Editorial

Frameworks and technologies for exchanging and sharing product life cycle knowledge

1. Product life cycle knowledge

Product Life cycle Knowledge (PLK) is the combination of knowledge about a product across its life time and the knowledge about all processes controlling the product life cycle. In other words, it is a kind of fusion of heterogeneous knowledge about the structure, the functions, the life cycle processes, and the operational environment having impact on the product life cycle. The origin of the term PLK is somewhat unclear. The concept of integrating and sharing heterogeneous product-internal and product-external knowledge emerged in the late 1990s, when Product Life cycle Management (PLM) systems were conceptualized and knowledge-based engineering started to attract attention, without mentioning the concrete term itself [1–5]. The term product life cycle knowledge came into customary use gradually over the past decade. Ameri and Dutta positioned PLK as an independent research problem, "with its own contingencies and needs". They see PLK as content to drive PLM processes [6]. The use of the term product life cycle knowledge further has been settled on in recent work [7].

PLK stretches beyond the domains of Computer-Aided Design (CAD) data and manufacturing-related data handled by Product Data Management (PDM) in several ways. It takes a holistic approach to the product and its life cycle and, consequently, it includes heterogeneous knowledge from a variety of domains and sources encompassing various stakeholders and targeting a variety of information users. Structured and unstructured engineering information and knowledge are captured for future use at all life cycle phases [8]. This is especially true for complex products of long life cycles, such as aircrafts. Closed loops of knowledge and information interconnect all phases of life cycles to pass on 'lessons learnt' as feedback for developers (upstream), and to equip asset, service, maintenance and recycling engineers with product development knowledge (downstream) [6]. Thereby, PLK can be knowledge at product family or product type level, but it can also be about individual items. A life cycle-centric knowledge management approach with stakeholders-in-the-loop allows for a life-long evaluation of the instantaneous performance (utility, asset value, carbon footprint, sustainability, etc.) and the consequential decision making about the rest of the product’s useful life. Depending on its current performance and the available alternatives, this decision can be upgrade, reconfiguration, refurbishment, overhaul, remanufacturing, reuse or recycling of parts, alternatively implying continuation, elongation, or termination of the product life cycle. Existing products may undergo a functional update or may keep the same functions with a different product structure.

Primarily, the introduction of concurrent engineering made the traditional waterfall model based product development and realization obsolete and replaced it by asynchronous online collaboration environments. The ever increasing societal and economic demands made it necessary that the design of products become also more holistic in terms of their throughout-life-cycle performance, optimally exploiting advancing material, and exploiting information technology (IT). As a consequence, current state-of-the-art and future product development no longer assumes static consumer requirements, or static products, but a life-long dynamic interplay between them. The move in this direction has been made possible by the advent of smart (intelligent) reconfigurable products and ubiquitous connectivity. Reconfiguring product features and functions by upgrading their internal logic is an exciting new phenomenon that allows for the reinforcement of product life in the mid- and end-of-life stages. Reinforcement can alternatively mean an enhancement of functionality and performance through innovation, or just extending the useful life without consuming new resources. Reinforcement may also aim at improving information streams to and from smart products. All these aspects are included in PLK and its manifestations in PLM processes across the entire product life cycle.

The relevance of PLK for the industry cannot be overestimated. Customer and market knowledge are essential to respond to the rapidly changing demands in the global competition. Supply chain related knowledge is essential for creating innovative products (bundles), as well as for the implementation of agile and innovative manufacturing [9]. The availability of PLK and the ability to share PLK are also important factors in establishing strategic partnerships and participating in competitive supplier networks [10]. Apart from increased responsiveness and agility, PLK is also essential for sustainable (green) products and manufacturing [11]. As a result, industry will find itself in a situation where competing by life cycle knowledge will be increasingly important. Among the expected societal benefits of PLK, the support for the closing of material, energy and product (component) loops, and enabling a rationalization of the use of natural resources are mentioned most frequently. This is achievable through closing the product life cycle knowledge loops. At company level, the benefits will be enhanced competitiveness and attractiveness, and increased strategic asset and stock value. At employee level, the benefit of PLK will be increased worker engagement.
2. Challenges and conditions

Industry experts contributing to this Special Issue assure that today’s industry recognizes this potential. However, the challenges of a successful adaptation and implementation of PLK management are tremendous. From an epistemological point of view, knowledge captured in one context must be made transferable and transposable for usage and modification in a different application and organizational context, in closed loops (back and forth continuously) [12–14]. From a methodological point of view, PLK covers a problem area which is too wide and too complex to allow the consideration of standardization in terms of terminology, models, frameworks, etc. But what is the alternative? It is difficult to explicitly describe, and notoriously hard to align, the business process, culture, and decision making parts of product realization, though they actually make up a large part of the context. As a consequence, from a computational point of view, it is a tough job to encode and convey information contents plus contexts in such a manner that they can be interpreted with sufficient accuracy and unambiguity by the receiving parties.

Going into more detail, a representative set of the current challenges can be as follows.

- A clear understanding and demarcation of what belongs to PLK, and what does not, are lacking mostly because there is no clear understanding of the PLM processes involved and of the decision making needed [15,16].
- Due to the absence of explicit procedures, tasks, roles, and responsibilities, we are lacking the infrastructure and cultures that would be able to support acquiring and managing product life cycle knowledge adequately and systematically [16,17].
- Only few manufacturers have experience with life cycle management covering the full life cycle (horizontal extent) as well as organizational levels (vertical extent) [16].
- Sharing and exchange of heterogeneous knowledge require semantically rich forms of descriptions, which are, in general, still in their infancy.
- In collaborative product development approaches, recruiting partners and suppliers based on their knowledge has been mastered by only few companies. Moreover, mixed roles in multiple collaborations and intellectual property protection seem to contradict each other.
- PLM systems need further maturation, as well as more capabilities for including, or connecting legacy systems. At present, these possibilities are still severely limited and far from generic.
- Aligning IT strategies, manufacturing, and supply and delivery chains is a complex and challenging task [18].
- End-of-life stages (from remanufacturing to recycling) are subject to rapidly changing societal demands and legislation, such as sustainable development.
- Specifically, the transfer of knowledge from manufacturers to recyclers is needed at the end-of-life stage. Although vital for the success of closing the material and energy loops, this type of knowledge transfer is still rare.

As a result, it is difficult for industrial organizations to carry out the following tasks:

- Define their requirements and needs towards PLK.
- Determine how to depart from the current situation and the state of technology towards PLK.
- Create a fitting PLK culture in which it is common practice to trace, make explicit, capture, value and manage tacit knowledge that is present in undocumented processes and practices, and in the minds of employees.
- Connect enterprise information systems, such as Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and cross-organizational systems like Supply Chain Management (SCM) with a PLM system.
- Oversee how to handle the tedious legacy problem.
- Determine how to align the infrastructure and processes with partners involved in the supply chain, so as to be able to share and exchange semantically crisp knowledge, whilst sufficiently protecting intellectual property assets, in a generic manner.
- Implement robust ways of handling ubiquitous engineering changes across the supply chain [19,20].
- Use and reuse PLK knowledge in technical tasks, as well as in exercising strategic positions in supply chains [18,21].
- Oversee what knowledge is needed to be transferred at the end-of-life in order to optimize reuse and recycling.
- Define strategies to manage the life cycle of life cycle knowledge itself: in other words, when to renew or abandon life cycle knowledge and when to make efforts to explore and discover new.

By a simultaneous consideration and careful examination of these challenges and difficulties, we can shed light on the generic requirements for next generation PLM systems which will be able to provide a fully fledged management of PLK, as discussed in industrial forums, such as [15]. In this context, the strong interdependence between the future of PLM and PLK should be well understood.

The solutions that are needed to address the above challenges and difficulties fundamentally, fall into two classes.

1. Solutions for semantic deepening of the description of product life cycle knowledge, allowing for generic capturing, sharing and exchanging of knowledge.
2. Solutions for improving the connectivity and coherence of life cycle processes, so as to permit the integration and closing of knowledge streams and material and energy streams at any point in the life cycle.

For both classes, various proposals have been published in the literature: For instance, the proposals for class 1 follow directly from the findings discussed in [22] and [12]. For class 2, proposals can be found, among others, in [13] and [14], which are actually further elaborated in this Special Issue in [23]. In [10] and [18] emphasis is put on the integration of the elements of interoperability and collaboration to obtain what Charalabidis et al. call enterprise interoperability, that is, a generic, inherent and open form of interoperability at all levels. Srinivasan points at the interplay between an integration gap and a collaboration gap in [21].

This Special Issue on Frameworks and technologies for exchanging and sharing of product life cycle knowledge is a logical continuation of our previous Special Issue on Product Data Technology (PDT) [22]. This compilation of papers presents the current state of technology and possible answers to some of the challenges that industry is currently facing. Experts from academia and industry present their views and thoughts on a number of these challenges and difficulties. In the previous Special Issue we concluded that, though still relevant, STEP (the Standard for the Exchange of Product model data; formally, ISO 10303) is not expected to be able to fulfill all of today’s industry demands. Admittedly, the goals of STEP were quite different at its outset some two decades ago. At the same time, STEP AP239 PLCS (STEP Application Protocol 239, Product Life Cycle Support) is a valuable extension into the direction that is now seen as right [16,21]. Given the early stages that the research area of PLK is in, the multiplicity and wideness of the domains it covers, and the limited maturity of the framing PLM technology, the obvious conclusion is that a lot remains to be done [15], actually much more than discussed in this Special Issue.
3. Introducing the papers

Srinivasan surveys the current state and possible development avenues for future PLM, starting out from a Chief Executive Officer (CEO) questionnaire and investigating from a business strategy point of view [21]. He discusses integration of product life cycle knowledge, and proposes a framework for organizing and structuring this knowledge. His work connects the framing product life cycle management environment with the driving PLK knowledge. According to Srinivasan’s view, three important preconditions should be fulfilled at the development of a PLM framework: (i) a mature state of standardization, (ii) service oriented architectures, and (iii) middleware to implement PLM services. Having merited these three enablers, Srinivasan shows an Enterprise Service Bus-based architecture connecting PLM services with Web Services-Based Business Process Executable Language (WS-BPEL) life cycle process descriptions. Legacy services are plugged into the web-services-based architecture, in addition to reusably and reconfigurable generic PLM service modules.

Kiritsis explores the limits of current PLM from the perspective of the future needs of industry at organizational and technological level [23]. The industry perspective is mainly based on European Union Framework Programme 6 (EU FP6) mixed academic industry research. Kiritsis suggests a classification of products according to their intelligence level. He shows that extensions of existing technology are needed for objects with higher level intelligence (“smart objects”). Kiritsis also discusses the concept of closed-loop PLM and explains how per-item life cycle knowledge streams (closed loops) allow for better decision making on the rest of individual product life. For products with higher level intelligence, product reconfiguration offers new strategies for keeping up the product functions and performance levels. Upstream knowledge flows also permit design improvements. Individualized, downstream knowledge flows allow for a per-item end-of-life strategy. His work shows a viable development avenue to improve life cycle processes connectivity and decision making. Important is the fact that Kiritsis systematically derives information on what ways current PLM needs to be extended in order to fully cater to data flows generated by intelligent objects. The obtained individual product state and performance snapshots allow for yet unseen, systematic, per-item, cross-life-cycle knowledge flows.

Rezgui et al. survey the present situation in the construction industry and evaluate possible pathways towards enhanced product life cycle knowledge through the application of web services and an e-construction framework [17]. The establishment of an e-construction framework, in which web services not only serve as an enabling technology for sharing and exchange of life cycle knowledge, but also allow for new business models to emerge, offers specific forms of shared knowledge. Rezgui et al. show in detail how new enabling technology can be exploited to reframe, optimize and partly transform business, and how to adapt it to the requirements of future decades.

In the next paper, Whitfield et al. present the results of an industry application from the EU academic-industry VRShips-ROPAX2000 project [24]. A ROPAX ship is a roll-on-roll-off passenger vessel. The relevance and meaning of their work are that they demonstrate how to advance from the current state of the engineer-to-order shipbuilding industry practice by using existing technology and including legacy. Established for through-life design of ROPAX ships, their integrated development environment (IDE) encompasses a wide variety of life cycle processes during the product development, placing emphasis on activities, tasks, roles and tools, and cross-organizational and cross-disciplinary aspects. While many companies have no idea how to take the first step and where to begin [21], this approach may serve as an example that also takes efforts to consider the legacy problem. As proposed, rather than implementing a full PLM for shared usage by all stakeholders, the first step might be to concentrate on through-life design views and analyses, but only during product development and redesign. Being STEP-based, their approach assumes a specifically designed fixed common model that needs to be agreed upon before put in use. Nevertheless, the proposed implementation has a large degree of flexibility and generality.

Wasmer et al. present a cross-organization engineering change management framework, serving the stakeholders involved in communicating and managing complex change processes [20]. The paper is based on a joint VDA (German association for the automotive industry) and ProSTEP (International association for information integration in the industry) effort to develop a generally applicable framework. Developed for the automotive industry, STEP AP 214 is used as the content model. The Object Group (OMG) PLM Services are being used to communicate engineering changes through touch points of communication, and BPEL is used for the executable process specifications. The value of this work clearly lies in the cross-organizational architecture for handling change communication and management in the supply chain in all aspects and disguises, and forwarding all the knowledge needed related to a fit-for-task, need-to-know role-based stakeholder model. Another value of this approach is that it builds upon directly and largely extends the existing infrastructure, composed of STEP AP214, web-services-based OMG PLM services, and OASIS BPEL technology for change communication protocols. OASIS is the Organization for the Advancement of Structured Information Standards.

Ouerhani et al. discuss a knowledge traceability framework to help industry discover and manage cross-life-cycle knowledge and manage engineering change affecting knowledge [19]. This problem is also signaled in [12]. They argue that knowledge is already being built up in the requirement specification phase. Relationships of functional requirements to design parts are being analyzed and discussed, as well as the dependences among requirements. Engineering changes originating in changed requirements can thus be long-term associated with design elements. The authors propose a surface for finding and acquiring knowledge from a different life cycle context for reuse in the life cycle stage at hand. They design and implement a traceability framework and demonstrate its usefulness in an industrial context. Given the wide variety of industrial application contexts, further evaluation is needed in order to obtain industrial strength for such tools. It has to be mentioned that their focus is on the begin-of-life processes of product development, whereas usage and maintenance engineering are also known to bring about significant engineering changes.

4. Some white spots

As explained, not all the challenges and difficulties could be discussed in this Special Issue and many white spots are deemed to remain. First of all, we must state that the STEP AP 239 PLCS basically leaves it up to industry practice to see which data exchange sets (DEXS) will emerge and which will grow into Conformance Classes and for how long [16,21,25]. STEP does not give a detailed demarcation of PLK. Moreover, although the scope is wide, the implementation and uptake are limited. Emerging PLM service implementations, such as OMG PLM, OASIS PLCS PLM, and the ISA-95/OAGIS SOA, the International Society for Automation/Open Application Group Integration Specification’s Service Oriented Architecture in manufacturing, focus on expanding their PLM services in a service oriented architecture, following industry requirements and desires [25,21].
This Special Issue does not offer a firm demarcation of what belongs to PLK and what does not. Nevertheless, relevant and innovative examples are given in Ouertani et al., and also in the paper of Rezgui et al., to some extent. These examples will help industry to further sharpen its ideas, define concrete goals and determine priorities, so that the targeted knowledge mining can be designed and conducted. The mentioned papers also convincingly show that service providers may be expected to enter the market, assisting industry in tracing and acquiring the necessary knowledge. Such services most likely start with widely used domain knowledge and customer knowledge, to become further specialized at later stages.

The infrastructure and culture that are needed to adequately and systematically acquire and manage product life cycle knowledge are lacking, and this is also reflected by this Special Issue. They are believed to emerge in the industry in the coming decades. Rezgui et al. stress the importance of establishing such culture, not only in the case of larger companies, but also for Small and Medium Enterprises (SMES) [17]. They explain how SMES might organize themselves in conglomerates, in order to empower themselves in this respect. Conglomeration forming can be on an infrastructure level, but they actually propose to step up on a service provision level in order to be more effective.

Finding and analyzing critical functional requirements are not always as easy as asking the customer [19]. Customer demands and preferences have become more and more volatile. Customers do not only buy more online, but they also leave their opinions and preferences there. As a result, mining unstructured information and knowledge on the web has become a relevant research topic. Actively mining for customer knowledge might subsequently become (and probably already is) an important service that can, as a service, be combined with the approach proposed by Rezgui et al. Another cross-link may be with the work by Ouertani et al., to improve and validate the knowledge based on the requirements, specifically the ranking and weighting of requirements.

Furthermore, for the purpose of structuring unstructured information, ontology can be used, which also enables us to define a back-and-forth mapping between source and receiver concepts [26,7]. The question is whether ontology can abridge the semantic gap between two domains in a generic way, or not? Associated questions are whether a single mapping is sufficient, and whether multiple mappings may co-exist? The interpretation of semantic content is facilitated by a common, shared semantics basis between the source and the receiver, and hence specific bases would be created for each source–receiver combination. Since not all information needs to be shared, domain-specific details may remain hidden. The approach taken is a semi-automatic application, rather than a fully generic application. Although, through the use of reference ontology a higher level of information semantics can be shared and exchanged than with product data technologies (PDT), semantic complexity is still limited. Even if ontologies are used, semantic incompatibility and ambiguity may occur. In addition, supervision by an expert remains, in general, necessary. Consequently, generic interoperability is a white spot and remains one of the core problems for the coming decades. Another white spot in this Special Issue is modeling the functional structure of products. Functional models are important to enhance the semantic understanding of the design intent (form-function) and to allow separation of functional intent and implementation technology. Ouertani et al. relate functional requirements and design elements, but ideally, further downstream life cycle aspects need to be linked as well. Unfortunately, no authors have mentioned and discussed this aspect.

A further white spot in this Special Issue is the relationship between decision making and the required knowledge, and between decision making and the life cycle process. None of the authors discusses this explicitly. Knowledge transfer from manufacturers to recyclers at the end-of-life is another topic which is not elaborated on in this Special Issue, although multiple researchers have identified the need to close the knowledge loops [6,13]. Moreover, as discussions with the industry reveal, remanufacturing and reusing parts lead to a debate about terms and concepts such as life cycle extensions and second life. Whereas life cycle knowledge about reconfigurable products can be organized and managed based on configuration management, remanufacturing and reuse require a more explicit and coherent terminology. None of the contributing authors have discussed this.

A further topic absent in this Special Issue is the identification and ranking of suppliers and partners for collaborative product development approaches, based on their knowledge. To some extent, Rezgui et al. address this issue in their discussion of new organizational forms for SMEs in the construction industry. Ouertani et al. discuss the tracing of knowledge across organizations. A relevant but complex issue in any form of knowledge sharing is the issue of intellectual property protection. This issue is complex, not only from a business and technical point of view, but also from a jurisdiction and administrative point of view. For this reason, we, Editors, decided to leave this topic out of this Special Issue, although several authors and experts from the industries pointed out its paramount importance.

5. Lessons learnt from the industry

What is the message to be taken from industry? Industry recognizes that the potential of PLM is great, but they should be exploited in a fit-for-industry-purpose manner. In order for PLK to be satisfying, the concepts should be owned and managed by all stakeholders-in-the-loop collectively. They should evaluate the product performance and make decisions on the further life cycle at any point, considering alternatives and alternative usages of existing products, their parts, materials and energies. Once advanced PLK cultures are in place, stakeholders will discover that exactly the same objectives can be defined for the very life cycle of PLK itself, as a driver of innovative products and a strategic asset. The Roadmap shows that industry is just at the start of creating and capturing life cycle knowledge; sharing and exchanging knowledge still happen primarily via human communication [15,22].

Legacy is the obstacle that is singled out in the discussions with industry. Legacy data models, legacy applications, legacy terminology, legacy processes etc. are still almost open issues. Legacy represents, perhaps, the biggest threat to PLK and innovation as a whole. The new investments in knowledge, applications, skills, education, procedures etc. required to wipe out bad performing and obstructive legacy are seen as a mere business risk [10]. Involved in the Roadmap construction process, one of the industry experts furthermore brought up the issue of shrinking labor force in many European countries as well as in the United States. Such demographic aspects may enforce a focus on the role of knowledge even more.

6. Towards the future

We selected the best papers from the pool of manuscripts that have been submitted by industry and academic experts, in which they share with us their views on this emerging domain and propose emerging technologies and frameworks enabling PLK development. Next, the various industries should weight factors and arguments indicated in these expert views, for their specific situation and find a fitting development scenario for their situation. Indeed, there is no such thing as a single industry; industry is heterogeneous in many respects. Different industries
may therefore have different needs, resources and priorities and consequently move ahead along different routes and paces.

Automotive and aerospace are often seen as frontrunners, but other industries may take the lead equally well. For any industry, we recommend all stakeholders involved to monitor and participate in this process. We underscore once again the versatility of PLK and the importance of constructing a holistic view on the product, product-related processes and product operational environments. We sincerely hope that this Special Issue ignites some joint holistic and structured thinking about PLK in the industry, among Original Equipment Manufacturers (OEMs), suppliers, vendors, service providers, consumers, governmental and regulatory bodies. All have an important and unique role to play.

References


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