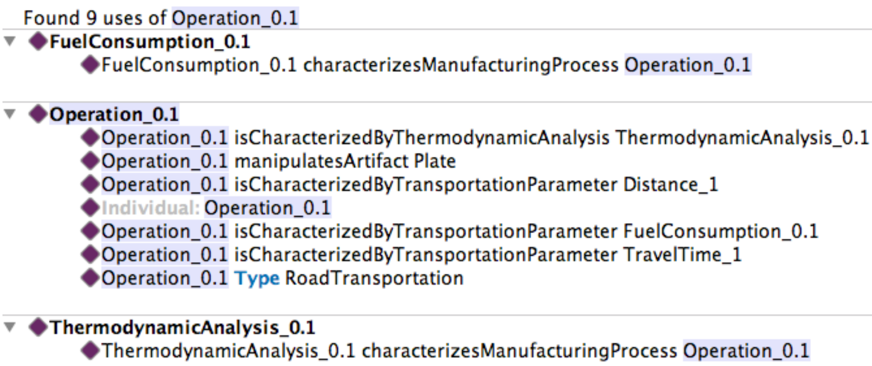

Figure 4.27 – Assertions of a supply chain operation individual.
Source: Author.

The efficiency indicator in an exergy-based thermodynamic analysis is called degree of perfection. In the application example, all singular balances have to be accounted. That is done in an individual named `ExergyBalance_0` (Figure 4.28), which is calculated based on the exergy balances that correspond to each and every one of the unit operations.

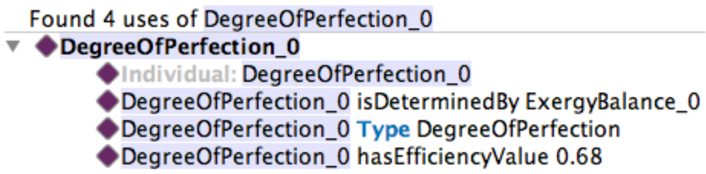

Figure 4.28 – Assertions for a degree of perfection individual.

Source: Author.

***

Next, final considerations for the present work are presented.

Chapter 5: Conclusion

The present research proposal aims at investigating the use of ontologies to represent knowledge in product lifecycle operations, integrate sustainability-related concepts and semantically connect product and manufacturing process data, for ultimately promoting interoperability between information systems in the context of the Integrated Enterprise.

The knowledge area of product life-cycle management demands more basic steps towards establishing a common vocabulary. From this scenario and a thorough literature review, the approach to develop ontologies was identified. The framework proposed by [30] was chosen for the present development. In the first phase of the present work, eight domains of application were structured with their respective scopes. These allowed establishing 624 classes, 80 properties and 211 restrictions that were implemented into the Protégé Suite software.

In order to cope with increasing demand for seamless reliable data exchange during a product's lifecycle, including disposal, an ontology for products and processes with emphasis in sustainability has been proposed. Compared with the standard-based approach to data exchange, ontology-based approaches carry the necessary semantics to allow unambiguous information sharing. However, negotiation agents and protocols must be based on ontologies that represent the domain where communication has to take place. A possible strategy for communicating relevant information between heterogeneous environments is the use of formal ontologies as *interlingua*.

In the second phase of the present research, terms that represent the domain of sustainability in manufacturing have been identified in reliable sources, selected and organized. The semantics around such terminology, represented by axioms, were built, so that querying, mapping and translation of information between heterogeneous information systems used throughout the lifecycle of a product can take place. A fundamental taxonomy has been proposed, as well as object properties that relate each class to other entities. Key entities such as **Product**, **Process**, **Material** and **Property** have been evaluated as for their original meaning, so that the resulting taxonomy is robust and capable of being extended as necessary.

The possibilities to use the proposed ontology are many. For example, interoperability test beds may benefit from non-human translation between data entities. New systems that support certain activities carried out to support product development, use and disposal, such as LCA and QFD efforts, may exchange data through an arbitrated means, such as an *interlingua* mapping agent or service. This allowed future work to be conducted around building object properties that could relate each manufacturing unit process with resources, such as **Material**, **Energy** and other relevant entities. Even regulatory restrictions could be represented through assertions that relate accounted amounts of toxic material to artifacts on the supply chain and for product disposal purposes.

In the third and last phase of this research, a knowledge base regarding product assemblies with focus on sustainability has been proposed. An OWL ontology that has classes, properties and axioms has been built and tested for consistency, representativeness and completeness. For a given assembly context, it is now possible to capture all the necessary information for calculating energy efficiency indicators such as the degree of perfection.

The OWL ontology hereby presented has unique features. It has been created using ontology design patterns, allowing modellers to reuse components, add new features and update modules, just as it is commonly done in object-oriented programming. In addition, feature-based assembly modelling has been applied for binding geometric features to manufacturing process operations. Process operations, in turn, are further described in a BPMN-like manner, resulting in a process model that can be reasoned and inferred. On the other hand, an approach to carry out energy analysis has been embedded in the model, linking physical phenomena data to process planning steps.

A product assembly model with focus on sustainability may be used for several purposes. It can provide the means to integrate data from different applications, such as PLM systems and energy performance prognostics, or CAPP software and decision-making support systems in product design, with focus on energy performance. In addition, it may facilitate data integration in the extended enterprise environment as well as the development of standards that can lead to seamless interoperability of manufacturing information systems.

The utility of ontologies has been verified against a welded assembly scenario. The manufacturing process has been modelled to the granularity of unit processes and supply chain operations, so that an exergy-based thermodynamic analysis can be performed. The present work main contribution has been twofold: (i) to bring up the idea of collecting the required knowledge on physics and modelling techniques and representing it in the form of an OWL ontology, and (ii) to demonstrate its feasibility, which is done by means of assertions that can be used to show how the degree of perfection can be derived from a logical description of the phenomena and primitive inputs.

Future work is suggested to implement ontology-based applications that can use data provided by CAD systems and other sources. Furthermore, advanced modelling of the welding process should be considered in upcoming developments of the present work. Other manufacturing processes, such as cutting or moulding, which require particular parameters can be modelled in the future, and tested for adaptability of the current approach, as it is believed the foundations launched by the present work can support further incursions into more complex processes.

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