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Thematic Section - Advances in Production Research

Diagnostic assessment of product lifecycle management based on Industry 4.0 requirements

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Abstract

Paper aims: Diagnostic analysis of PLM (Product Lifecycle Management) based on Industry 4.0 requirements supported by the AHP (Analytic Hierarchy Process) method.

Originality: The literature review found no research papers on PLM Maturity Models linked to requirements of Industry 4.0, attesting to the originality of the research and the topic proposed by the study.

Research method: The analysis is performed using an assessment framework that organizes and lists I4.0 attributes and PLM categories, supported by a multicriteria diagnostic assessment model based on the AHP method. The case study used in the research is an automotive industry located in the city of Curitiba, Brazil.

Main findings: A diagnostic analysis of the PLM categories and attributes of the I4.0 was performed, and the company's overall levels of maturity were observed.

Implication for theory and practice: The results obtained from the diagnostic analysis indicate that the company maturity is Level 2, analyses were also undertaken with respect to PLM categories and Industry 4.0 attributes. Proposals for improvements were made with the objective of increasing the level of maturity and reducing gaps and problems identified in the diagnostic assessment.

Keywords

PLM, I4.0. Maturity model. AHP.

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1. Introduction

The current globalization has been causing a great process of change in the world economy. We are experiencing a revolution in the way products and services are developed and delivered, as compared to mechanization, mass production, and automation. With smart factories and products, changes will take place in the way in which products are manufactured, impacting a large number of market sectors. Personalization of products by consumers tends to be one more variable in the manufacturing process, and smart factories will have to be able to personalize what each customer wants, adapting to their individual preferences.

Even though the development of industry has lasted hundreds of years, Industry 4.0, as it is called, will revolutionize all these processes. The main principles of Industry 4.0 were first published by Kagermann et al. (2013) and have built the foundation for the Industry 4.0 manifesto published in 2013 by the German National Academy of Science and Engineering. Some of the elements that conceptualize I4.0 have already been used in industry and manufacturing. However, their integration will transform production, resulting in better integrated, optimized, and automated flows. The transformation will also change the usual relationship among suppliers, manufacturers, and customers, as well as humans and machines (Rüßmann et al., 2015).

Product lifecycles are becoming increasingly shorter, which drives the continual and ongoing flow of product development projects in the sector. The increased competition imposes on companies the need to enhance their information systems, decision-making techniques and processes, with one of the alternatives that comes up being the implementation of PLM in this scenario of changes promoted by I4.0. According to Stark (2011), PLM are management practices for a company's products throughout their entire lifecycles, in a better and more effective way, from the first idea of creating it until the moment it is retired. PLM is an essential tool to deal with the challenges of increasingly demanding global competition and continually shorter product lifecycles (Silventoinen et al., 2009).

When companies plan to implement PLM, maturity assessment is one of the main issues to be addressed. Evaluating maturity requires all PLM elements: technology, infrastructure, processes, people, information and practices. This assessment must be performed in a clearly structured, systematic and understandable way that compares the current situation of the company with its desired, target position. With the integration of Industry 4.0 and PLM throughout all the steps of manufacturing, a better management can be obtained, with easier and faster answers, pushing the productive system to deliver better usage of data, once each sector has specific challenges and different needs.

Organization maturity classification parameters in relation to the lifecycle of its products and the Industry 4.0 requirements can be deployed as an alternative to monitor, promote gains and ensure the efficiency of projects that increasingly more require flexibility, performance and cost reduction. Given this scenario the research question is: How to carry out the diagnostic and maturity assessment for PLM under the requirements of Industry 4.0?

The research performed a diagnostic assessment of PLM under the requirements of Industry 4.0, using an automotive industry company for the case study. In this analysis, a diagnostic positioning of the PLM categories and attributes of the Industry 4.0 is obtained, as well as the company's overall levels of maturity were observed. Improvement proposals were also tendered for the indices found with the highest levels of fragility.

The paper is structured as follows. In section 2, a literature review was carried out with a view to comprehending the concepts in connection with PLM and Industry 4.0 maturity models. Section 3 enunciates the methodologies applied in classifying the phases of PLM, selection of Industry 4.0attributes, creation of assessment forms and application of the AHP method. The following section presents the results obtained in the diagnostic analysis and the resulting improvement proposals. The conclusion of this research is presented in section 5.

2. Background and related works

2.1. Industry 4.0 maturity models

Industry 4.0 refers to recent technological advances where the internet and supporting technologies (e.g., embedded systems) serve as a backbone to integrate physical objects, human players, intelligent machines, production lines and processes across organizational boundaries to form a new kind of intelligent, networked and agile value chain (Salkin et al., 2018).Concerning the rupture and impact brought about by I4.0 on operations, Coelho (2016) states that these go beyond simple digitizing, being based on combining different technologies. This will force companies to rethink the way they manage their business and processes, their positioning on the value chain, and the way of thinking about new product development and their introduction on the market (Coelho, 2016).

According to Kagermann the Industry 4.0 is a new level of value chain organization and management across the lifecycle of products. Recent concepts, such as the Internet of Things, Industrial Internet, Cloud based Manufacturing and Smart Manufacturing (Zhong et al., 2017), address these requirements in part and are commonly subsumed by the concept of a Fourth Industrial Revolution (Industry 4.0) (Lee et al., 2015). Industry 4.0 concepts involve the integration of physical and digital technologies with the phases of the Product. When this integration happens, companies can efficiently allocate their machines, quickly identifying problems, optimizing processes, reducing bottlenecks as well as products failures, thereby preventing problems before manufacturing the prototype (Santos et al., 2018). The integration between these areas provides more customization for production and products, reducing development time along with the required time-to-market for the final product.

For Schuh et al. (2020), the development of Industry 4.0 will be different in each company. Thus, companies must begin by analyzing their current situation and strategic objectives, considering medium and long term horizons, the technologies and systems effectively in place, in particular when these are related to product lifecycle information management. The faster a company adapts and anticipates events that drive changes in their business, the higher will be the benefits of this adaptation (Yongxin et al., 2017).

Companies must recognize the current state of compliance with Industry 4.0 concepts and technologies, before any transformation. Undertaking a systematic and strategic analysis is advisable, involving not just the company performance as such, but of all stakeholders involved in its value chain. This analysis is performed through the deployment of maturity models. The maturity of a company may be understood as a metric of its excellence. The maturity models described next are some of the ones available in literature related to Industry 4.0 concepts.

The IMPULS - Industry 4.0 is a self-evaluation tool, developed by the German Mechanical Engineering Industry Association (VDMA) and the Impuls Foundation, which is applied once the company is interested in establishing its level of preparation or conditions transformed by Industry 4.0. Readiness practice assessment works in 6 dimensions including 18 items to indicate readiness in 5 levels; barriers for progressing to the next stage are defined as well as advice on how to overcome them.

The Maturity Model for Industry, proposed by Schumacher et al. (2016) presents eight dimensions involving different perspectives. This Model is easy to apply for assessing the maturity level. However, the model only produces an overall score indicating the maturity level.

The model suggested by Leyh et al. (2017) is known as the *System Integration Maturity Model Industry* 4.0 (SIMMI) and only focuses on software/technology aspects of Industry 4.0 maturity. The organizational (i.e., employees, company vision) and environmental aspects (i.e., competition, market structure) are not considered in the maturity assessment.

Schuh et al. (2020) introduced the Acatech Maturity Index model, composed of four dimensions: *resources, information systems, culture and organizational structure*. The *resource* dimension refers to the company workforce, machinery, equipment, tools, other materials and the final product. *Information Systems* is the range applied to preparing, processing, storing and transferring data and information steps. The *culture* dimension presumes that organizations will not be able to achieve their goals nor become more agile, if digital technologies are introduced without addressing the corporate culture. *Organization structure* outlines the company's internal organization (structures and operating processes) and the company's position regarding its value chain, establishing rules to organize internal and external collaboration. The Acatech Maturity Index characterizes descriptive evaluation (assessments allow the current maturity stage in the different functional areas to be identified) and prescriptive one (identify actions to achieve maturity stage consistency).

An Industry 4.0 readiness assessment tool (Warwick University) identifies the organizations' Industry 4.0 readiness and prescribes actions, by benchmarking against other organizations. The Gokalp Maturity model targets providing complete and comprehensive guidelines and enables organizations to observe their problem areas and weaknesses as well as practices for applying transformations towards Industry 4.0 in a consistent way.

The analyses of these models result in perceiving relevant revelations in relation to the PLM perspectives.

The IMPULS (Industry 4.0) define that smart products are the foundation of smart factories and smart operations. Many features of the smart factories and potential benefits of data-driven services rely on the availability of comprehensive information about a particular product. The smart factory needs to know which product is at which location in the production stage to communicate with the order status in real-time. Equipment manufacturers need extensive information about how long and how intensively a piece of equipment is used in order to offer customers a predictive maintenance plan based on actual usage.

The Industry 4.0 maturity model (Schumacher) and Industry 4.0 readiness assessment tool (The University of Warnick) have some technical features and data about customers demand, like product function, configuration, packaging in the Data of Beginning life. The SIMMI 4.0 (Industry 4.0 maturity/ Leyh et al., 2017) have a strong relation with maintenance and product failure information concern.

Industry 4.0 (Acatech), has in the information flow the strong vertical integration of companies, supported by the application of intelligent technologies, like digital Kanban systems, used as a smart device in intralogistics and a high degree of automation characterizing the competence in the field of material and information flow.

The analysis of these maturity models indicates a common approach covering the general I4.0 process focusing particularly on connectivity, interoperability and technology infrastructure.

2.2. PLM approaches and maturity models

Product Lifecycle Management – PLM is the business approximation strategy capable of helping organizations to reducing costs, improving and protecting intellectual property, upscaling quality and reducing time to market, i.e., the time interval between conceiving and having the product available on the market (Stark, 2006).

PLM stemmed from a need resulting from a number of changes in the manufactured product environment. One of these changes was the fast growth in the quantity and complexity of information in the corporate value chain (Stark, 2006). Companies, given the constant changes of the market, seek competitive advantages basing themselves on emerging theories and technologies.

Authors Zancul (2009) and Grieves (2006) define PLM as a concept in integration, based on Information Technology (IT), in organizing information about products and processes, throughout their entire lifecycle. The fundamental importance of IT in PLM is also emphasized by (Ma & Fuh, 2008).

Li (2015), mention that currently, the underpinning concept of PLM is data and product information management – from the product's initial conception to final disposal. As a sort of managerial definition, manufacturing companies propose PLM for the purpose of information management. Thus, an information management platform is put in place capable of supporting the entire product development, production and maintenance process, as well as the continued improvement capability.

The steps in these processes are divided into three characteristic periods: beginning of life (BOL), middle of life (MOL) and end of life (EOL). The first stage of the product lifecycle is often considered the most critical part of the process. In the BOL period, the main phases are design and production. The second stage is where the importance of using PLM really comes into play. Designers and developers need to be able to collaborate. Without access to accurate product information bad decisions can be made. This final stage is often forgotten in the cycle. A product's life does not simply end once it is sold. Eventually, the product will become obsolete or unusable.

According to Li (2015), the main attributes entered in the product lifecycle (BOL) are: Customer's Demands, Maintenance and Failure Information, Cooperative Corporation Information, Design Specifications, Bill of Materials, Production Information. The MOL phase comprises: User Manual, Production Information, Maintenance Support Information, Product Status Information, Use Environment Information, and Maintenance Plan. The EOL phase is composed of: Maintenance History Information, Product Status Information, Use Environment Information, Part Recycling Information, EOL Product Status Information, and Dismantling Information.

According to Stark (2011), the full product lifecycle can be broken down into five stages / phases, starting with an image generation stage when the product is at the idea level. In the definition phase, a detailed description is built. The achievement phase, transforms this into the physical format used by customers. The use phase takes place on the customer side and, in the end, when the product is no longer necessary, it is disposed.

Exploring PLM as management approach, literature defines in a generic way four macro phases for product lifecycle. The first phase of the lifecycle is started by a market analysis to highlight opportunities through product planning (Rozenfeld, 2009). The second phase is the production phase, and starts when the sizing of the manufacturing resources is estimated. Still in this stage, the product is manufactured according to the specifications established in the project phase.

The subsequent macro phase, called use and services, is explained by Rozenfeld (2009) as the time during which the product remains useful for the customer, also covering all the maintenance and update services that, depending on the segment, may be required by the product. The final phase defined is the one for disposal which is segmented between disassembly and recycling/remanufacture. This phase marks the end of the product lifecycle.

In recent years, academics and consultants have developed maturity models with the objective of measuring and describing certain aspects of maturity in PLM. According to Savino et al. (2012), the PLM maturity models permit to assess the relative position of companies on their road to full PLM implementation.

The approach to assess PLM maturity in companies consists in going in-depth into its functionalities and using different elements. One of the central elements in the approach is a reference model, structured in levels of maturity, for the assessment of PLM in the company. This is usually split into three categories: (a) Organizational examines the way the organization is structured, trained, operates and manages in applying the PLM strategies and working with PLM processes and tools; (b) Processes PLM explores the processes used to provide support for PLM, including communication, control of changes. Collaboration in and outside the organization apply processes defined for product development; (c) Technology PLM determines the level of IT infrastructure and the implementation of solutions available to provide support for a PLM strategy, including consistency in the use of tools, the way the data is maintained, the maturity of the tools, integration of tools and information.

PLM enables evaluating the relative position of companies in the implementation of this concept. However, selecting the adequate PLM maturity model is a difficult task, since each model has different attributes (Li, 2015).

Batenburg et al. (2006), developed a MM based on an analysis of literature and empirical research in the model called "Framework for assessment and guidance in implementation of PLM", in two separate lines: PLM maturity and business/IT alignment. The former is to explore the strategy for the implementation of the "ideal" PLM for companies to obtain added value, significant advantages and, in this way, achieve their target through

PLM. In the framework targeted at business/IT, the author uses the self-assessment method in which the employees themselves evaluate the company's current situation and provide guidelines for the implementation of PLM.

Stark's model defined a maturity model for PDM (Product Data Management), an important component within PLM. The maturity model was devised with three different visions: a) company, b) product development, c) product data management. Schuh et al (2008) propose implementing a structure that comprises seven elements of maturity of PLM: Definition, Foundation, Reference models for the process, Neutral description of vendor software, PLM software support, and PLM knowledge base.

The Kärkkäinen et al. (2012) model examined how organizational maturity ought to be assessed in order to implement and successfully develop a working PLM framework. They define maturity of the customer dimension and provide preliminary descriptions of the level of maturity for this dimension.

The maturity model proposed by Zhang et al. (2014) evaluates a few PLM components, in order to evaluate the current and future situations. Components are selected and based on the assessment and analysis of KPIs. The suitable PLM models are investigated and, after six months or a year, the feedback loop can be used to discover whether the model is adequate for achieving the desired level of maturity.

Santos et al. (2018), investigate on how is the relation between the PLM maturity models and Industry 4.0. Through an AHP analysis, a comparison (weighting) on the maturity models characteristics with the layers of the RAMI 4.0 was carried out. In the research, it was identified that the PLM maturity model with greater adherence to industry 4.0 dimensions was the Batenburg maturity model highlighting highest final score (Santos et al., 2018).

2.3. PLM maturity models under Industry 4.0 perspectives

With the objective of undertaking an analysis between the PLM maturity models and the Industry 4.0 perspectives, a relation based on three I4.0 integration needs, pointed out by Kagermann et al. (2013) is proposed:

(i) Horizontal Integration: integration of the different IT systems used in the different stages of manufacturing and business planning processes within a company (e.g., inbound logistics, production, outbound logistics, marketing) and among several different companies (value networks);

(ii) Vertical Integration: integration of the various IT systems at the different hierarchical levels (e.g., actuator and sensor level, manufacturing and execution level, production management level, and corporate planning levels) to deliver an end-to-end solution;

(iii) End-to-End Digital Integration: integration throughout the engineering process so that the digital and real worlds are integrated across a product's entire value chain and across different companies, whilst also incorporating customer requirements.

Based on these integration dimensions, in order to get an overview about the maturity models in PLM domain, some common aspects describing the relation between the Industry 4.0 concerns with the PLM maturity models are shown in Table 1.

A qualitative relation (or adherence degree) of the models is defined: "+++" indicates if there is a strong concern, and the model meets the criteria better; "+" denotes a weak relation;"++" is in between."-" indicates that the model has a very low adherence to the criteria (lower than the "+"). To facilitate this analysis, the maturity models names were abbreviated: Batenburg (MM1), Stark (MM2), Schuh (MM3), Kärkkäinen (MM4), and Zhang (MM5).

The Horizontal integration realizes the integration of the various IT systems used in different stages of the manufacturing and business planning processes, within a company, and all the PLM maturity models were realized in this integration, with highlights to the Schuh and Kärkkäinen models. The central point of the framework, proposed by Schuh, consists of a set of lifecycle-oriented business process reference models, which

Table 1. Relations of PLM Maturity Models with Industry 4.0 concerns

Industry 4.0 Concerns		MM1	MM2	MM3	MM4	MM5
ThreeNecessary Integration Features	Horizontal Integration	+	+	++	++	+
	Vertical Integration	++	++	-	++	++
	End to End Digital Integration	-	-	-	-	+

links the necessary fundamental concepts to the enterprise knowledge and software solutions, deploying the PLM effectively. The Kärkkäinen models define the maturity of the customer dimension and provide preliminary maturity level descriptions for this dimension with the IT systems support.

Concerning Vertical Integration, which is the integration of these various IT systems at a different hierarchical level (e.g., actuator and sensor level, manufacturing and execution level), the Batenburg and Stark maturity models have strong characteristics that demonstrate this relationship. The Batenburg "organizational" and "inter-organizational" levels of maturity model require a corporate vision and an integral approach. PLM systems are integrated with other major enterprise systems, such as ERP. It is also seen as a business problem that spans the complete product lifecycle, making the PLM systems integrate with those of the suppliers to enable collaboration. The Batenburg and Zhang models have an important relationship with the "safety and security area", being the Batenburg model also strongly concerned about the "training and continuing" area. The Zhang model is the only that has some characteristics of End-to-End Integration.

The evaluated literature and this relation analysis between the PLM with Industry 4.0 concerns, show research gaps and opportunities for a PLM diagnostic analysis.

2.3.1. Research Gap 1: end to end digital integration

The PLM maturity models still have gaps with regards to the real world integration and the digital one, through all the product life cycle phases and also in incorporation of the customer requirements in these phases.

2.3.2. Research Gap 2: managing complex systems

PLM maturity models do not have a structural plan for a complex system to be built. In fact, there is a difficulty to exchange data and information between different systems and the lack of interoperability may represent a loss of production and resources.

2.3.3. Research Gap 3: regulatory framework

In the PLM maturity model was found, in the literature review that mutually adapts the innovations to the existing legislation. There are a few comments on some Industry 4.0 maturity models about the legislation, but the legal discussions regarding these challenges are very recent, and jurisdiction is still rare. In general, the efforts for the companies to safeguard their business from a legal point of view have to increase.

2.3.4. Research Gap 4: resource productivity and effciency

In the context of PLM maturity models, calculations about the trade-off have not been clarified yet and it has to be done to figure the additional resources that will be needed in smart factories and the potential generated savings.

2.3.5. Research Gap 5: recycling part information, EOL product information and dismantling information

Industry 4.0 brings to the remanufacturing industry a perspective of "Smart Life Cycle Data", "Smart Factory", and "Smart Services", however, the data of EOL Product Information is not very used. Some maturity models bring some specific information, but it is still a great opportunity to search.

The potential to transform a business through the use of Industry 4.0 requirements is leading to significant disruption across the manufacturing industries. Structuring IoT data across the entire manufacturing lifecycle, enables real time connectivity and customer monitoring, improves customer insights and monitors product performance throughout their entire lifecycles, providing an in-depth view of how the product is used along with those elements that are not of interest and usage, as well as the capability of maintaining both, predicatively and remotely.

Driven by big data information, PLM changes due to Industry 4.0 requirements also involves predictive analytics, data mining, data migration, simulation and optimization, and the collaboration among people and increasingly smarter machines.

3. Relational analysis of I4.0 and PLM

A relational analysis between the PLM categories and the attributes of Industry 4.0 is conducted following the research strategy shown in Figure 1.

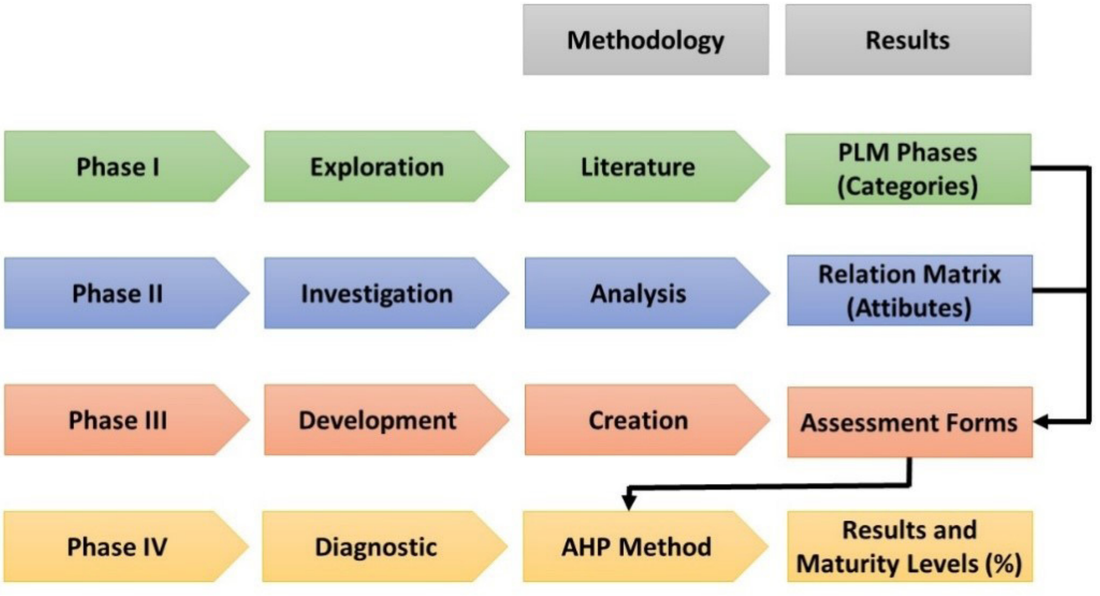

Figure 1. Research strategy.

Phase I (exploration) addresses a review of the literature and analysis of the content with the objective of identifying the most important categories within the BOL, MOL and EOL phases of PLM.

Phase II (investigation), a relational matrix takes place, established with the intent of mapping the relationship among the attributes of the different Industry 4.0 maturity levels and the categories of the PLM phases, resulting the attributes that will be addressed in the assessment forms.

Phase III (development) is related to the creation of the assessment forms, which will be deployed when performing the assessment and organizing information. Four assessment forms were established by attributes, relating the four levels of maturity.

Phase IV (diagnostic), the assessment forms will be used in the AHP method for diagnostic positioning of attributes in maturity levels.

3.1. Exploration

In this exploration phase, eight specialists from both the academia and manufacturing industry were consulted in the 2020 period, in order to know which PLM categories are considered them of important in each phase. The terms were extracted from the literature review proposed by (Li, 2015; Stark, 2011; Zancul, 2009). Figure 2 shows the essential components of PLM solutions in the three phases Bol, Mol and Eol.

Customer demands are related to the configuration, packaging, quality brand and other related items expected by the customer. Design Specifications represents material list, drawing, tolerance parameters. Production Information describes assembles instruction, production specifications, production history data, production plan, and inventory status. Product Status Information measure the degree of quality of each component, performance definition. Maintenance Plan relates tools, dates, places, cost, failure causes. EOL Product Status Information related to Product/part/component lifetime, recycling/reuse rate of each component or part. Recycling Part Information works with reuse part or component, remanufacturing information, quality of remanufacturing part or component. Maintenance History Information describe Components' IDs in problem, installed date, maintenance engineers' IDs, list of replaced parts, aging statistics after substitution, maintenance cost.

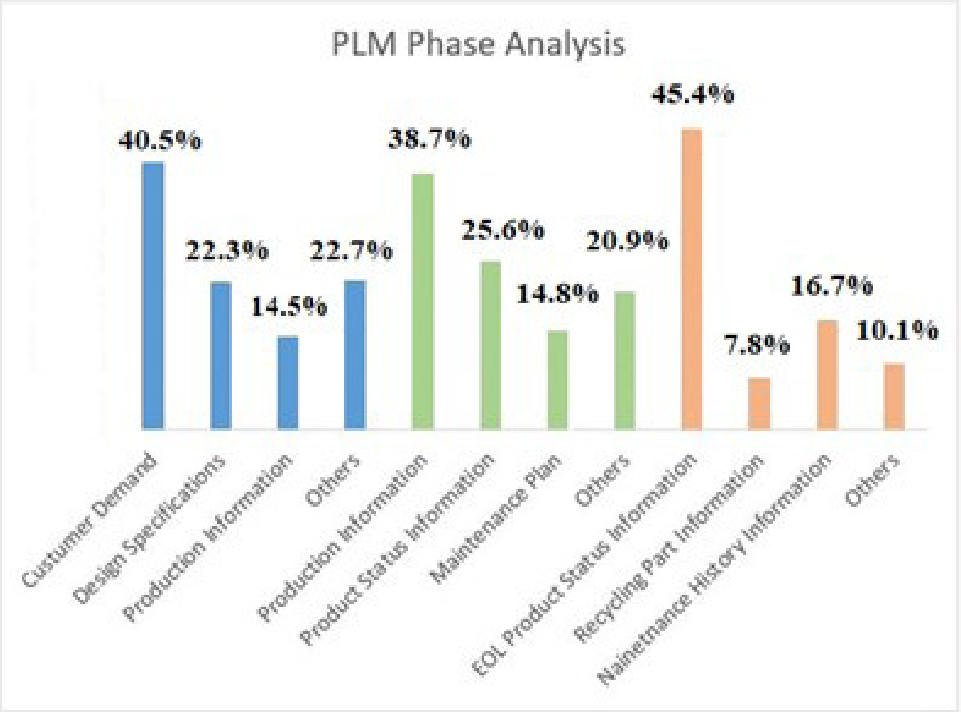

Figure 2. PLM phases analysis.

3.2. Investigation

In this stage, a relational matrix was built with the objective of mapping the relations among the attributes of the Industry 4.0 Maturity Models (Impuls-VDMA, Industry 4.0 Maturity Model, Simmi 4.0, Index (Acatech), Industry 4.0 readiness (University of Warnick) and Gokalp Maturity Model under the categories of the BOL, MOL and EOL phases of PLM. These analyses will be used as an instrument of analysis to determine which attributes should be selected and used in development and diagnostic phase.

During the applications, each Industry 4.0 attribute was compared to the characteristics of PLM phases, through a rating of 0 (null), 1 (low ratio), 3 (average ratio) and 9 (high ratio). The scale was used the QFD (Quality Function Deployment) tool as a reference. The research development by Stehn & Bergström (2002), employed 9-point scale (1-9), and was adopted by the authors in this project.

For instance, in the assessment of the Impuls Maturity Model, a score of 9 was given to the strong relationship existing between the Digital Modeling attribute and the Design Specification category. The score was weighted by specialists in the manufacturing sector relating the PLM and Industry 4.0 characteristics, and are showed in Table 2.

The MM I.4.0 and MM PLM naming are in reference to the attributes extracted from the maturity models corresponding. In this work, some exclusion criteria were selected, such as attributes that don't allow for maturity assessment (e.g., Liders Will, with very broad scope (e.g., Inovation Openning) and redundant scope (e.g., PLM).

After the reported analysis result, some attributes were selected with a rating 9,that is to say with a high ratio. Later on, the attributes selected will be used to develop the assessment forms and evaluated according to the phases of the PLM:

- BOL: Customer Data, Remote Monitoring, Data and Information Sharing, Digital Modeling, Efficient Communication, Data Analysis, Data Utilization;
- MOL: Customer Focus, Supply Chain Management, Digital portfolio of Product and Service Portfolio, Big Data, Cloud, Data Analysis, Human Machine Interface, Remote Monitoring;

Table 2. Relational Matrix: Industry 4.0 MMs and PLM.

MM PLM						
MM I4.0			BOL			
Maturity Models	Dimensions	Attributes	Customers Demands	Cooperative Corporation Information	Design Specifications	Production Information
Impuls	Smart Factory	Digital Modeling	1	0	9	3
Impuls	Smart Factory	Data Utilization	9	9	1	9
Impuls	Smart Factory	Data Analysis	9	9	0	3
Impuls	Data-Driven Services	Data Sharing	0	9	0	3
Impuls	Data-Driven Services	Result Sharing	0	9	0	0
Impuls	Data-Driven Services	Data-driven services	9	0	0	0
Impuls	Smart Operations	Cloud	9	3	0	3
I4.0 Maturity Model	Customer	Customers data usage	9	3	9	0
I4.0 Maturity Model	Products	Product Individualization	9	0	0	1
I4.0 Maturity Model	Products	Product Digitalization	1	0	0	0
Index	Resources	Efficient Communication	0	1	1	9
Index	Resources	Task Based design and interfaces	3	0	3	0
Index	Information Systems	Vertical and Horizontal Integration	0	9	0	9
Index	Information Systems	Data Management	0	1	3	3
Index	Information Systems	Standard Data Interface	3	0	3	1
Waterhouse	Agile IT Architecture	Unified Database	3	1	9	9
Waterhouse	Agile IT Architecture	External Data Integration	0	9	0	0
Waterhouse	Compliance, security, legal & ta	Optimized Supply Chain	0	9	0	0
Waterhouse	Compliance, security, legal & ta	Collaboration as Value	9	9	1	1

- EOL: Remote Monitoring, Data Analysis, Data Analysis and Sharing, Efficient Communication, Data Utilization and Analysis and Customers Data Usage.

3.3. Development

The forms are responsible for organizing information inherent to the maturity level correlated to the attributes. Four forms were drafted for attributes, representing the four levels of maturity. These structure information is in connection with: the PLM phase, attribute to be assessed, related attribute, level of maturity, description of the attribute proposed for assessment, indicators to be evaluated, results expected in that level. Table 3 shows an example of a structured form.

The need to organize the assessment knowledge in a hierarchal structure, from the standpoint of the perception of addressing organizational attributes, led to the AHP (Analytic Hierarchy Process) method. To perform the comparisons the software Super Decision was used. The tool allows the graphical modeling of the decision model, organizing the comparisons according to the characteristics of the AHP methods, maintaining the basic structure of the Goal, Criteria, and Alternatives (Adams, 2019). The structure of the Super Decisions model was created based on the structure of PLM with Industry 4.0 requirements. The information input comes from the evaluation form after the data gathering.

Table 3. Example of evaluation form.

PLM Phase	BOL	
Attribute	Customer Data	Example
Relates Attribute	Customer Demand	
Maturity Level	Level 1	
Attribute Description	Are expected from the customer related to the needs of the product function, configuration, packing, costs and other expectants. The company will use this data (information) for the product development process	
Assessment Propose	Check how this data is reported by customers and how the company will use t	
Evaluation Indicators	a) Data Availability b) Data Sharing c) Data Dissemination	
Results	There and no sharing of costumer data and the company carries out the product development process without this information	

3.4. Diagnostic

AHP is appropriate for the phase of the evaluation criteria, which aims to provide a broader diagnostic view of the priorities of the criteria from the standpoint of organizations. The diagnostic stage allows, through the mathematical basis of AHP, the formulation of the quantitative elements of the priority criteria by the attribution of weightings (Cestari et al., 2018).

The pairwise comparison between the n criteria is performed from a square matrix n x n, where the criteria are arranged in the same order along rows and columns. Figure 3 presents the hierarchical structure for AHP comprising the objective of the evaluation, criteria, and alternatives.

The AHP structure shown in Figure 3 is comprised of the following elements:

Level 1 - (Goal) Objective: represent the objective of AHP, assessment of PLM under requirements of I4.0;

Level 2 – (Criteria) represent three macro phases of PLM (BOL, MOL, EOL);

Level 3 – (Sub-criteria) represent the categories (perspectives) of each PLM phase;

Level 4 – (Sub-criteria) attributes of Industry 4.0 extracted from the relational matrix, weightings will be driven by the assessment forms;

Level 5 – (Alternatives) represent the maturity level that the company is currently positioned.

Based on the AHP structure, criteria and sub-criteria are subjected to pairwise comparison in a scale ranging from 1 to 9, the Saaty scale (Saaty, 2000). In this stage of the research, thirteen specialists involving different sectors of PLM in the company under study attributed weightings in the comparison among attributes. In Figure 4, a pairwise comparison illustrates the assessment related to “BOL Phase” layer of AHP structure. Grade 4 was assigned to “Production Information”, representing that is moderately important than “Customer Demand”.

The stage performs a pairwise judgment of elements in a given level of hierarchy from the standpoint of each element, in connection with a higher level. A synthesis of the priorities is also carried out, i.e., calculation of the final value for each alternative, to enable ordering these alternatives in accordance with their respective levels of importance. This value is obtained by multiplying the priority matrices by the alternative attribute vectors. Thus, for each alternative, the weighted sum of the relative importance of each attribute will be obtained. This sum represents the level of preference for a given alternative in connection with the respective criterion, therefore, the alternatives with the higher sum values are preferable. This parity analysis comprises the matrix, represented by Table 4 in the BOL Phase as example.

Values obtained will be converted into matrices and, the “weightings” are allocated in accordance with each attribute. The number of comparisons is represented in Equation 1.

$$Comp = n(n - 1) \ / \ 2 \tag{1}$$

Where n is the number of criteria in the level in case in point. The elements of the main diagonal will be equal to 1, the elements in the lower triangle of each square matrix will be the inverse of each element of the upper triangle.

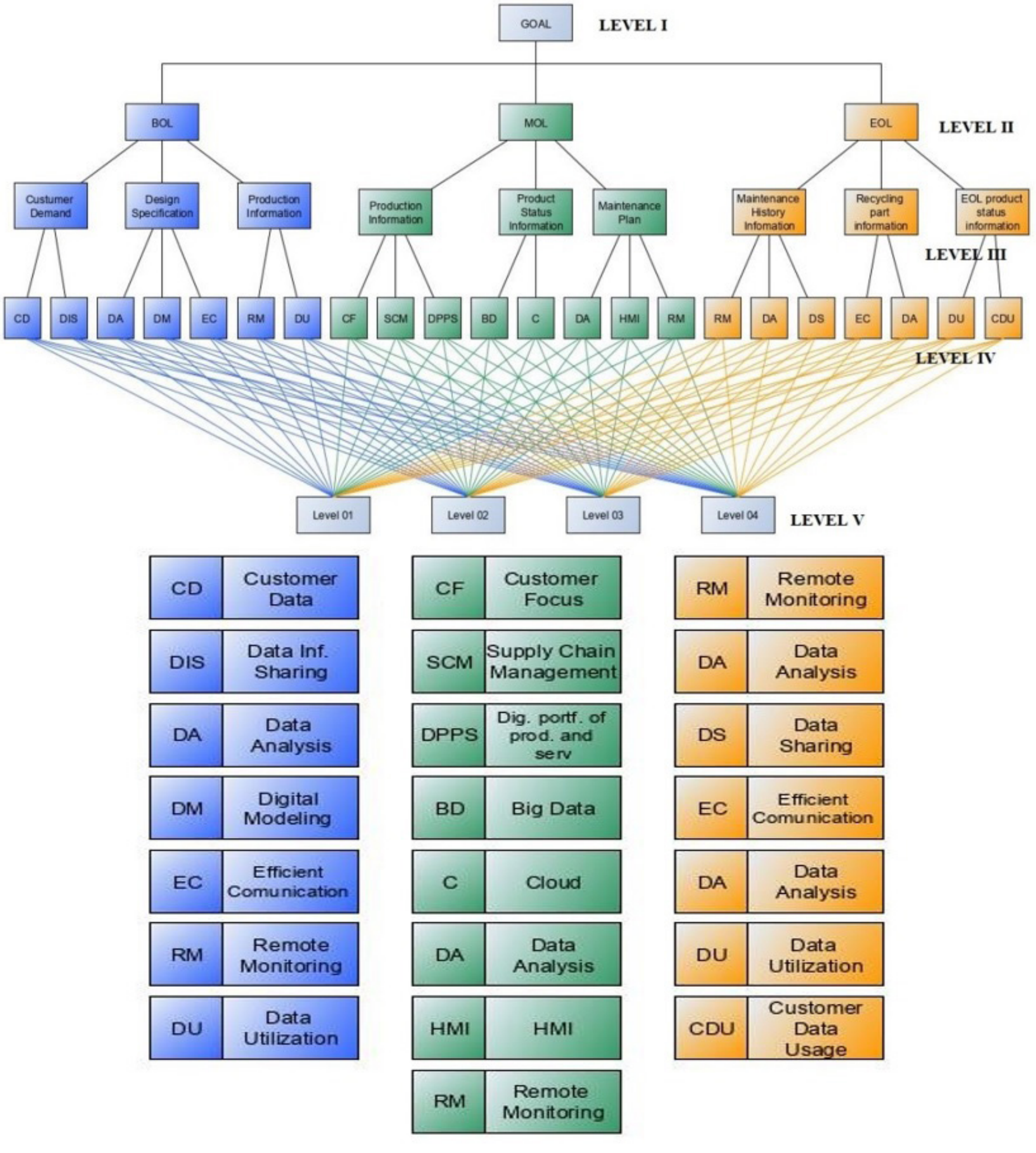

Figure 3. Hierarchical structure of AHP.

The purpose of AHP is to compare criteria not by their absolute values, but rather for the value within a given context. This process is also known as matrix normatizing (2).

$$a_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}},\ where\ j = 1,2,3,\ldots,n \tag{2}$$

After normalizing the matrix, the Eigenvector must be calculated, which is a matrix not linked to magnitudes, given that it only contains the relative order of priority among the elements, with the objective of allocating weighting to the criteria. The equation for building the eigenvector (3).

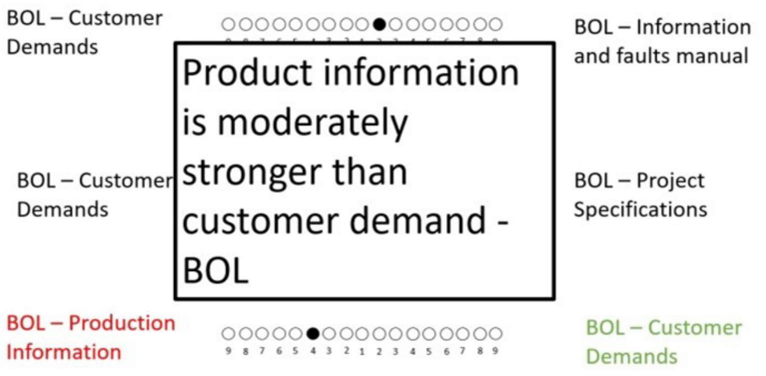

Figure 4. Pairwise performed between the attributes "Customer Demands" and "Production Information" in BOL (Beginning of lifecycle) Phase.

Table 4. Pairwise evaluation matrix for the PLM categories.

BOL	Customer Demand	Design Specification	Production Information	Relative Weight	Rank
Customer Demand	1	2	0.25	0.32748	2
Design Specification	0.5	1	0.33	0.25992	3
Production Information	4	3	1	0.4126	1

$$w_i = \frac{\sum_{i=1}^{n} a_{ij}}{n}, \ where\, i = 1, 2, 3, \ldots, n \tag{3}$$

So, the sum of the elements in the eigenvector must always be equal to one, as shown by Equation 4 – Sum of Self-vector (4).

$$\sum_{i=1}^{n} w_i = 1 \tag{4}$$

The consistency ratio (CR) is calculated to ensure the consistency of the evaluation model. The mathematical expression used to find the CR is given by CR = CI / RI, where the consistency index is denoted by (CI) = (λmax - n) / (n - 1) (λmax is the maximum mean value), and the value of the random consistency index (RCI) depends on the value of (n). In this example (BOL Phase AHP level – Table 2) the consistence is 0.08734. If the CR is excess of 0.1 the judgments are untrustworthy and the analysis valueless or must be repeated.

4. Results and discussions

In this section, the results of the case study are presented. Thirteen employees from different sectors of an automotive industry concern located in the city of Curitiba, Brazil took part in the diagnostic analysis with the results being shown in Table 5.

In so far as PLM phases are concerned, the MOL phase received the highest degree of importance (42%), followed by the BOL (30%) and EOL (28%).

For the BOL Phase, the Product Information category received a percentage value of 41%.At this stage, product information has to be shared along the production chain, to be synchronized with future updates. Assembly instruction, production specifications, production history data, production plan, inventory status are all related to this phase. Categories Customer Demand and Design Specifications received percentages of 36% and 26% respectively.

Table 5. Pairwise evaluation matrix for the PLM categories.

		Customer Demand		Design Specification		Production Information	
BOL	0.296	Customer Data	0.33949	Data Analysis	0.459	Remote Monitoring	0.66127
		Data Information Sharing	0.66052	Digital Modeling	0.15	Data Utilization	0.33873
				Efficient Communication	0.391		
		0.32748		0.25992		0.4126	
		Production Information		**Product Information**		**Maintenance Plan**	
MOL	0.4208	Customer Focus	0.16195	Big Data	0.87995	Data Analysis	0.43017
		Supply Chain Management	0.55122	Cloud	0.12005	HMI	0.03983
		Digital Port. of Prod. And Services	0.28692			Remote Monitoring	0.53
		0.3713		0.3972		0.2315	
		Maintenance History Information		**Recycling Part Information**		**Product Status Information**	
EOL	0.2832	Remote Monitoring	0.16108	Efficient Communication	0.29633	Data Utilization	0.53593
		Data Analysis	0.56851	Data Analysis	0.70367	Customer Data Usage	0.46407
		Data Sharing	0.27041				
		0.37899		0.3523		0.26871	

In the analysis of the MOL phase in PLM, the different categories received the following percentage values Product Status Information (39%), Product Information (37%) and Maintenance Plan (24%). The midlife phase is post-manufacture when the product has been distributed, used and repaired. In this phase, it is important to collect data about any form of failure, maintenance rates and user experience to obtain information for immediate solutions and future development. In the EOL phase of PLM, the categories received the following percentages Maintenance History Information (38%), Recycling Part Information (35%), and EOL Product Status Information (27%). The end-of-life phase is the removal of the product, recycling and disposal. This is when the reverse logistics takes place for the company. EOL starts when users no longer need the product. In this stage, companies collect information about which parts and materials still have value.

By applying this model, a diagnostic analysis can be performed with respect to the Industry 4.0 attributes correlated to the PLM categories. In the BOL phase, the attributes with the more representative values are Data Information Sharing (66%) in category Customer Demand, Data Analysis (46%) in category Design Specifications e Remote Monitoring (66%).The attribute Data Utilization is related to services and use of data and information by production at the onset of the product lifecycle. Attribute Data and Information Sharing checks the state of the speed and understanding of sharing information among suppliers and third-party companies. Attribute Remote Monitoring checks remote access to data in connection with maintenance and information related to failures at the onset of the product lifecycle. Items deserving attention in this phase are related to Digital Modeling (15%), which are digital models supplied up-to-date during the beginning of the product lifecycle, in accordance with their requirements. And Customer Data (33%), which are the customer data in connection with the need for the function delivered by the product, packaging configurations, costs and other expectations. The company will use this data (information) throughout the entire product development process.

In the MOL phase, the most representative Industry 4.0 attributes are Supply Chain Management (55%) in category Production Information, which is the management of information for the entire logistics chain (covering logistic processes from the reception of customer orders all the way to the delivery of the product at its final destination), using as data the production information throughout the product lifecycle and Remote Monitoring (53%) which is the remote access to data in connection with maintenance and failure information preventive and predictive maintenance during the midterm of the product lifecycle. Attributes Customer Focus in phase MOL (16%) describing what is expected from the user manual and with requirements defined by customer needs, and Big Data (12%), large volumes of information and integration of any data collected on the status of the product in the middle of its lifecycle, have lower grades in the assessments and need to be improved.

In the EOL phaseIndustry4.0 categories and Data Analysis (57%) and Data Utilization (27%) attributes, intelligent analysis of large volumes of information stored by companies, such as data collected through tools like Big Data and BI for components affected and parts replaced had the highest representation among the attributes evaluated. Attributes Efficient Communication (29%) efficient exchanges and communication on the status of product at the end of their lifecycle and Customer Data Usage (32%),which is the use of the customer information for interaction of data in terms of reuse and recycling.

The diagnostic assessment done by AHP was detailed with respect to positioning the Industry 4.0 attributes in a PLM perspective view and the Figure 5 shows the global maturity level apply in the case study.

The results from the deployment of the model have shown the current status for the company evaluated, revealing its global level of maturity (2). Different points for improvement were identified and will be discussed in the next section.

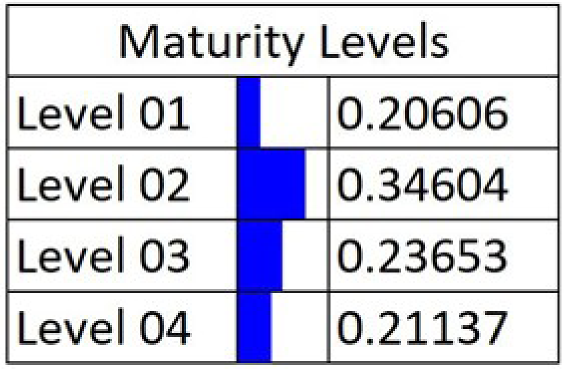

Figure 5. Maturity Levels.

4.1. Improvement proposals

The initial phase of the product lifecycle (BOL) is considered to be the most critical stage, the introduction stage covers product design, its development, tests and initial marketing. One of the most important assignments is to understand the market's claims and the availability of customer data, through sharing platforms, is one of the ways to deal with this. The amount of information about the product is related to the great volume and the great rates of change. The attributes linked to Data Utilization refer to Production Information, with Data and Information Sharing and Remote Monitoring referring to Customer Demand and Design Specifications, the ones that were given the highest values in the answers. The Customer Data (33%) and Digital Modeling (15%) are the attributes that need more attention. So that the attributes related to sharing and usage of data can be enhanced by using a CDP (Customer Data Platform) that cross matches relevant data such as purchase history, browsing behavior on the Internet and relationship with the product. For Digital Modeling, one of the characteristics found in the case study was the 3D modeling in low resolution, for this is recommended use the concepts of virtual reality.

During the MOL phase, with the final product established, the information provided to the manufacturer must enable full use and promote engagement, information on the usage phase, product status and updates have to be provided and passed on to manufacturers. Tracking this use information provides instructions to support the maintenance phase, enabling to predict failure before they actually happen. The attributes related to Customer Focus are related to Production Information, likewise Remote Monitoring is related to Maintenance Plan. Those attributes have gotten the highest averages in the answers. In this phase (MOL), so that the Cloud (12%) and Customer Focus (16%) attributes can have their levels of maturity enhanced, is suggested the promoting the analysis and storage of online analytic data processing (OLAP), using a large volume of multidimensional data is advisable.

When a product is at the End-of-life stage, the decisions that are part of the end of the lifecycle are based on recycling or disposal. Information obtained on the previous stage, the middle of life stage, such as maintenance history, product usage or status, contribute to a better and easier evaluation of the condition status (or its degradation) and the value of components. Therefore, the record becomes the basis for making decisions that involve the end-of-life stage, providing some of the options for this phase, such as recycling, remanufacturing, or final disposal. Attributes related to Data Analysis of Maintenance History Plan, and the Recycling Part Information received the highest values.

In the product's final phase (EOL), for attributes Efficient Communication (29%) and Data Sharing (27%), the recommendation is to use IoT (Internet of Things) technologies that enable tracking products from portals or readers, making it possible to control and calculate costs automatically, in addition to automatically registering on the system the entrance and exit of production.

5. Conclusions

In the first step of this research, a literature review was conducted, in order to identify the relationships between Product Lifecycle Management maturity models and Industry 4.0 concepts. As a result, gaps and improvement opportunities were identified.

In the second step, a relational analysis between the PLM Maturity Models and Industry 4.0, was carried out. This was the first in-depth literature review comparing these concepts, which may be needed to be considered as a great value to future practices. Through the literature review, the originality of the diagnostic assessment was established and, to date, it is the only one that presents PLM integrated with I4.0 requirements.

The case study performed a diagnostic analysis of the more relevant attributes of each phase of the product lifecycle, enabling inferring the organization's level of maturity at level of maturity (2), being characterized for having a medium level of development for its products in all phases of their lifecycles, with respect to the concepts of Industry 4.0.

Through the AHP method, it was possible to perform a diagnostic analysis of the attributes with the highest relevance within each phase of the product lifecycle (BOL, MOL and EOL), and, as final alternatives, there are levels of maturity which indicate the organization's overall positioning.

At the level of maturity established, data integration among the company's sectors presents a level of difficulty, direct access to real information about the product is not performed continually and remotely, the design and manufacturing sectors are not fully integrated, with the possibility of failures related to product performance and efficiency. At the maintenance department, monitoring is often performed physically, and there is a difficulty in storing information, lacking integration with the other departments.

The paper features some limitations: (1) the definition of Industry 4.0 attributes may be a challenge due to the speed of update of the literature on Industry 4.0. (2) the evaluation of attributes uses data from specialists and, therefore, a careful execution of the procedure is recommended. The execution of AHP may be reviewed with other rounds of assessment performed by different groups of specialists from the academia or professionals.

As proposal for continuity of the research, there is the combination of methods by deploying the weightings of the attributes resulting from AHP with the DEMATEL (Decision making trial and evaluation laboratory).This hybrid approach will serve to identify what is actually important from a standpoint of diagnostic assessment, combining the fragile aspects of the company established through the AHP (weightings of attributes) method with the influences of the DEMATEL method.

Following the diagnostic assessment (AHP + DEMATEL), a decisional analysis performed using the PROMETHEE II method could be a promising direction towards the definition of master plans to digital transformations based on the organization's reality. The prioritization of guidelines and organizational projects carried out with PROMETHEE II, will address important areas for the company from the PLM standpoint and characteristics from the Industry 4.0 perspective. The integration between PLM and Industry 4.0 will transform how the product is designed, manufactured and realized the maintenance process, will help the align and integrate key resources, quickly making product information accessible to the organization.

References

Adams, B. (2019). *Creative decisions foundation, super decisions (Version 2.10)* [Software]. Retrieved in 2021, July 5, from http://www.superdecisions.com

Batenburg, R., Helms, R. W., & Versendaal, J. (2006). PLM roadmap: stepwise PLM implementation based on the concepts of maturity and alignment. *International Journal of Product Lifecycle Management*, *1*(4), 333-351. http://dx.doi.org/10.1504/IJPLM.2006.011053.

Cestari, J. M. A. P., Loures, E. D. F. R., & Santos, E. A. P. (2018). A method to diagnose public administration interoperability capability levels based on multi-criteria decision-making. *International Journal of Information Technology & Decision Making*, *17*(1), 209-245. http://dx.doi.org/10.1142/S0219622017500365.

Coelho, P. M. N. (2016). *Rumo à Indústria 4.0* (Dissertação de mestrado). Curso de Engenharia Mecânica, Universidade de Coimbra, Coimbra.

Grieves, M. (2006). *Product lifecycle management: driving the next generation of lean thinking*. New York: McGraw-Hill.

Kagermann H., Walhster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0*. München: Acatech-Deutsche Akademie der Technikwissenschaften. Final report of the Industrie 4.0 Working Group.

Kärkkäinen, H., Pels, H. J., & Silventoinen, A. (2012). Defining the customer dimension of PLM maturity. *IFIP International Conference on Product Lifecycle Management*, *388*:623-634. http://dx.doi.org/10.1007/978-3-642-35758-9_56.

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18-23. http://dx.doi.org/10.1016/j.mfglet.2014.12.001.

Leyh, C., Bley, K., Schäffer, T., & Bay, L. (2017). The application of the maturity model SIMMI 4.0 in selected enterprises. In *Proceedings of the 23th Americas Conference on Information System* (pp. 1-10). Boston: AMCIS.

Li, J. (2015). Big Data in PLM. *The International Journal of Advanced Manufacturing Technology*, *81*(1-4), 667-684.

Ma, Y. S., & Fuh, J. Y. H. (2008). Product lifecycle modelling, analysis and management. *Computers in Industry*, *59*(2-3), 2-3, 107-109. http://dx.doi.org/10.1016/j.compind.2007.06.005.

Rozenfeld, H. (2009). Remanufacturing on a framework for integrated technology and product-system lifecycle management (ITPSLM). In *Proceedings of the 19th CIRP Design Conference–Competitive Design*. Cranfield: University Press.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., &Harnisch, M. (2015). Industry 4.0: the future of productivity and growth in manufacturing industries. *Boston Consulting Group*, *9*(1), 54-89.

Saaty, T. L. (2000). *Decision making for leaders*. Pittsburg, USA: WS. Publications.

Salkin, C., Oner, M., Ustundag, A., & Cevikcan, E. (2018). A conceptual framework for Industry 4.0. In A. Ustundag & E. Cevikcan. *Industry 4.0: managing the digital transformation* (pp. 3-23). Cham: Springer. http://dx.doi.org/10.1007/978-3-319-57870-5_1.

Santos, K. C. P., Loures, E. F. R., Junior, O. C., & Santos, E. A. P. (2018, July). Product lifecycle management maturity models in Industry 4.0. In P. Chiabert, A. Bouras, F. Noël, & J. Ríos (Eds.), *Product Lifecycle Management to Support Industry 4.0. PLM 2018. IFIP Advances in Information and Communication Technology* (pp. 659-669). Cham: Springer. IFIP Advances in Information and Communication Technology. http://dx.doi.org/10.1007/978-3-030-01614-2_60.

Savino, M. M., Mazza, A., & Ouzrout, Y. (2012). PLM maturity model: a multi-criteria assessment in southern Italy companies. *International Journal of Operations and Quantitative Management*, *18*(3), 159-180.

Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M., & Wahlster, W. (2020). *Industrie 4.0 maturity index. Managing the digital transformation of companies.* Munich*:* Herbert Utz.

Schuh, G., Rozenfeld, H., Assmus, D., & Zancul, E. (2008). Process oriented framework to support PLM implementation. *Computers in Industry*, *59*(2-3), 210-218. http://dx.doi.org/10.1016/j.compind.2007.06.015.

Schumacher, A., Erol, S., & Sihn, W. (2016). A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. *Procedia Cirp*, *52*, 161-166. http://dx.doi.org/10.1016/j.procir.2016.07.040.

Silventoinen, A., Papinniemi, J., & Lampela, H. (2009). A roadmap for product lifecycle management implementation in SMEs. In *The XX ISPIM Conference.* USA: Springer.

Stark, J. (2006). Product lifecycle management. In L. Stehn & M. Bergström. *Product lifecycle management* (Vol. *2*, pp. 1-35). Cham: Springer.

Stark, J. (2011). *Decision engineering: product lifecycle management: 21st century paradigm for product realization*. USA: Springer.

Stehn, L. A. R. S., & Bergström, M. A. X. (2002). Integrated design and production of multistory timber frame houses–production effects caused by customer-oriented design. *International Journal of Production Economics*, *77*(3), 259-269. http://dx.doi.org/10.1016/S0925-5273(00)00153-5.

Yongxin, L., Deschamps, F., Loures, E., & Ramos, L. (2017). Past, present and future of Industry 4.0 – a systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609-3629.

Zancul, E. D. S. (2009). *Gestão do ciclo de vida de produtos: seleção de sistemas PLM com base em modelos de referência* (Tese de doutorado). Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos.

Zhang, H., Bouras, A., Sekhari, A., Ouzrout, Y., & Yu, S. (2014). A PLM components monitoring framework for SMEs based on a PLM maturity model and FAHP methodology. *The Journal of Modern Project Management*, *2*(1), 108-119.

Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of industry 4.0: a review. *Engineering*, *3*(5), 616-630. http://dx.doi.org/10.1016/J.ENG.2017.05.015.