Semantic Interoperability and Sustainability an Industry 4.0 Product Life Cycle Issue

Yasamin Eslami, Sahand Ashouri, Mario Lezoche

Semantic Interoperability and Sustainability an Industry 4.0 Product Life Cycle issue

Yasamin Eslami[1[0000-0003-4767-7724]], Sahand Ashouri[2[0000-0001-5196-756X]] and Mario Lezoche[1[0000-0002-3271-1742]]

[1] Université de Lorraine, CNRS, CRAN, Nancy, France
[2] Politecnico di Milano, Milan, Italy
yasamin.eslami@univ-lorraine.fr, sahand.ashouri@mail.polimi.it, mario.lezoche@univ-lorraine.fr

Abstract. Four concepts stand out in the current landscape of modern industrial production. The product life cycle, sustainability, Industry 4.0 and semantic interoperability. The article will be focused on creating a link between the four and expresses the strong causal relationship between them in order to optimise production processes. To that point, a 3D model will be developed to bridge sustainability and product life cycle inside an organization. Then, knowledge formalisation techniques will be discussed for constructing a mutual understanding of the semantics in the context on Industry 4.0 throughout the developed model.
Keywords: Product Life Cycle, Semantic Interoperability, Knowledge Formalization, Big Data, Data Mining, Sustainability models, Industry 4.0.

1 Introduction

The concept of the Product Life Cycle (PLC) has been introduced since the 1950s[1], and it is a biological metaphor that describes every phase a product goes through, from the first initial requirement until it is retired and disposed.

Product lifecycle management (PLM) expresses the engineering point of view of product life-cycle concept and integrates the aspects of people, processes, and data to manage the entire life cycle of the product. It is also defined as a set of capabilities that enable an enterprise to effectively and efficiently innovate and manage its product and related service throughout the entire Product lifecycle (PLC) [1]. PLM offers a shared platform through which the process of capturing, representing, retrieving and reusing knowledge is supported to collate various enterprise system at each stage of PLC. The knowledge concerning a product along its life cycle, which is named as PLC-related knowledge, has become one of the essential concepts in a PLM solution[2]. Therefore, abilities like knowledge discovery, data cleansing and inferencing must be inactivated through the PLM solutions to exchange information, data and knowledge in a meaningful way.

knowledge brings to its owner the capability of grasping the meaning (Semantics) from the received information. Semantic interoperability is the ability to ensure that the exchanged information has got the same meaning considering the point of view of both the sender and the receiver[3]. In order to have a more connected and thus sustainable organization, the systems inside have to work together on the exchanged information and take decisions based on this information. They have different procedures, backgrounds, unique knowledge, particular needs and specific practices, which increase the difficulty to achieve the semantic interoperability[4]. The same problem goes for PLM, as its stakeholders, who operate on the information systems, have different traits which itself increases the difficulty to achieve semantic interoperability. This situation interferes in achieving a mutual understanding between all the systems, and so does in the cooperation across the enterprises. To overcome the obstacle, the implicit knowledge should be brought to the surface and be formalized explicitly with the help of knowledge formalization techniques so that it is mutually and semantically understood by all parties. This way semantic interoperability and consequently cooperation can be achieved inter and intra systems in an organization and throughout PLC. Putting altogether, the present study will be mainly focused on the issue of mutual understanding of the semantics for supporting knowledge management in the context of PLC inside an organization through modelling and knowledge formalisation techniques, all aiming at achieving sustainability inside an organization.

2 Product life cycle and sustainability

PLM evolves around data visualization and transformation, a context in which ICT (Information and Communication Technology) plays an important role. Together with ICT, there are two other important levels that establish PLM: Process and Methodology. The former points at the data flow among the actors/resources while the latter is practice and techniques adopted along the processes, using and generating product data [8]. The three elements move through the life cycle of the product to reach a better connectedness in all the stages (see Fig.1).

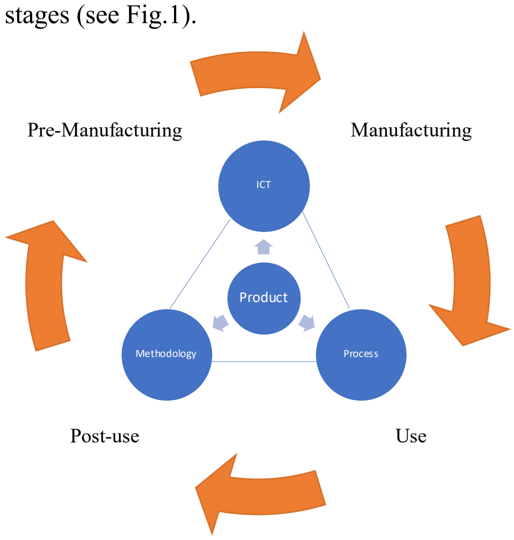

Fig. 1. PLM and its elements [inspired by [8]]

Enterprises are forced by several increasing challenges such as resource depletion, economic stagnation, human being pursuing higher life quality and stricter regulations and banning policies. Sustainability has intended to empower the companies to cope with such challenges and guide them to stand out in the competitive market today. Due to [3], there are main aspects to be considered in terms of sustainability to help enterprises cope with the challenges they are faced. The study shows that, sustainability should be looked at in a holistic way inside the enterprise and the big picture must be considered to avoid ad hoc solutions. The Triple Bottom Line (TBL: economic, environment and social) must be considered at the three associated levels that matter in an enterprise namely product, process and system. In addition to that, no product life cycle stage is excluded from sustainability concerns, therefore another aspect would be to visualize and standardize the relationships and links between activities needs to be performed throughout the life of a product.

The closed loop life cycle of the product consists of four main stages: Pre-manufacturing, Manufacturing, Use and Post-use. In addition, attempts to close the material loop and to transform the life cycle have been made to support product and material reutilization and product end-of-life management. Many works like[5] accomplished the task by using 3R (Reduce, Reuse and Recycle) or the 6R (Reduce, Reuse, Recover, Redesign, Remanufacture and Recycle) throughout the manufacturing cycle and the product life cycle. On the other hand, based on the analysis [5] and [6] made, the concept “6R” was announced as the one factor that plays the most important role in reaching environmental sustainability, and the one with the highest influential level in sustainable manufacturing respectively. Therefore, to understand thoroughly the content of sustainability of a product, it is necessary to have a total analysis of the life cycle of the product and it’s imperative to have all the 4 stages plus the 6R in any new evolutionary sustainability methods [7].

3 The Life Cycle and Industry 4.0 issue of the semantic interoperability

PLC can be classified into five main phases[6] from production point of view (shown in the Fig.2): (1) Imagination phase, in which, a product only exists as an idea in human’s mind; (2) Definition phase, in which, the idea of product is formulated by various kinds of description; (3) Realization phase, in which, an actual product is manufactured following the description;(4) Using and Supporting phase, in which, a product is used by a customer and benefits the supports from the enterprise; (5) Retiring and Disposing of phase, in which, a product is no longer used by a customer and needs to be recycled or disposed of. In fact, this categorization is at a high abstraction level. Actual PLC models are always represented in a more complete way through extending more details in one or several of these phases. The Computer Aided Design systems appears in the early 1980s, along with its evolution, the problems of locating the required data and losing control of change process associated with these data become increasingly intense[7]. The needs of easy, quick and secure access to valid data during the product design phase became the primary motivation to the development of a Product Data Management (PDM) solution[8].

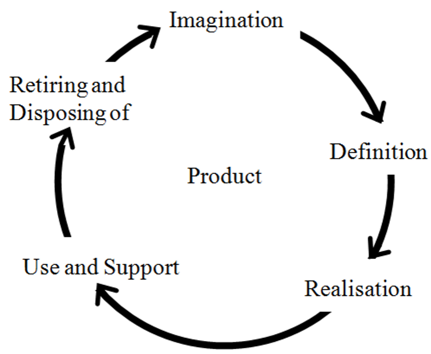

Fig. 2. Product Life Cycle [3]

However, due to the limited scope and the initial design of PDM solution, it is usually restricted to handling the product data in the engineering domain, but it remains inadequate with the non-engineering data, such as sales, planning, after sale services and so on. To be more specific, unlike the comprehensive supports to Computer Aided Design (CAD), Computer Aided Engineering (CAE), Computer Aided Process Planning (CAPP) and Computer Aided Manufacturing (CAM), PDM solutions cannot provide all the necessary supports to Enterprise Resource Planning (ERP), Supply Chain Management (SCM) and Customer Relationship Management (CRM).

In order to further extend the functionalities of a PDM solution and to fill the gap between the PDM proposal and the enterprise business activities, during the 1990s, the concept of Product Lifecycle Management (PLM) is proposed. Different from a PDM solution that only focuses on managing product data, a PLM solution focuses on managing all the PLC-related knowledge throughout the different phases of the PLC [9]. It aims at providing a shared platform for facilitating the process of capturing, representing, organizing, retrieving and reusing the knowledge concerning the related product in or across enterprises, and to provide the integration strategies and technological supports to bring together all existing enterprise systems that dealt with the product [10].

More and more enterprises adopted the PLM solutions and discovered the benefits for their complex engineered products in the last decade. According to the market research in IT enterprises, PLM became one of the fastest growing markets and the total revenues of PLM in 2006 is projected to increase by $ 5.5 billion compared with the corresponding period in 2001[8]. Presently, an increasing number of commercial PLM solutions have been developed, for example, to mention only a few, Agilie PLM solutions, Siemens PLM Software, Arena PLM solution, SAP PLM, PTC Windchill. Based on their functions, the existing PLM solutions can be classified into three groups [11]: (1) Information management, which provides methods to identify, structure, store, retrieve and share product, process and project-related data. (2) Process management, which provides methods for modelling and operating formal and semi-formal processes. (3) Application integration, which defines and manages the interfaces between the PLM platform and the variety of enterprise systems (such as CAD, CAM, CAE, ERP, MES, CRM, etc.).

Though, all existing PLM solutions try to propose an efficient and powerful collaboration environment for the variety of enterprise systems, they are still obstructed by various kinds of issues. From the collaboration point of view, due to multiplicity of formats, standards and versions, [10] considered the information sharing and exchange as one of the main challenges in PLM. From the implementation point of view, CIM data concluded that the cost, the quality, the time-to-market and the innovation are the four main challenges for a PLM solution[7]. Hewett indicated six main directions for improving the current PLM solutions: data exchange, design collaboration, enterprise-centric view, scale to reality, standard and technique for engineering processes, information and knowledge representation[12]. Among all these issues, one of the main drawbacks of existing solutions draws our attention: they are mainly focusing on dealing with the syntax but rarely the semantics of the objects that are produced, transformed, exchanged during the PLC. One of the first purpose of this research is to propose a way for assisting the mutual understanding of the semantics that embedded inside the shared and exchanged objects for further supporting the knowledge management processes in the context of PLC.

Industry 4.0 reflects a combination of digital and manufacturing technologies, Specifically the new technological transformation embraces technological advances that concern the production process (i.e., advanced manufacturing systems, autonomous robots, additive manufacturing), the use of smart products and/or data tools and analytics [13]. The increasing multiplication and complexity of the information necessary for the management of production processes pushes to the structuring of knowledge to accelerate its passage and optimize the interoperability of systems. In Fig.3 we can see all the different steps where the implicit knowledge of the systems is a brake to the knowledge passage itself between the various systems.

In the face of this new epochal change, two characterizations were highlighted:

- The importance of knowledge as a means of development and evolution. The information needed to manage production processes is increasingly numerous, more heterogeneous, more volatile and more distributed. This implies the use of business information systems increasingly linked to real processes in a continuous way in order to retrieve and process data, contextualize them into information and apply knowledge to improve performance.
- The key role that some technologies, such as cyber-physical systems, are playing in the restructuring of dominant roles in society.

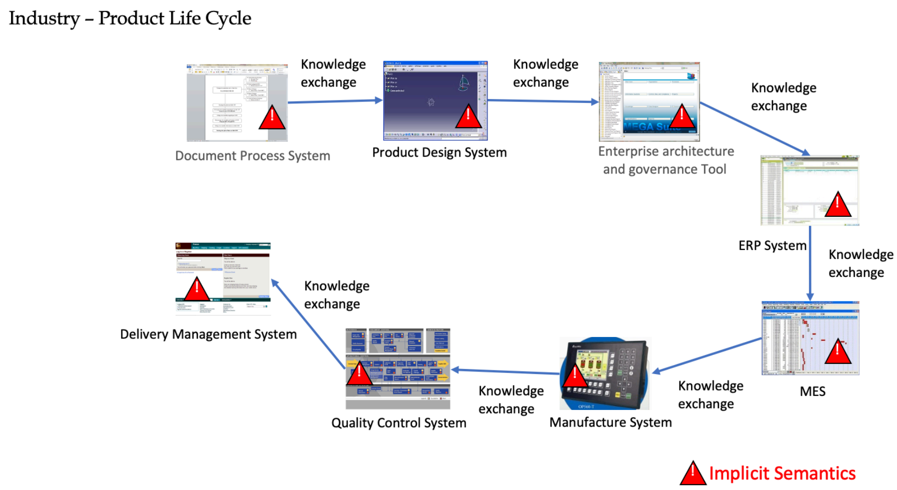

Fig. 3. Implicit semantics and semantic interoperability problem[3]

The exploitation of the knowledge accumulated in the various systems involves two different issues. The first is the need to model systems so that they can semantically interoperate without problems of meaning. The second is to highlight methods to formalize and extract knowledge from all systems that are part of the value creation chain.

The two issues are discussed in the following:

3.1 Modelling

Due to the aforementioned, connectedness and interoperability in terms of data, meaning and process between life cycle stages is prominent to characterize sustainability. Otherwise, information from not connected parts can be lost and knowledge cannot be formalized correctly. Therefore, there would be the risk to have missed or incomplete knowledge and the process of knowledge formalization gets into a repeated loop which can be both time and resource consuming. That itself misleads the enterprise form the context of sustainability, the very first goal all the attempts were put for.

To cover the discussed issues above, a 3D model (see Fig.4) is introduced here to make help reach sustainability in an organization. The reference model aims at sustainability in diverse aspects in a holistic view. It combines the functional level inside the enterprise with the life cycle of the product in line with the TBL. The reference model maximum traceability of information is provided as it clarifies description, implementation and accessibility to sustainability in each intersection of dimensions inside the model. It looks at the big picture while it maintains the awareness of the interconnectedness of the components of the picture; its combination of hierarchical level inside an enterprise (product, process and system) with the life cycle of the product (pre-manufacturing, manufacturing, use and post-use) for the three main dimensions of sustainability (economic, social and environmental). In addition, and due to the derived essence of sustainability, the 6R concept (Redesign, Remanufacture, Reuse, Recover, Recycle and Reduce) will be considered inside the life cycle of the product at the "post-use" stage.

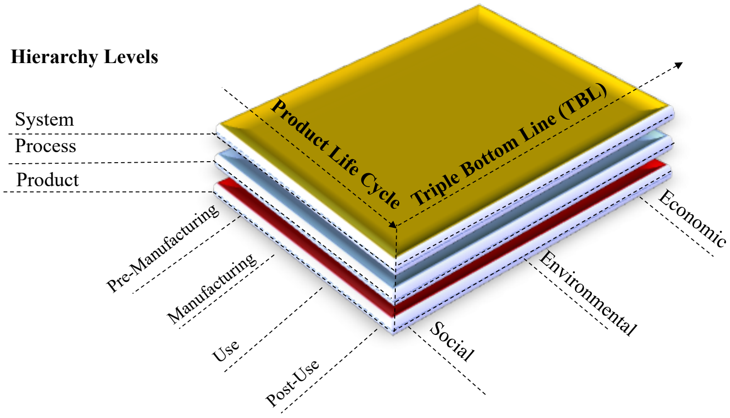

Fig. 4. 3D model for sustainability in an enterprise [14]

To employ sustainability in the context of life cycle, all activities belonging to the life cycle of the product should be optimized to reach an efficient management of information and process. As mentioned before, the lifecycle sustainability approach, means to deal with product or service evaluation from material extraction (pre manufacturing) to manufacturing and use and ends it by recycle in post use stage. Going through all the stages, information is generated and needs to be analysed and formalized to create knowledge.

3.2 Knowledge formalization

As already has been discussed above, Cooperation is achieved inside an information system if the information is physically exchanged, is understood and is used for the purpose for which it has been produced. Therefore, an obstacle towards having the systems cooperate to reach sustainability inside the model described in Fig 4, is the semantic interoperability [15]issue. To overcome that, two important obstacles are on the way:

- The implicit semantics that is necessary for understanding a knowledge representation that is not made explicit.
- The lack of mechanisms to verify the correctness of explicit semantics in the exchanged knowledge representation.

A mutual understanding of the semantics inside the shared and exchanged knowledge representations is the cornerstone in the quest for semantic interoperability. To achieve this goal is crucial to formalize the knowledge exchanged between the systems inside the organization. This way, semantic explication of the exchanged knowledge is represented and is mutually understood while cooperation.

Formal concept analysis (FCA) [16] has been proven as a versatile framework for Knowledge discovery from data (KDD)[17] in many practical applications[18]. It extracts knowledge as a compact set of association rules. Relational concept analysis (RCA)[19] is MRDM extension of FCA. However, straightforwardly defined relational association rules may easily contain circular references or references from conclusion to premise, thus preventing a meaningful interpretation. FCA[16] is an algebraic approach for eliciting the conceptual structure of a dataset. Input data format is a triple $K = (O, A, I)$ called a (formal) context. O is a set of objects, A is a set of attributes and $I \subseteq O \times A$ an incidence relation listing valid pairs (o, a) (object o has the attribute a). FCA reveals all pairs of sets $(X, Y) \in \wp(O) \times \wp(A)$ strongly correlated, meaning that all objects having the attributes in Y are in X and vice-versa. Such pair is a (formal) concepts with an extent X and intent Y. Relational concept analysis assumes datasets are made of several contexts, one per type of object, and context-to-context relations. Any relational intent can be described with only non-relational attributes. Such expansion avoids circular dependencies, even if one may exist between full intents.

4 Conclusion

The product life cycle is one of the pillars of modern industry. The advent of the industry 4.0 paradigm has introduced the possibility of using data, information and above all knowledge to optimize production and introduce the concept of sustainability in an extremely important way. These three concepts are made cohesive by a fourth and central concept which is semantic interoperability. In this article, the strong link between these four concepts is highlighted, through a developed model and knowledge formalization inside the model to reach semantic interoperability. This way, semantic explication of the exchanged knowledge throughout PLC is represented in forms of lattices and is mutually understood while all defined dimension of the model will cooperate inside the organization. Accordingly, the link among the four concept is quantified by the help of clustering techniques as FCA in order to create an automated process for structuring automated industrial production.

References

1. Rink DR, Swan JE (1979) Product life cycle research: A literature review. Journal of Business Research 7:219–242. https://doi.org/10.1016/0148-2963(79)90030-4
2. Gupta S, Dangayach GS, Singh AK (2015) Key Determinants of Sustainable Product Design and Manufacturing. Procedia CIRP 26:99–102. https://doi.org/10.1016/j.procir.2014.07.166
3. Liao YX, Lezoche M, Rocha Loures E, et al (2014) A Semantic Annotation Framework to Assist the Knowledge Interoperability along a Product Life Cycle. Advanced Materials Research 945–949:424–429. https://doi.org/10.4028/www.scientific.net/AMR.945-949.424

4. ETIENNE A, GUYOT E, VAN WIJK D, Roucoules L (2011) Specifications and Development of Interoperability Solution dedicated to Multiple Expertise Collaboration in a Design Framework. International Journal of Product Lifecycle Management 5:272–274
5. Lu T, Gupta A, Jayal AD, et al (2011) A Framework of Product and Process Metrics for Sustainable Manufacturing. In: Advances in Sustainable Manufacturing. Springer, Berlin, Heidelberg, pp 333–338
6. Stark J (2011) Product Lifecycle Management: 21st Century Paradigm for Product Realisation, 2nd ed. Springer-Verlag, London
7. PDM to PLM: growth of an industry. / Conteúdo / Home - Portal de Conhecimentos. http://www5.eesc.usp.br/portaldeconhecimentos/index.php/por/content/view/full/11623/(relations)/all. Accessed 11 Apr 2021
8. Ameri F, Dutta D (2013) Product Lifecycle Management: Closing the Knowledge Loops. Computer-Aided Design and Applications 2:577–590.
9. Ameri F, Dutta D (2005) Product Lifecycle Management: Closing the Knowledge Loops. Computer-Aided Design and Applications 2:577–590. https://doi.org/10.1080/16864360.2005.10738322
10. Ball A, Ding L, Patel M (2008) An approach to accessing product data across system and software revisions. Advanced Engineering Informatics 22:222–235.
11. Abramovici M (2007) Future Trends in Product Lifecycle Management (PLM). In: Krause F-L (ed) The Future of Product Development. Springer, Berlin, Heidelberg, pp 665–674
12. Hewett A (2009) Product Lifecycle Management (PLM): Critical Issues and Challenges in Implementation. In: Nambisan S (ed) Information Technology and Product Development. Springer US, Boston, MA, pp 81–105
13. Porter ME, Heppelmann JE The operations and organizational structure of firms are being radically reshaped by products' evolution into intelligent, connected devices. 19
14. Eslami Y (2019) A Modelling-Based Sustainability Assessment in Manufacturing Organizations. Phdthesis, Politecnico di Bari
15. Panetto H (2007) Towards a classification framework for interoperability of enterprise applications. International Journal of Computer Integrated Manufacturing 20:727–740.
16. Džeroski S (2003) Multi-relational data mining: an introduction. SIGKDD Explor Newsl 5:1–16. https://doi.org/10.1145/959242.959245
17. Porter ME, Heppelmann JE (2014) How Smart, Connected Products Are Transforming Competition. Harvard Business Review
18. Baader F, Ganter B, Sertkaya B, Sattler U (2007) Completing description logic knowledge bases using formal concept analysis. In: Proceedings of the 20th international joint conference on Artifical intelligence. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, pp 230–235
19. Rouane-Hacene M, Huchard M, Napoli A, Valtchev P (2013) Relational concept analysis: mining concept lattices from multi-relational data. Ann Math Artif Intell 67:81–108.