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Project Lifecycle Management (PLM): evolution and state of the art

Daniela Silva dos Santos[a], Diane Aparecida Reis[a], André Leme Fleury[a]
[a]Universidade de São Paulo – USP, São Paulo, SP, Brasil
e-mails: engenheiradaniela.s@gmail.com; diane.reis@hotmail.com; andreleme.fleury@gmail.com

Abstract: Intelligent manufacturing has produced a revolutionary change, mainly driven by the current competitive world, reinforcing the importance of inserting Product Lifecycle Management (PLM) approach. PLM emerges with the aim of efficiently managing product-related information throughout the product lifecycle with sustainability. It also satisfies the interest in managing the services and products lifecycle, and in the case of products, their management, from their insertion in production processes, to their lifecycle end, generating a closed management cycle. This paper aims mainly to understand how the concept of PLM is being approached and defined by academics. For this, a systematic literature review with bibliometrics, networks and contents analysis were applied. The goal of this paper to evidencing the main PLM definitions, providing a comprehensive view of the current researches and raising knowledge gaps for future research about it.

Keywords: Product Lifecycle, Product Lifecycle Management (PLM), Lifecycle Management.

1. Introduction

Currently, new business challenges are constantly emerging in a scenario of short product lifecycles, increase of outsourcing, mass customization demands, geographical dispersal of teams and fast depreciation. This scenario enhances collaborative and integrated engineering, caused by the management need of products are increasing in diversity and complexity (Ming et al., 2008; Fortineau et al., 2013). This demands the reduction of the time-to-market and production costs, while improving quality (Fortineau et al., 2013), resulting in a highly competitive and fast change of the global marketplace, challenging for a modern collaborative business environment, requiring the industry to consider design, control and optimization of the whole product lifecycle, besides the capability to operate in a dynamic global environment. It also demands the acquisition of new capabilities for competitive advantages in the current Internet Economy (Jun et al., 2009; Young et al., 2007; Ming et al., 2008). This way, the management of the lifecycle becomes critical to innovations, meeting the customer needs, without driving up costs, sacrificing quality or delaying deliveries (Jun et al., 2009; Young et al., 2007).

Academics and industrial researchers engage tremendous efforts in research and develop industrial information technologies, pursuing more competitive business advantages in product lifecycle, highlighting the increasing interest in the benefits of the effective use of lifecycle Big Data (Ming et al., 2008; Zhang et al., 2017b). This way, information management has received a considerable attention, mainly because organizations work in a complex business environment characterized by information overload, high levels of competitiveness and acceleration of technological change. These efforts led to the Product Lifecycle Management (PLM) software, offering powerful tools and enabling high levels of manageable information (Soto-Acosta et al., 2016; Jun et al., 2009; Sharma, 2005).

PLM has been recognized for evidencing challenges and opportunities, once modern technological advances have resulted in innumerable complex systems, processes, and products, and this increasing complexity offers considerable challenges in design, analyses, production and management, for their whole lifecycle (Venkatasubramanian, 2005). A new knowledge research field is thus provided which aims to assist in the current industry challenges (Fortineau et al., 2013).

Therefore, this study aims to understand and to evidence: How is the PLM concept being approached and defined by academics? The paper also investigated the evolution of PLM, providing an overview of the researches already conducted and the knowledge gaps for future researches. A systematic literature review was applied, assisted by bibliometrics, networks and contents analysis.

This paper comprises five sections. The first section details the context and relevance of this study. Section two presents the method. Section three evidences the results. Section four discusses the results, while section five provides the conclusions.

2. Research method

The research conducted a systematic literature review to understand the use of PLM by academics. The purpose was to evidence the state of the art about PLM, providing a comprehensive view of the research already conducted about the theme and the possible knowledge gaps for future research.

The systematic literature review was used for searching the state of the art to detect the advances and the limitations of the research already published (Palmarini et al., 2018). This allows identifying the future research opportunities, the research gaps and evidencing the subject structure, causes, effects and processes (Dikici et al., 2018; Maier et al., 2016).

2.1. Sample and procedures

The sample of analyzed papers is a result of searches in two databases, Scopus and Web of Science (WoS).

Figure 1 summarizes the research based on 962 documents, selected after different filters, resulting in 469 papers about the subject of interest, used for the bibliometrics and networks analysis, and 56 most relevant articles for full reading, forming the database for this article content analysis. The method is detailed in the next topics.

2.2. Research method steps

Bibliometrics analysis uses empirical evidence to explore a research field (Neely, 2005), summarizing the major research trends and subjects (Kolle et al., 2017; Yu et al., 2016; Zhang et al., 2017b), guiding future researches (Zhang et al., 2017b). Assuming that the authors of a theme cited the most relevant researches in the field, evidencing the most relevant citations and co-citations (Ramos-Rodríguez & Ruíz-Navarro, 2004). The network analysis evidences a photograph of the publications (Takey & Carvalho, 2016). The application of bibliometrics and networks analysis allows the active investigation of publications (Yataganbaba et al., 2017). The content analysis assists in the conceptualization of the research in different ways (Hazen et al., 2015), assisting in the analysis of the information (Wasike, 2017; Arslan, 2012) and evidencing common practices, interpretations, and relationships (Allen et al., 2014).

The research methods steps were first analyzing the number of publications per year and per journal, highlighting the evolution of the subject published over the years, and the journals that published about it. The second step, all the publications were analyzed to develop a coding

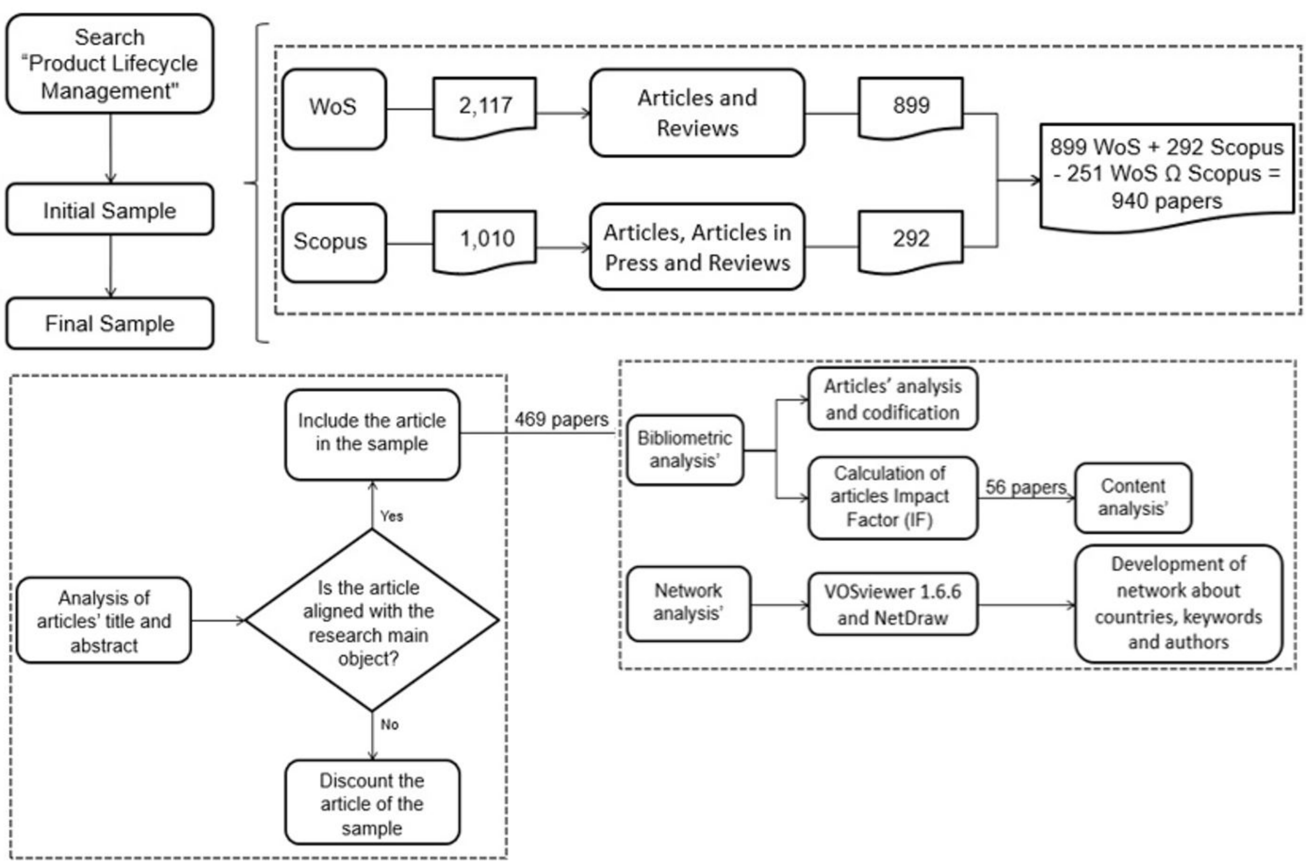


Figure 1. Systematic literature review workflow.

scheme involving the publication methods and main subject. The third step consists of the network's development, using the VOSviewer 1.6.6 software to elaborate and to visualize the networks and the NetDraw software to edit the networks, analyzing all the publications, developing three networks: co-authorship countries, co-occurrence keywords, and citation authors. The fourth step, the database for the qualitative analysis were developed; for that, the papers' Impact Factor (IF) was calculated, using Equation 1, as in Carvalho et al. (2013). Pareto's analysis from Takey & Carvalho (2016) was used to select the papers representing an 80% IF, resulting in 56 publications, composing this study content analysis.

$$IF = C * \left(JCR + 1 \right) \quad (1)$$

Equation 1**.** Impact Factor (IF).
C - represents the number of citations and JCR - the impact factor of the journal in which the paper was published, based on its Journal Citation Report. Source: Carvalho et al. (2013).

3. Results

The results of this research were classified into two main categories, quantitative results and qualitative results.

3.1. Quantitative results

This section presents the quantitative results of this research, divided into two groups, bibliometrics and networks results.

3.1.1. Bibliometrics results

Analyzing the publications, it is possible to evidence 469 papers meeting to this study interest, in an evolution along the years evidenced in Figure 2, with the number of accumulated publications increasing along the analyzed years (2001-2018), since the first publication in the theme of interest.

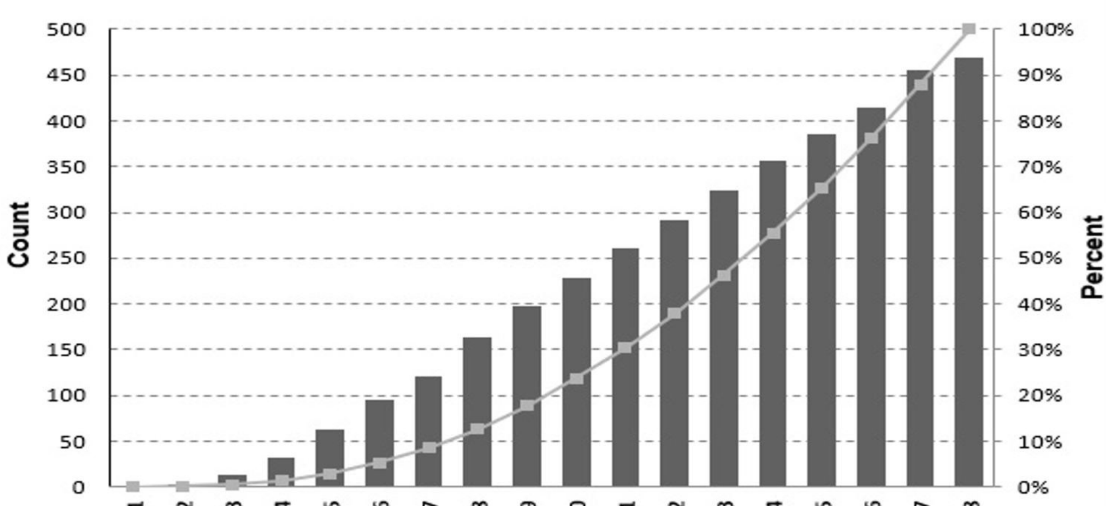
This evidenced that the main journals publishing in the subject were Computers in Industry (8%), International Journal of Product Lifecycle Management (5%) and Concurrent Engineering Research and Applications (4%). The other journals have a representatively inferior to 3%, being a subject of interest from different journals.

3.1.2. Networks results

Out of 56 different countries, 21 countries presented a minimum of five documents published; the co-authorship countries network evidences the countries publishing together, see Figure 3.

The main connections are between France and the United Kingdom; France and Switzerland; Germany and the United States of America; and China and Singapore. Only four countries represent 53% of the citations and 51% of the publications number, respectively, the United States of America (20%; 13%), China (13%; 14%), the United Kingdom (11%; 10%) and France (10%; 14%).

There are 3,194 different keywords, 31 keywords have a minimum of 17 occurrences, leading a three main clusters, see Figure 4.



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Count	1	3	13	32	63	95	121	163	198	228	260	292	324	356	386	414	456	469
Percent	0%	0%	0%	1%	2%	2%	3%	4%	5%	6%	7%	8%	8%	9%	10%	11%	12%	12%
Sum %	0%	0%	0%	1%	3%	5%	8%	13%	18%	24%	30%	38%	46%	55%	65%	76%	88%	100%

Figure 2. Accumulated view of the publications, evolution along the years.

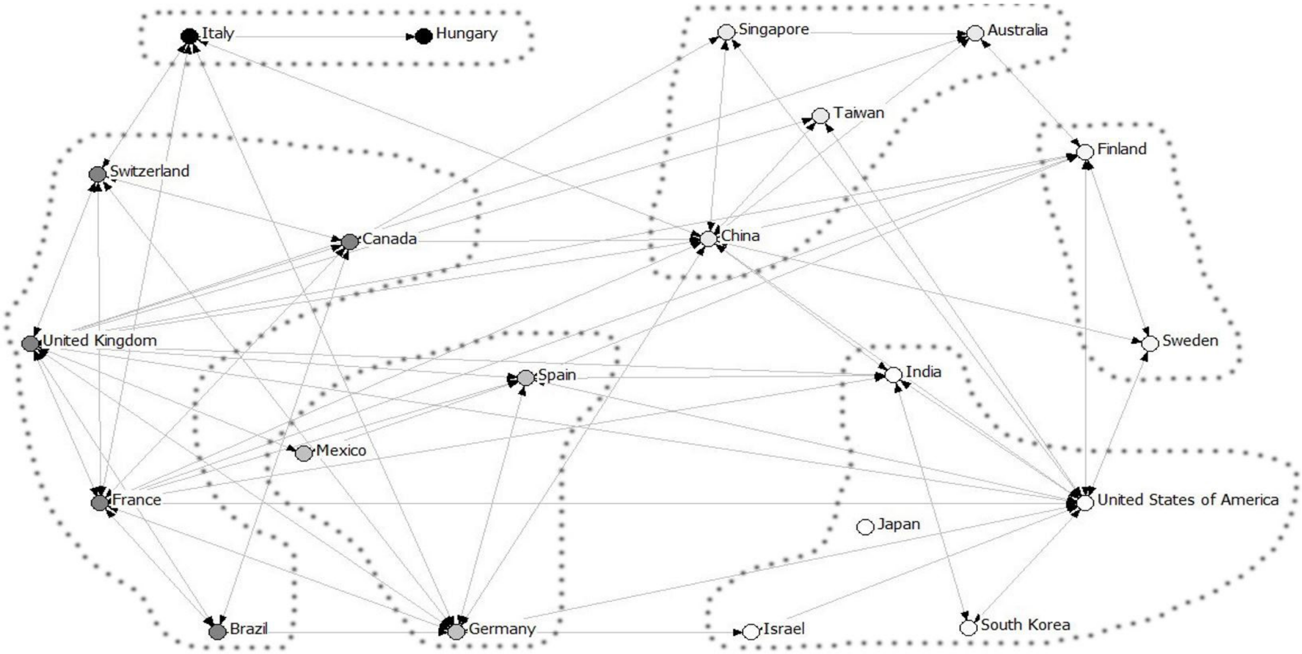


Figure 3. Co-authorship countries network.

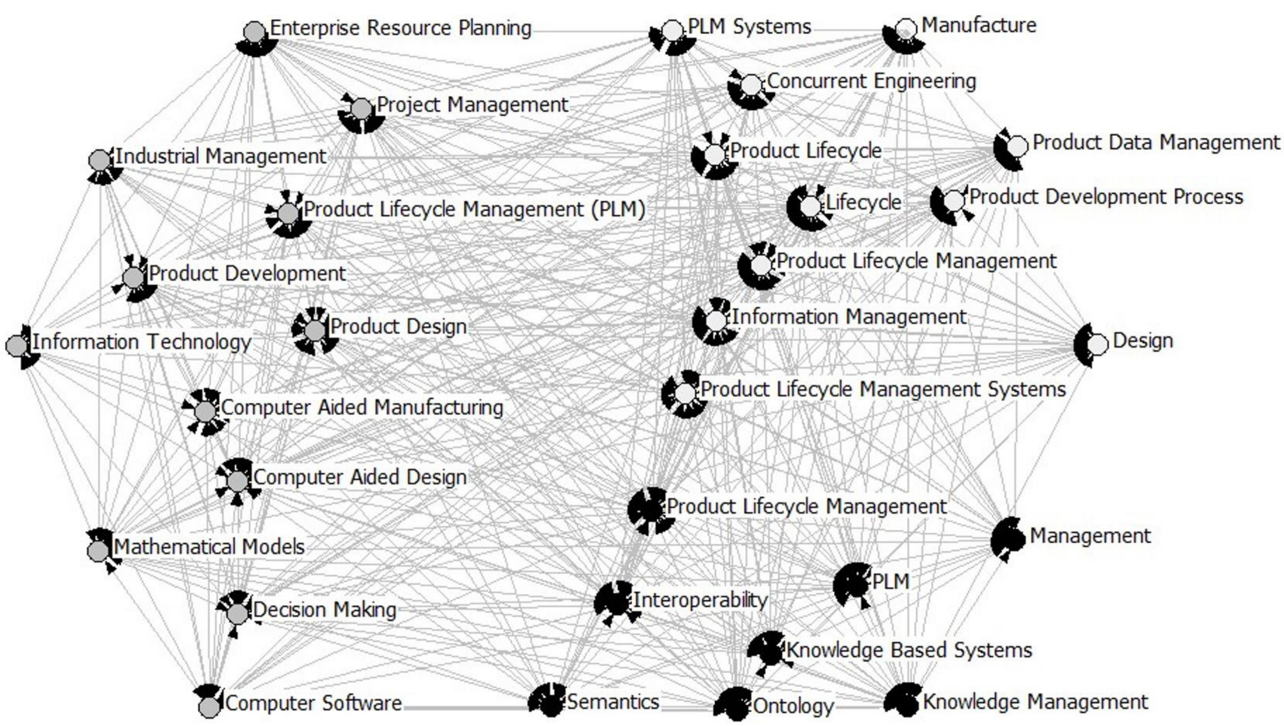


Figure 4. Co-occurrence keywords network.

The major clusters were Management, Development and Systems, the pillars of currently concept of PLM. The main connections are between Product Lifecycle Management and Lifecycle; Product Lifecycle Management and Product Design; Lifecycle and Product Lifecycle Management; and Lifecycle and Product Development. Only five keywords represented 51% of the occurrences, Product Lifecycle Management (20%), Lifecycle (15%), Product Development (9%) and Product Design (7%).

Out of 1,074 different authors, only 16 authors present a minimum of five publications; forming five main clusters, see Figure 5.

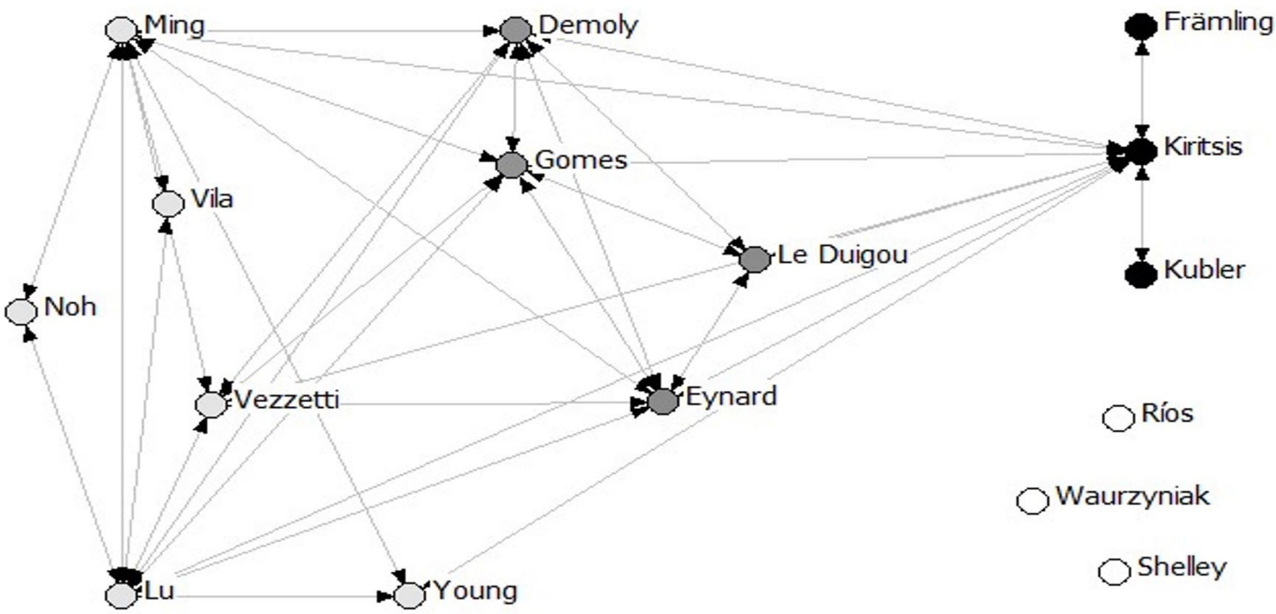


Figure 5. Citation authors network.

Only three authors represented 51% of the citations, detailing, Kiritsis (32%), Eynard (10%) and Vezzetti (9%). The main connections are between Demoly and Gomes; Demoly and Kiritsis; Demoly and Eynard; and Kiritsis and Eynard. Evidencing only few authors publishing about the theme.

3.2. Qualitative results

This section presents these research qualitative results, presenting the contents analysis, which can also be considered as the literature review of this study.

3.2.1. PLM evolution and concept

The concept of Product Lifecycle Management (PLM) appeared in the 90s as an extension of Product Data Management (PDM) (Stark, 2011), providing more information related to large organizations (Kiritsis, 2011). The PDM has been developed to improve the data management and documented knowledge for new products design, allowing the focus on the product design and production phases (Kiritsis, 2011). In this view, PLM development depended upon the idea of an evolution and continual assimilation of computer-oriented product-based solutions, from early engineering design applications (e.g. Computer-Aided Design (CAD) or Computer-Aided Manufacturing (CAM)) in the 70s and 80s, through to the integration of Enterprise Resource Planning (ERP), Customer Relationship Management (CRM) and Supply Chain Management (SCM) solutions (Ameri & Dutta 2005). The importance of product information management during the whole product lifecycle has increased due to the technical sophistication of products as well as stricter governmental regulations for lifecycle management (Främling et al., 2006).

PLM concept provides a definition of a complete product lifecycle, including all information and processes required to plan, develop, manufacture and support the product from conception through the end of its lifecycle, integrating: people, processes, business systems and information (Lee et al., 2008a). Appearing to focus on a design perspective with the best association with the manufacture components parts (Young et al., 2007). This concept evidence the importance of a manufacturing model that not only provides a common information source to support design decisions, but which focus in the business core competencies, providing a new understanding of the product manufacturer, with a model that can be updated for future benefits (Young et al., 2007).

As benefits, the PLM is a strategic business system that allows effective communication among different groups at dispersed locations, to share ideas and access information, to develop new products and execute innovative processes (Lee et al., 2008a). In summary, PLM not only provide process management throughout the entire product lifecycle, but also enables effective collaboration among networked participants in product value chain, which distinguishes it from other enterprise application systems, such as Enterprise Resource Planning (ERP), Supply Chain Management (SCM), Customer Relationship Management (CRM), etc. (Ming et al., 2008). With the goal of reducing the product time to market improving the product functionality and increasing the ability to customize (Schuh et al., 2008). Under these circumstances, new PLM system development technologies are being employed to develop attractive PLM systems that will provide more satisfaction to customers (Schuh et al., 2008).

In the literature review, several different PLM definitions were found, summarized in the Table 1.

3.2.2. PLM in the products' lifecycle

The product lifecycle consists of three main phases:

- **Beginning-Of-Life (BOL):** including design and manufacture;
- **Middle-Of-Life (MOL):** including use, service, maintenance, and distribution (logistics);
- **End-Of-Life (EOL):** where products are recollected, disassembled, remanufactured, recycled, reused, or disposed.

During BOL, information flow is quite complete and supported by information systems such as Computer Aided Design (CAD)/Computer Aided Manufacture (CAM), Product Data Management (PDM) and Knowledge Management systems (Jun et al., 2009; Cao & Folan, 2011; Kiritsis, 2011; Cao et al., 2009). However, the information flow becomes vague or unrecognized after BOL, demanding the feedbacks of product-related information such as product usage data, and disposal conditions to have information supporting the MOL and EOL phases (Jun et al., 2007). In a scenario where the lifecycle activities of MOL and EOL phases have limited visibility of the product-related information (Jun et al., 2007), emerging the PLM to allow the management of product lifecycle data, offering the features present in Figure 6.

Detailing the PLM system, they are generally computer-based information systems which assist the organization's PLM strategy. The components in a full PLM system include the items evidenced in Figure 7.

The idea is that information of MOL could be used at the EOL to support deciding the most appropriate EOL option (specially to plan for re-manufacturing and reuse), providing feedback for the BOL, improving a new generation of products (Demoly et al., 2012).

All these phases have as objective to minimize cost and time by understanding problems before the product development and manufacturing processes, improving the

Table 1. PLM definitions.

Author	Definition
Sharma (2005)	A concept that aims to integrate the various processes and phases involved during a typical product lifecycle. Based on horizontal business processes without a single tool or a package that can describe the whole PLM.
Jun et al. (2007)	A new strategic approach to manage the product lifecycle information efficiently. Enabling to gather and analyze the product lifecycle information and make decisions on several issues.
Chen et al. (2008)	A strategic business approach that manage all the product lifecycle stages.
Lee et al. (2008a)	A concept that evidence the information management, throughout all the stages of a products' lifecycle.
Ming et al. (2008)	New strategic business model to support collaborative creation, management, dissemination, and use of product assets, including data, information, knowledge, etc. Assist organizations in conceptualizing end of life, integrating people, processes and technology.
Rachuri et al. (2008)	A strategic approach to create and manage the organization's intellectual capital, from the since a product initial conception until its discontinuity of production. Supports the product lifecycle by modeling, capturing, manipulating and exchanging the information.
Alemanni et al. (2010)	An extension of Product Data Management (PDM), representing the missing link between Computer Aided Design (CAD), digital manufacturing, and simulation. Representing the virtual world and interfaces with the Enterprise Resource Planning (ERP) system supporting the physical side of modern manufacturing along the supply chain.
Kiritsis (2011)	Strategical approach with three fundamental dimensions: (i) universal, secure, managed access and use of product definition information, (ii) maintaining the integrity of the product definition, being related with information throughout the life of the product or plant and (iii) managing and maintaining business processes used to create, manage, disseminate, share and use of information.
Marchetta et al. (2011)	A key concept for manufacturing industries to improve product quality, time-to-market and costs.
Al-Ashaab et al. (2012)	Strategy and technique that assist the organizations to succeed in the manufacturing industry. Assisting to maintain the product data timeliness, validity, accuracy, and traceability.
Kubler et al. (2015a)	A wide-ranging concept that aim to integrate the product lifecycle, including people, data, products, processes, metrics and so forth.
Zhao et al. (2015)	Integrated management of relevant information throughout the product lifecycle from customer needs capture, through product design and engineering, manufacturing, maintenance, and service, to market.
Bonou et al. (2016)	Is the overarching process for all the product development activities. Including the customer-oriented strategic planning, design, and development, monitoring the whole product lifecycle activities.
Soto-Acosta et al. (2016)	A new approach for management information along the product lifecycle, enabling organizations to reduce products' time to market as well as to respond to a growing demand for quality and customization of products.

Figure 6. Features obtained by PLM for product lifecycle data management. Source: Adapted from Cao et al. (2009).

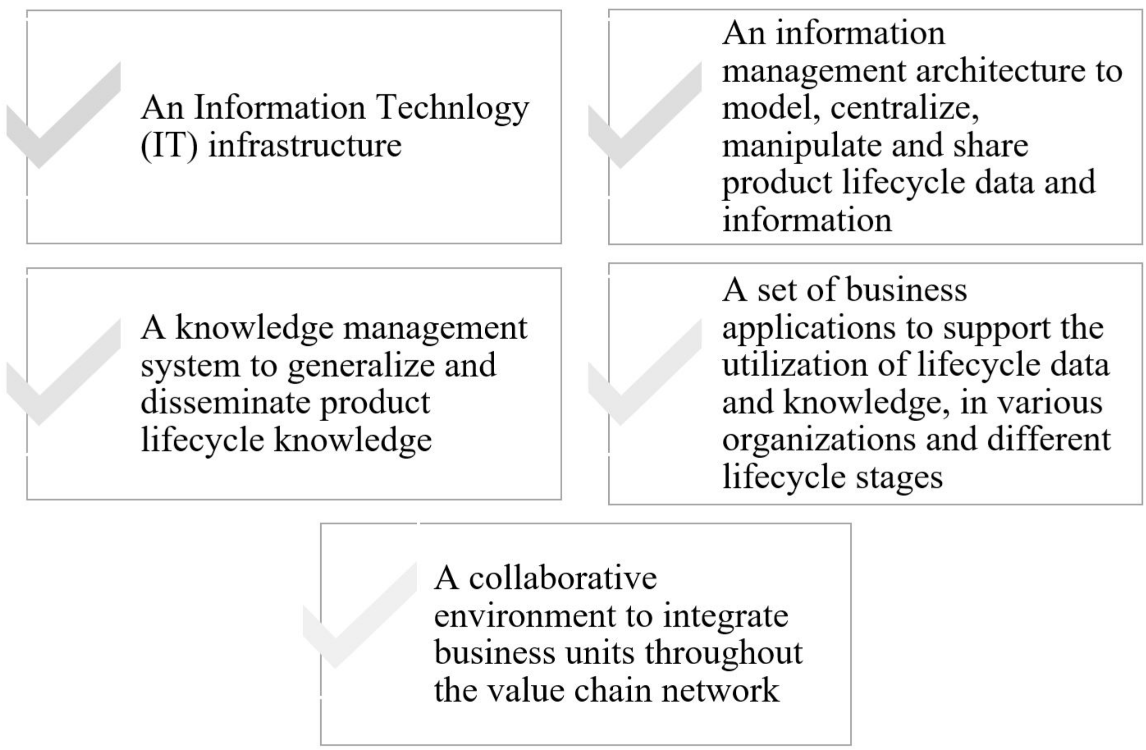


Figure 7. PLM system components.
Source: Adapted from Cao et al. (2009).

organization's performance utilizing technology and support (Soto-Acosta et al., 2016). Around 40% of engineer's time is spent to connect the information about the processes, with information search and sharing, and in this scenario, the correct usage of PLM can save at least 50% of this time, which could be used to develop more value-adding tasks (Soto-Acosta et al., 2016).

PLM offers a range of tools to support the business, including the ability to manage workflows, but the heart of an effective PLM system is the database structuration, ensuring that all users have access to effective information support (Young et al., 2007). Companies need to connect the product design and analysis processes to the production and supply chain processes with PLM support, including: Product Data Management (PDM), Component Supplier Management (CSM), Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), Customer Relationship Management (CRM), Supply and Planning Management (SPM), and others (Rachuri et al., 2008). Occurring the PLM optimization achievement only when the knowledge sharing happens in the whole product lifecycle, with the PLM development being the result of integrating many lifecycle data (Zhang et al., 2017a).

Still on PLM in the product's life cycle, some relevant improvement opportunities emerge, evidenced in Figure 8.

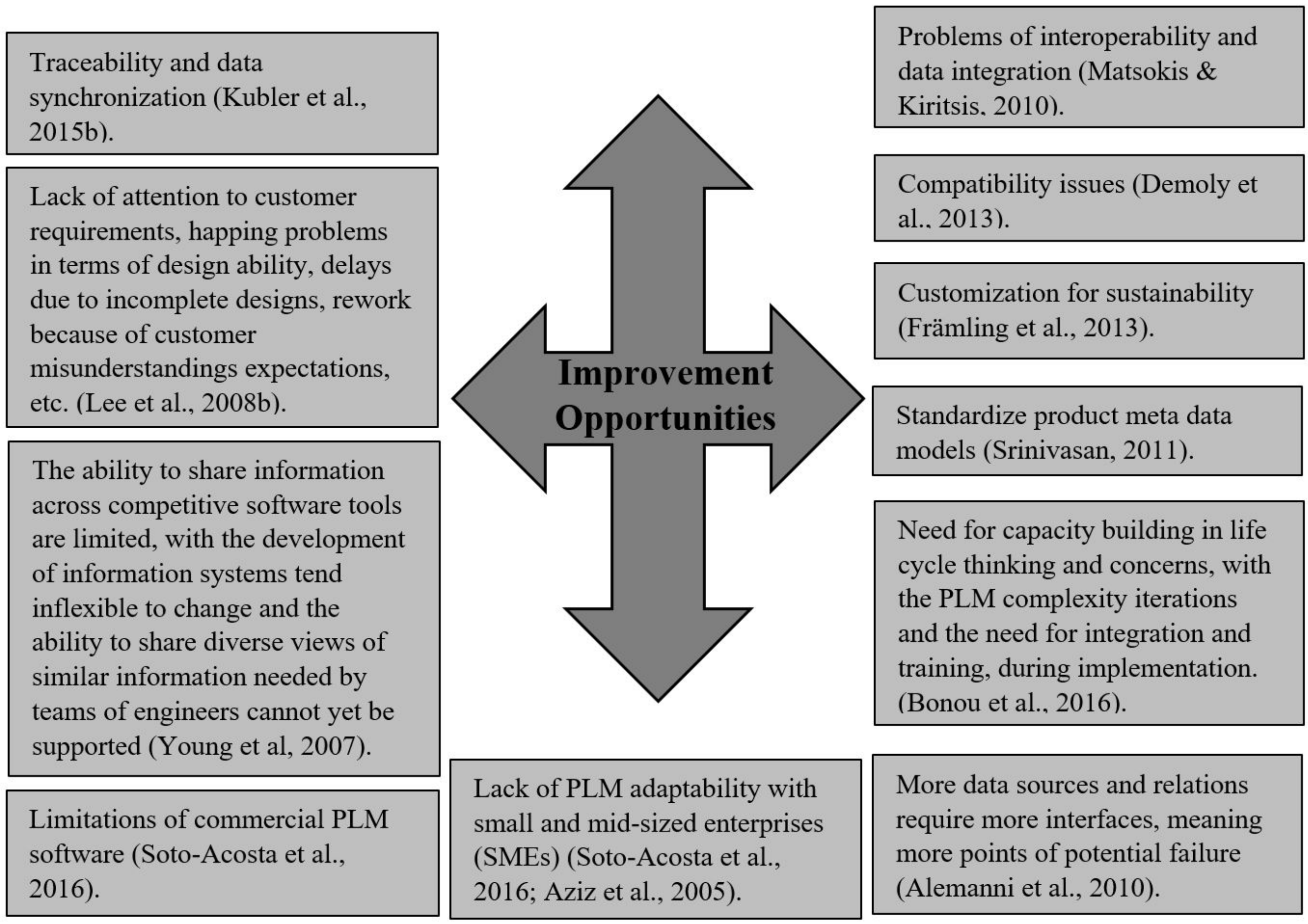


Figure 8. Improvement opportunities

Opportunities which can be seeen as gaps/needs that can be filled in with the improvement of PLM.

3.2.3. PLM applications

A big challenge is to understand the implications of developing and interoperating across different types of knowledge environments and product lifecycle systems (Chungoora et al., 2013). Thereby, there is a tendency in converting existing models into ontologies and the creation of new models, and because of this in the PLM field, there are several recent works dealing with ontologies (Matsokis & Kiritsis, 2010). Besides that, the past years have presenting growing investments in the field of PLM, by the automotive sector and the manufacturing industry, that is facing tremendous pressure on environmental regulations, such as the reduction of pollutants, e.g., carbon dioxide (Tang & Qian, 2008).

In this scenario, the researchers classified the application fields according to the number of published papers, 68% of the publications are from the application areas shown in Figure 9 and the other 32% of the articles are from application areas that have less than 1% of representativeness on the PLM topic which can be seen by the author in Appendix 1.

Besides that, the articles were separated by subject, see Figure 10, evidencing the most published articles on the topic are related to systems from which it can be connected and used in conjunction with PLM.

The more representative keywords can be visualized in Figure 11, and the detailing with the authors are in Appendix 2.

3.2.4. PLM implementation

When a company adopts PLM for the first time, the implementation process itself becomes a process of change (Soto-Acosta et al., 2016). This is because these changes should occur not only at the IT level but also at strategic and process level, more specifically, at the level of the individual skills and capabilities of employees (Soto-Acosta et al., 2016). With the PLM being currently a technological solution for a system with a high number and variety of information systems that need to communicate over organizational limits and overtime (Främling et al., 2013).

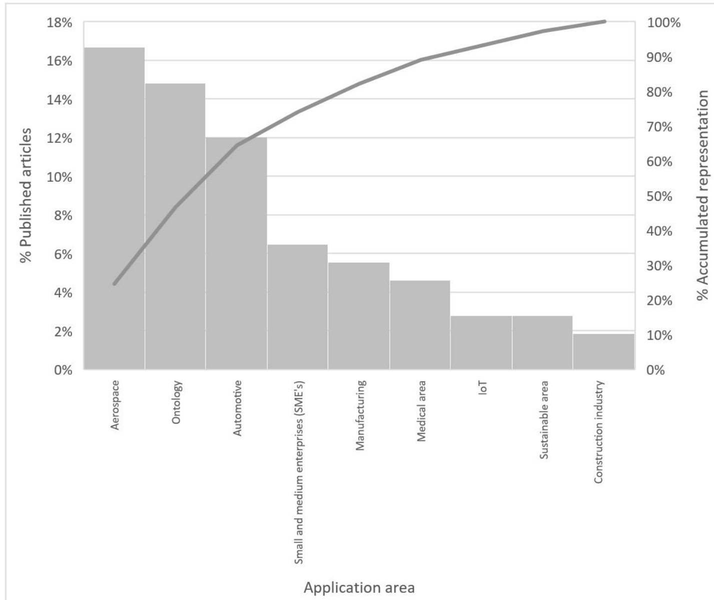


Figure 9. Representativeness of the most relevant application areas x Published articles

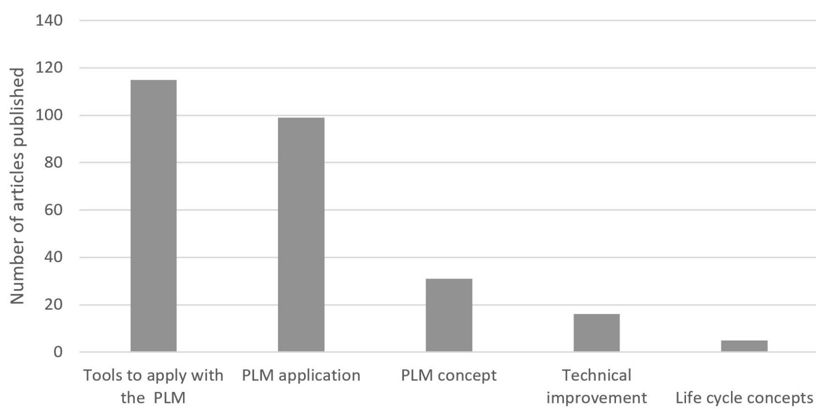


Figure 10. Number of articles published x Subject article.

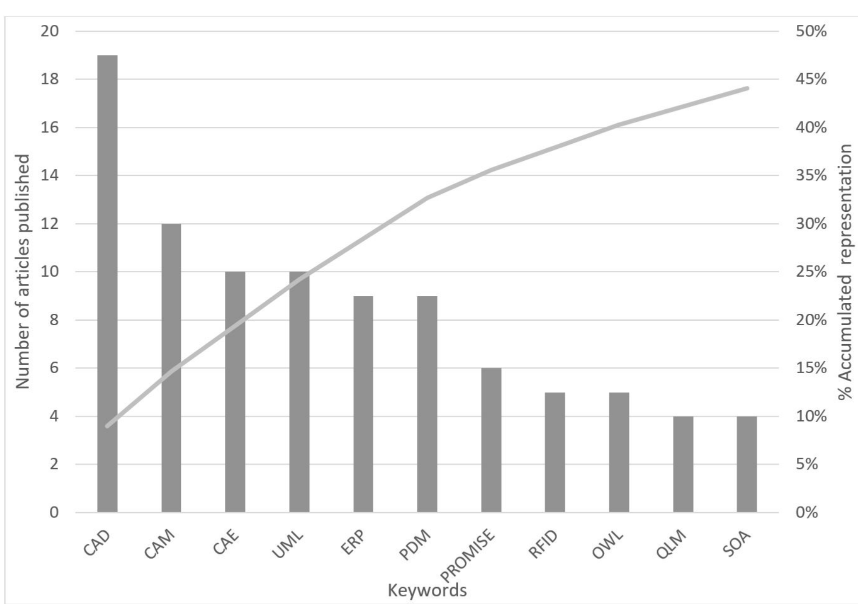


Figure 11. Keywords x Articles published.

Companies aiming to implement PLM can refer to the provided conceptual framework to establish their own framework, linking the company elements in a comprehensive PLM environment (Schuh et al., 2008). Therefore, the following ten steps are necessary: define the goal of PLM implementation; analyze the existent PLM foundation; rank processes; identify company maturity level (as-is process); select an appropriate reference model; customize reference model; specify requirements for system selection; select software solution; define the evolution path; implement software solution; and teach employees (Schuh et al., 2008). Besides the fact that the implementation of PLM strategy is a very long-period investment and the benefits are not measurable in a short period.

PLM implementation failures in cases of incompatibly between the selected software and the company philosophy (Soto-Acosta et al., 2016). In order to avoid this type of issue, the choice of the PLM solution must be preceded by an extensive analysis of business processes and procedures (Soto-Acosta et al., 2016), and ever-stricter environmental legislation over the past decade has led to the search for greater efficiencies everywhere, including the whole product lifecycle (Cao et al., 2009).

Although the potential of closed-loop PLM is widely recognized and have started to address its challenge, there are still fundamental questions and issues that need to be addressed. (Främling et al., 2014). There are limitations of commercial PLM software which means that adopting commercial PLM software implies assuming certain limitations since the beginning. For instance, the integration of the PLM with other systems (Soto-Acosta et al., 2016). It's necessary to manage a set of relations to provide consistency of data spread across different media and formats, sometimes referred to as "associativity" (Alemanni et al., 2010) and, there is also opportunity for improvement at architectures which tend to be inflexible at data interface (Främling et al. 2014; Young et al., 2007), meaning more points of potential failure (Alemanni et al., 2010). Also, it's necessary to improve the traceability and data synchronization (Kubler et al., 2015a), and the ability to share information across competitive software tools (Young et al., 2007).

4. Discussion

The main objective of the article is to understand how the concept of PLM was approached in the academy. The article presents the main approaches on the subject aiming to give a comprehensive view of the researches already done and gaps in studies that can be focused in future researches.

With this study, it is possible to show that among the articles studied there are more studies approaching only the applications of the system in few areas or studies that are focused in PLM applications in conjunction with other tools. Another discovery was that the three most advanced areas are Ontology, Automotive, and Manufacturing. Areas such as Oil and Gas, Healthcare and Food Industry have a high potential for the development of application of PLM.

The co-occurrence keywords evidenced the keyword Product Lifecycle Management in all clusters, but being evidenced as the abbreviation PLM only in one cluster, more related to product development and information technology with mathematical models. The bibliographical research evidence that the published articles are centralized in some journals and in a few countries.

In a highly competitive and fast-changing global marketplace, PLM is a new strategic approach to efficient management, its concept is composed of the following steps: beginning-of-life, middle-of-life and end-of-life, which includes the design and the manufacture until the recycle, reuse and disposing of the product. Therefore, the PLM enables to gather and analyze the product lifecycle information, which means that it is a key approach for industries who are searching to improve product quality, time-to-market and costs.

The article also has the PLM implementation perspective. It becomes as a process of change, that presents opportunities for improvement at architectures, and requires a high company maturity level to the software implementation. However, it is possible to admit that the concept of PLM is evolving and has already brought benefits, but still demand more specific case studies to better evidence the theoretical studies about the relevance of the system, the stages of the cycle, the results of system implementation and the best practices for the ones who participate of the implementation and for those who receive this change in their process.

5. Conclusion

This paper has provided an overview of PLM state of the art. The PLM was described through PLM justification; goals; concept; applications and implementation showing the benefits and the gaps for all steps. Thereby, the study brings into view of the main authors and their approaches to the theme with different and complementary views of the concept. Besides that, it can also show the difficulties found by them during their studies.

Thus, for future researchers, it is important to understand these difficulties and to explore these points and other elements such as PLM applications with real cases studies. Mainly with application in the strategical decision making; more management indicators that involve PLM; to include semantic, heuristics and mathematical models; to explore the data synchronization mechanisms; reinforce the connection and the challenges between the PLM, the big data, and the IoT. Exploring also the communication, the intelligent products and the integration between them with the objective of reducing environmental impacts and applying all these studies with the goal to explore in Closed-Loop Lifecycle Management (CL2M) as well.

In conclusion, with this, PLM is a complex concept and there is a lack of a deep understanding of the real potential of its application. And there is also a need to have more studies with more integration between all the parts that integrate it through real applications. With this article having as limitations the fact that only used the Scopus and WoS databases, and some figures and analysis were developed only for the papers that compose the contents analysis.

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Appendix 1. Author x Application Area.

Author	Application area
Alemanni et al. (2008, 2010), Brière-Côté et al. (2010), Cantamessa et al. (2012), Zhu et al. (2012, 2016), El Souri et al. (2017), Vieira et al. (2016), Navarro et al. (2013), Venugopalan et al. (2012), Eynard et al. (2010), Taverna (2004, 2017), Schmitt (2007), Hughes & Taverna (2004), Teresko (2004), Anderson (2002)	Aerospace
Alemanni et al. (2010), Cao et al. (2009), Matsokis & Kiritsis (2010), Srinivasan (2011), Tang & Qian (2008), Venugopalan et al. (2012), Baughey (2009), Shelley (2007), Tran (2006), Case (2006), Brincheck (2005), Teresko (2004), Trappey & Hsiao (2008)	Automotive
Lee et al. (2008a)	Aviation maintenance, repair, and overhaul (MRO)
Young (2012)	Back-end systems, front-end commerce applications, and the data warehouse
Hachani et al. (2013)	Business Processes (BPs)
Brezgin et al. (2013)	Cogeneration turbines
Demoly et al. (2013)	Concurrent engineering
Barthorpe et al. (2004), Holzer (2014)	Construction industry
Vezzetti et al. (2011)	Consumer Packaged Goods (CPG) industry
Sharma (2005)	CPI - Collaborative Product Innovation
Cáceres et al. (2010)	Digital Manufacturing
Iosif et al. (2018)	Electric aircraft
Courtney (2014), Savino et al. (2012)	Electromechanical sectors
Kultyshev et al. (2013)	Energy machine building enterprise
Brunsmann et al. (2012)	Engineering industry
D'Avolio et al. (2017)	Fashion companies
Pinna et al. (2017)	Food industry
Anderson (2002), Forcinio (2007)	Goods industries
Kubler et al. (2015b)	Healthcare
Venugopalan et al. (2012)	Hi-tech area
Avventuroso et al. (2017), Vila et al. (2017)	Industry 4.0
Cai et al. (2014), Fortineau et al. (2013), Främling et al. (2014)	IoT
Portillo-Barco & Charnley (2015)	Jet engine
Shi et al. (2018), Camarillo et al. (2017), Marconnet et al. (2017), Essop et al. (2016), Waurzyniak (2014), Bartholomew (2005), Wang & Xu (2005), Trappey & Hsiao (2008)	Manufacturing
Sodhro et al. (2018), Tang & Hu (2015), Allanic et al. (2014), Kang (2008), Kubler et al. (2015a)	Medical area
Caro et al. (2011)	Naval shipbuilding
Stephens (2006)	Nuclear energy
Tinham (2003)	Oil and gas
Aziz et al. (2005), Borsato (2014), Cai et al. (2014), Chungoora et al. (2013), Demoly et al. (2012), Fortineau et al. (2013), Kiritsis (2011), Matsokis & Kiritsis (2010), Young et al. (2007), Sriti et al. (2015), Talhi et al. (2015), Yoo et al. (2014), Matsokis & Kiritsis (2011), Yu et al. (2010), Borsato et al. (2010), Feng et al. (2009), Skarka (2005), Qiu et al. (2015)	Ontology
Venkatasubramanian (2005)	Pharmaceutical
Mejía et al. (2016)	Plastic injection
Lazarevic et al. (2011)	Radio-frequency identification (RFID
Falkiewicz (2011)	Sales, purchasing, accounting, manufacturing, and service.
Gulledge & Simon (2009)	Single Army Logistics Enterprise (SALE)
Marucheck et al. (2011)	Safety and security
Le Duigou et al. (2011), Zhang et al. (2011), Alison (2010), Pitcher (2005), Tinham (2004), Bruno et al. (2016)	Small and medium enterprises (SME's)
Främling et al. (2013), Zhao et al. (2015), Trotta (2010)	Sustainable area
Mo et al. (2010)	Teamcenter (TC) architecture
Golovatchev et al. (2010)	Telecommunications industry
Zhang et al. (2017b)	Turbomachinery
Bonou et al. (2016)	Wind turbines

Appendix 2. Author x Keywords.

Authors	Keywords
Iosif et al. (2018)	2D/3D design software
Brière-Côté et al. (2010)	Adaptive Generic Product Structure (AGPS)
Chen et al. (2008)	Analytic network process (ANP)
Trappey & Hsiao (2008)	Advanced product quality planning (APQP) &
Gomes et al. (2009b)	Atelier Cooperatif de Suivi de Projet in French (ACSP)
El Souri et al. (2017)	BAE Systems
Liao & Zhang (2005)	Based Access Control Model (RBAC)
Zhang et al. (2017a), Li et al. (2015), Wan et al. (2017),	Big Data
Marchetta et al. (2011)	Business Process Model (BPM)
Lundin et al. (2017), Waurzyniak (2015a, 2015b, 2017), Zscheile (2017), Farish (2008, 2012), Ding et al. (2011), Gomes et al. (2009a), Neil (2009), Walker & Cox (2008), Shelley (2007), Sudarsan et al. (2005), Lundin et al. (2017), Zscheile (2017), Lee et al. (2008a), Denkena et al. (2007), Alemanni et al. (2010), Ming et al. (2008)	Computer-aided design (CAD)
Piancastelli et al.(2015).	CADembedded FSI (Fluid System Interaction)
Waurzyniak (2015a, 2015b, 2017), Pullin (2013), Falkiewicz (2011), Walker & Cox (2008), Teresko (2004), Sudarsan et al. (2005), Lee et al. (2008a), Ming et al. (2008)	Computer-aided engineering (CAE)
Waurzyniak (2015a, 2015b, 2017), Walker & Cox (2008), Shelley (2007), Meloni (2007), Woods (2005), Teresko (2004), Sudarsan et al. (2005), Lee et al. (2008a), Denkena et al. (2007), Ming et al. (2008)	Computer-aided manufacturing (CAM)
Denkena et al. (2007), Ming et al. (2008)	Computer Aided Process Planning (CAPP)
Nathan (2009), Palmer (2004)	CATIA PLM
Chungoora et al. (2013)	Computation Independent Model (CIM)
Kärkkäinen & Silventoinen (2016)	Capability maturity modeling (CMM)
Sharma (2005)	Collaborative Product Innovation (CPI)
Lundin et al. (2017), Vila et al. (2017), Shen & Zhou (2003).	Computer-aided technologies (CAx)
Cole (2009)	Concept2Market (C2M)
Borsato (2014)	Core Product Model / Open Assembly Model (CPM/OAM)
Cui et al. (2008)	Customer architecture hierarchy (CAH) method
Young (2012), Bartholomew (2004), Shen & Zhou (2003),	Customer relationship management (CRM)
Fortineau et al. (2017)	Data Linked Through Occurrences Network (DALTON)
Hincapié et al. (2014)	Dassault Systemes (DELMIA)
Lee et al. (2008b)	Delphi methods
Ducellier et al. (2014)	Design Change Orders (DCO)
Wiens (2006)	Design data management (DDM) system.
Anišić et al. (2013)	Design for Excellence (DFX)
Marconnet et al. (2017)	Design For Manufacturing and Assembly (DFMA)
Vadoudi et al. (2017)	Design for sustainability (DfS)
Dhuieb (2014)	Digital Factory Assistant (DFA)
Sodhro et al. (2018)	Duty-cycle optimization-based (JEHDO) algorithm
Case (2006)	Electrical control unit (ECU)
Zhao et al. (2015)	EnergyPlus' program
Tang & Hu (2015), Holzer (2014), Simonova & Khisamutdinov (2013), Young (2012), Falkiewicz (2011), Wong (2006), Gort (2015), Barthorpe et al. (2004), Shen & Zhou (2003)	Enterprise Resource planning (ERP)
Li & Wu (2005)	Extensible Markup Language (XML)
Tait (2006)	Fashion Lifecycle Management (FLM)
Shelley (2007)	Finite element analysis (FEA) computation
Paavel et al. (2017), Kubler et al. (2014), Lee et al. (2008b)	Fuzzy analytic hierarchy process [FAHP]
Granros (2009)	Hazard Analysis and Critical Control Points (HACCP)
Portillo-Barco & Charnley (2015)	High pressure nozzle guide vane (HPNGV)
Främling et al. (2014)	Hypertext transfer protocol (HTTP)
Chungoora et al. (2013)	Knowledge Systems (IMKS)
Holzer (2014)	Information Modeling (BIM)

Appendix 2. Continued...

Authors	Keywords
Legardeur et al. (2006)	Innovation Development and Diffusion (ID2) system
Li & Qi (2008)	Integrated product model (IPM)
Camarillo et al. (2017, 2018), Shi et al. (2018)	Integrates Case-Based Reasoning (CBR)
Lee et al. (2008b)	Kano model
Al-Ashaab et al. (2012)	Knowledge-based environment (KBEnv)
Al-Ashaab et al. (2012)	Knowledge-Based Environment to Support Product Design Validation (KBE)
Garcia & Fan (2008)	Knowledge Management (KM)
Ibrahim & Paulson (2008).	
Bonou et al. (2016).	Life cycle management (LCM)
Chiappinelli (2008).	Manufacturing execution software (MES)
Johnson & Gavilanes (2003)	
Spera (2008)	Manufacturing operations system (MOS) software
Camarillo et al. (2018)	Manufacturing Problem Solving (MPS)
Tinham (2004)	MatrixOne and Smartteam
Abid et al. (2014)	Mechatronic system e System Modelling Language (SysML).
Sodhro et al. (2018)	Medical Things (IoMT)
Zhu et al. (2016)	Model-Based Definition (MBD)
Li & Wu (2005), Chungoora et al. (2013)	Model-Driven Architecture (MDA)
Aziz et al. (2005)	MySQL
Ilieva et al. (2009)	Multi-Project Management (MPM)
Venugopalan et al. (2012)	New product development (NPD)
Srinivasan (2011)	OMG PLM Services
Fortineau et al. (2013)	OntoStep
Srinivasan (2011)	Open Applications Group Integration Specifications OAGIS BODs
Joshi & Dutta (2008)	Original Equipment Manufacturers (OEMs)
Demoly et al. (2010, 2011a, 2013)	Product design Engineering based on Generative Assembly Sequences planning (PEGASUS)
Huang et al. (2009), Jun et al. (2009), Cao et al. (2009)	Product embedded information devices (PEIDs)
Marchetta et al. (2011), Chungoora et al. (2013).	Product Information Model (PIM)
Soto-Acosta et al. (2016)	Pladomin
Chungoora et al. (2013)	Platform Specific Model (PSM)
Camarillo et al. (2018)	Process Failure Mode and Effect Analysis (PFMEA)
Young et al. (2007)	Process Specification Language (PSL)
Paavel et al. (2017), Löwer & Heller (2014), Falkiewicz (2011), Cummings (2006), Crawford (2006), Seibert (2005), Kahlert & Rezaie (2005), Ryan (2003), Von Buchstab (2003)	Product Data Management (PDM)
Löwer & Heller (2014)	Product Data Management Systems (PDMS)
Kiritsis (2011), Främling et al. (2014), Huang et al. (2009), Jun et al. (2009), Cao et al. (2009), Kubler et al. (2015a)	Product Lifecycle Management and Information Tracking using Smart Embedded Systems (PROMISE)
Sassanelli et al.(2018)	Product service systems (PSSs)
Thilmany (2011).	Project portfolio management (PPM)
Bruun et al. (2015)	PTC Windchill PDMLink 9.1.
Lee et al. (2008b), Vezzetti et al. (2011)	Quality Function Deployment (QFD)
Främling et al. (2014), Främling et al. (2013), Tang & Qian (2008), Kubler et al. (2015a)	Quantum lifecycle management (QLM)
Kiritsis (2011), Huang et al. (2009), Jun et al. (2009), Cao et al. (2009), Kubler et al. (2015a)	Radio frequency identification (RFID)
Feng et al. (2010)	Reliability, Maintainability and Supportability (RMS)
Camarillo et al. (2018)	Shared Experience using an Agent-based System Architecture LayouT (SEASALT)
Chen et al. (2008)	Sensitivity analysis
Demoly et al. (2012)	Semantic WebRuleLanguage (SWRL)

Appendix 2. Continued...

Authors	Keywords
Hachani et al. (2012), Baughey (2009), Meng et al. (2008), Srinivasan (2011)	Server-Oriented Architecture (SOA)
Al-Ashaab et al. (2012)	Siemens Teamcenter Software (TcSE)
Demoly et al. (2011b)	SKeLeton geometry-based Assembly Context Definition (SKLACD)
Kiritsis (2011), Srinivasan (2011)	Standard for the Exchange of Product data model (STEP)
Zhang et al. (2014)	TechnoWare, InforWare, FunctionWare, and OrgaWare (TIFO)
Vezzetti et al. (2011)	Teoriya Resheniya Izobreatatelskikh Zadatch (TRIZ)
Tran (2006)	UGS' Teamcenter Express
Vadoudi et al. (2017), Eynard et al. (2010), Li & Wu (2005), Sudarsan et al. (2005), Matsokis & Kiritsis (2010), Srinivasan (2011), Zhao et al. (2015), Demoly et al. (2013), Young et al. (2007), Cao et al. (2009)	Unified Modeling Language (UML)
Kultyshev et al. (2013)	Ural Turbine Works (UTW)
Lin et al. (2011)	Value Stream Mapping (VSM)
Polcar & Horejsi (2015), Stelzer et al. (2009)	Virtual Reality (VR)
Zhu et al. (2012)	World Wide Web Consortium (W3C)
Yoo et al. (2014), Matsokis & Kiritsis (2010), Fortineau et al. (2013), Zhu et al. (2012), Demoly et al. (2012)	Web Ontology Language (OWL)
Adami-Sampson (2007)	Waste electrical and electronic equipment, Restriction of hazardous substances, and end of life Vehicle (WEEE, RoHS, and ELV).
Alemanni et al. (2008)	Wide Alenia space Network Data (WAND)
Feng et al. (2009)	Windchill FIexPLM
Liao & Zhang (2005)	Workflow Management System (WfMS)