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Towards Digital Lean Manufacturing: A Brazilian Case

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ABSTRACT

Purpose – The purpose of this paper is to present a case study to describe the contact points between industry 4.0 technologies and lean manufacturing practices, that characterize the concept of digital lean manufacturing.

Design/methodology/approach – After building a research framework extracted from the literature review, a single and in-depth case study was carried out in a Brazilian factory to understand the implementation of the digital lean manufacturing. The data were analyzed using descriptive statistics and content analysis, and resulted in the development of a conceptual map.

Findings - The results revealed characteristics regarding six contact points implemented in the organization investigated. Also, it was observed that the results with the digitization of lean practices are consistent with the traditional literature, as they are aimed at reducing operating costs, eliminating waste, increasing quality, reducing lead time and real-time information.

Research limitations/implications - The results of the research are based on a single case study and cannot be generalized. Therefore, the application of the same research framework will be conducted in other companies.

Practical implications - Understanding the requirements for implementing the contact points illustrated in this case can help lean practitioners in the process of converting to the digital lean manufacturing model. However, it is understood that the implementation of DLM requires investments in technology and organizational culture aligned to the digital transformation.

Originality/value – This work represents the first attempt to verify the adequacy of a research framework for the characterization of digital lean manufacturing practices.

Keywords: Lean Manufacturing, Industry 4.0, Digital Lean Manufacturing.

Paper type: Case study.

INTRODUCTION

Several industrial sectors have adopted operational excellence strategies to achieve better performance in terms of quality, cost, and delivery. From this perspective, the Lean Manufacturing (LM) represents a fundamental approach able to accelerate the manufacturing processes and eliminate waste. Either, the paradigm of the fourth industrial revolution, also known as "Industry 4.0" (I4.0), has become part of the business agenda to develop strategies to convert the current manufacturing process into a new digital manufacturing model. The digital transformation process can be conducted through the implementation of Cyber-Physical Systems (CPS) or Smart Factories complementary to the improvement initiatives inherent to the LM approach.

The LM was idealized by Taiichi Ohno in the 1950s with the implementation of the efficient Toyota Production System (TPS), whose objective was to reduce operating costs and increase industrial productivity based on two essential pillars: *just-in-time* and *jidoka*. While the *just-in-time* method allows the production of the right quantity and the right time (mainly through pulled systems and continuous flow), the *jidoka* concept proposes the integration between operator and machine to ensure the quality of the production (right quality) by specific techniques, such as mistake-proofing, visual controls and automated inspection (Ohno, 1988; Womack and Jones, 1996).

The basic principles of TPS were also presented by Womack and Jones, who suggests the following sequence of five principles for the LM implementation: (1) identify value; (2) map the value stream for each product family; (3) create continuous flow; (4) establish a pulled system; and (5) seek perfection (Womack and Jones, 1996). The implementation of these principles can follow different strategies, from hiring specialized consultants, to training internal specialists who can implement LM tools and techniques.

Recently, the integration between information technologies (IT) and industrial automation (IA) has changed the *modus operandi* of manufacturing processes. The IT tools transform products into complex systems that combine hardware, software, sensors, microprocessors, databases, and connectivity, forcing companies to rethink how they do everything internally to face new threats and opportunities (Porter and Heppelmann, 2014). In the scope of operational excellence practices, it is expected that the integration of I4.0 technologies will optimize the collection and analysis of data from manufacturing processes with high accuracy and speed, increasing the possibilities for improving business performance (Agarwal and Brem, 2015; Tamás *et al.*, 2016).

The fourth industrial revolution has created new opportunities and challenges for operational excellence initiatives, enabling the use of the I4.0 technologies, such as the Industrial Internet of Things (IIoT), CPS, Radio-Frequency Identification (RFID), and Big Data Analytics. (Tamás *et al.*, 2016; Schwab, 2017). Given the considerations presented, it is believed that the interaction between digital technologies and operational excellence practices may expand the scope of improvement actions conducted under the light of the LM approach. Hence, three research questions emerge in this context: *RQ1 - What are the Contact Points (CPs) between I4.0 technologies and LM practices? RQ2 -How is it possible to integrate these two subjects empirically*? *RQ3 - What are the results of this interaction?*

The purpose of this paper is to present a case study carried out in a Brazilian factory to describe the CPs between the newly I4.0 technologies and the LM practices investigated in the organization. Therefore, a single and in-depth case study was conducted based on a theoretical framework. The results show the adherence between the two subjects (LM and I4.0) and may represent a reference guide for conducting future research towards Digital Lean Manufacturing (DLM) practices.

The present paper is organized as follows. The next section presents a brief literature review on the I4.0 and CPs. The next one presents the methodological approach chosen for the research. Then, a discussion of the main results from the Brazilian case study is presented. The paper ends with a short discussion of conclusions, limitations, and future research.

THEORETICAL BACKGROUND

The Fourth Industrial Revolution emerged at the turn of the 21st Century, primarily based on advances in mobile internet, miniaturization, and the cheapening of sensors, along with artificial intelligence and the creation of machine learning (Schwab, 2017). However, the term "Industry 4.0" became globally recognized after an event held in 2011 in Germany (Hannover Fair) to stimulate business around Smart Factories and to promote digital solutions into the CPS concept (Kagermann *et al.*, 2013; Sanders *et al.*, 2016).

According to the report entitled *"Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries"*, published by Boston Consulting Group, a set of nine technologies associated with I4.0 will transform the manufacturing environment in the next years. They are: (1) Big Data Analytics; (2) Autonomous robotics; (3) Simulation; (4) Integration of horizontal and vertical systems; (5) Industrial Internet of Things or Internet of Things - IIoT; (6) Cybersecurity; (7) Cloud computing; (8) Additive manufacturing; and (9) Augmented reality (Rüßmann *et al.*, 2015).

The idea around CPS is consistent with the Smart Factory concept. However, it is necessary to understand “how” the connection between the physical and virtual worlds can be operationalized in an integrated system. Several authors refer to the classic pyramid automation model, which is structured from hierarchical levels and starts with the connection of sensors until reaching the level of business control (Brettel *et al.,* 2014; Rüßmann *et al.,* 2015; Bartodziej, 2016; Gilchrist, 2016; Marques *et al.,* 2017). The Reference Architecture Model for Industry 4.0 (RAMI 4.0) offers a guide for converting to the I4.0 model, according to IEC 62264 and 61512 standards (Adolphs *et al.,* 2015; Kolberg *et al.,* 2017; Ma *et al.,* 2017).

In terms of shop floor management, I4.0 technologies will be aligned to the Smart Factory concept, characterized by the use of CPS to enable the efficient connection between machines, robots, sensors, people, products, transport vehicles and computers (Kagermann *et al.,* 2013; Guo *et al.,* 2014; Marques *et al.,* 2017). Therefore, the Smart Factory must deal with the complexities of the production environment using decentralized communication and information structures, with the following specificities (Lucke *et al.,* 2008):

- Object recognition through tags, sensors, and readers.
- Positioning system and location recognition object to reduce idle times.
- Real-time machine and process monitoring.
- Embedded systems with low power consumption integrated into mobile devices.
- Wireless communication between manufacturing technologies and objects.
- Automatic identification of objects such as barcode and RFID devices.
- Systems for connecting different sensors and actuators on the shop floor.

Although the state-of-the-art of I4.0 emphasizes the CPS concept and the enabling technologies, it is essential to understand how these technologies can be implemented on the shop floor in a context of continuous improvement. In this sense, the literature highlights as technical requirements, the IT and automation architectures involved in the implementation of the CPS (Kagermann *et al.,* 2013; Brettel *et al.,* 2014; Guo *et al.,* 2014; Adolphs *et al.*, 2015; Bartodziej, 2016; Gilchrist, 2016; Pfeiffer *et al.*, 2016; Kolberg *et al.,* 2017; Ma *et al.*, 2017; Marques *et al.,* 2017; Wagner *et al.*, 2017), as well as the skills and competencies requirements (Rüßmann *et al.,* 2015; Susskind and Susskind, 2015; Schumacher *et al*., 2016; Romero *et al.,* 2018).

The literature on I4.0 is still developing. Recent studies from different areas of knowledge, including information sciences, operations management, industrial engineering, and computer sciences, have addressed in a theoretical and practical way, clear examples of CPs between I4.0 technologies and LM practices. Table 1 summarizes the primary studies on these CPs, which were identified through a literature review. In addition to lean principles, these studies show the connection between specific techniques of the LM approach, such as Value Stream Mapping (VSM), Overall Equipment

Effectiveness (OEE), among others. It is important to highlight that this reference gave rise to the research framework used in the case study.

Table 1 – Contact Points extracted from the literature.

Contact Points		LM Practices	I4.0 Technologies	Authors (Year)
CP.01	Value Stream Mapping (VSM) in real-time, aided by Big Data Analytics from the integration between RFID and ERP/MES systems.	VSM	CPS and Big Data Analytics	Tamás *et al.*, (2016); Lugert *et al.*, (2018); Ante *et al.*, (2018); Mayr *et al.*, (2018).
CP.02	Key Performance Indicators (KPIs) automatically generated through CPS and monitored in real-time.	*Hoshin Kanri* and OEE	CPS	Ante *et al.*, (2018).
CP.03	Data generated in the CPS can be stored on the cloud and used to prevent equipment failures using Big Data Analytics.	*Jidoka*	CPS, IoT, cloud computing and Big Data Analytics	Sanders *et al.*, (2016); Mrugalska and Wyrwicka (2017).
CP.04	Replacing paper cards with electronic controls (*e-kanbans*) to control inventory levels in real-time and promote the pull system.	Pull System	CPS, RFID and Vertical Integration	Kolberg and Zühlke (2015); Sanders *et al.*, (2016); Mrugalska and Wyrwicka (2017); Wagner *et al.*, (2017).
CP.05	Operators equipped with smartwatches will receive messages about failures in real-time, and a CPS will respond with corrective actions.	*Andon / Jidoka*	Smartwatches, IoT and CPS	Kolberg and Zühlke (2015).
CP.06	Industrial robots will be used in inspection and control activities to prevent errors in the manufacturing process.	*Jidoka*	Advanced Robotics	Hedelind and Jackson (2011); Ma *et al.*, (2017).
CP.07	Reduced setup time through plug-and-play, RFID, and machine learning solutions.	SMED	RFID, CPS and Big Data Analytics	Sanders *et al.*, (2016).
CP.08	Additive Manufacturing allows printing of parts on-demand, man-machine separation, and waste elimination.	7 Wastes and Pull System	Additive Manufacturing	Chen and Lin (2017).
CP.09	Preventive and predictive maintenance activities can be optimized through CPS, giving rise to the "*e-maintenance*" concept.	TPM	CPS and Big Data Analytics	Li *et al.*, (2015).
CP.10	Augmented reality can assist operational tasks and identifying problems in real-time.	Standardized work	Augmented Reality	Kolberg and Zühlke (2015); Pfeiffer *et al.*, (2016); Sanders *et al.*, (2017).
CP.11	Optimization of internal logistics through simulation, CPS, AGVs, and Big Data Analytics.	Continuous-flow	Simulation, CPS, AGVs and Big Data Analytics	Neradilova and Fedorko (2017); Powell *et al.*, (2018).

RESEARCH METHODOLOGY

This study can be classified as a descriptive approach since the research aims to describe a specific phenomenon (a real case about the implementation of the CPs) without the interference of the researchers. To respond to the research questions presented in the introduction section, a single and in-depth case study was carried out. The research was conducted in a company that manufactures metal structures and stringers for the heavy automotive industry, identified in this paper as "Alpha." The study was carried out between June 2019 and February 2020, based on interviews, *in loco* observations, and documents. The company has manufacturing plants located in six countries and employs approximately 15,000 people worldwide. The unit chosen for the study employs 300 people. Altogether, eight employees with different functions were interviewed, including directors, managers, developers, and analysts. All participants graduated in different engineering areas and have worked on internal projects related to CPs implementation. Experience in LM practices and participation in digital transformation projects were the selection criteria for the interviewees.

The following aspects were considered for the selection of the company: (1) size of the organization; (2) culture of operational excellence and experience of over five years in LM practices; and (3) evidence of conversion to the I4.0 model. Figure 1 illustrates the research planning based on a theoretical structure (Figure 1a), built from the literature synthesized in the previous section. This structure can be understood through a bottom-up perspective, where the investigation begins with the understanding of the manufacturing process (where), goes through the identification of the CPs between I4.0 technologies and LM practices (what), evolving to the understanding of IT, automation and people requirements (how), until finally reaching the results achieved (why). The steps for carrying out the case study (Figure 1b) were properly structured in a research protocol.

The data collection was focused on the process with more evidence of digitization to specify where the research would be carried out. A closed questions questionnaire using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) was applied to respondents in order to verify the level of implementation of CPs in the company, according to the interviewees' perceptions. Otherwise, the open questions allowed the interviewees' free explanation regarding the requirements and results obtained.

Yin (2009) explains that the case study is recommended for research that seeks to find answers to questions such as “how” and “why” the phenomenon to be investigated occurs. All interviews were transcribed through software NVivo (version 11) and subsequently analyzed using content analysis techniques. The coding system and the frequency of occurrences of the codes allowed the construction of a conceptual map to synthesize the elements present in the research framework.

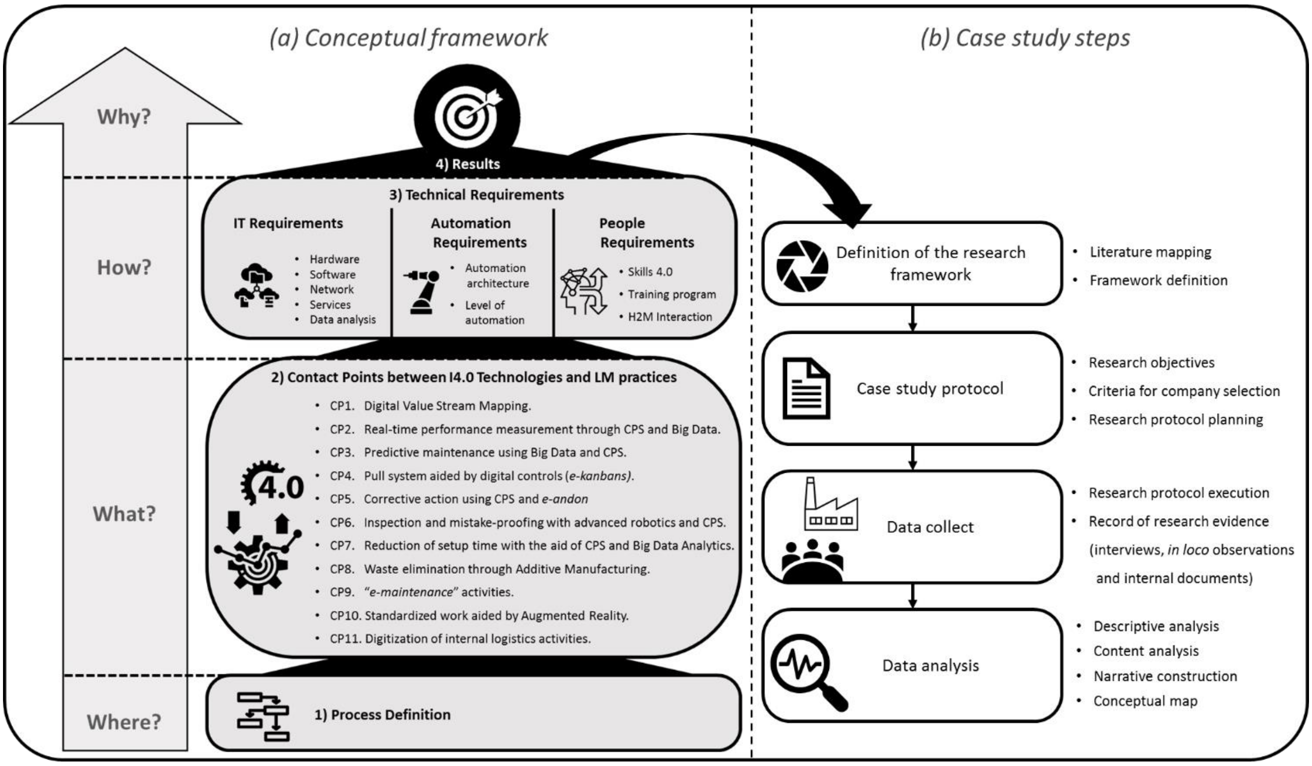

Figure 3 – Research planning.

RESULTS

The content of the qualitative interviews was used to find out answers to the research questions and empirical evidence. The research framework shown in Figure 1a synthesizes the main characteristics used to describe the implementation of the CPs at Alpha. Next, the considerations regarding the integration between these elements will be presented, as well as the analysis of the DLM practices observed in the organization.

The data collection was aimed at the manufacturing process of structural components for trucks representing the process with the highest adherence to I4.0 technologies. This process covers several activities, such as cutting, forming tooling charge, and assembly. Multifunctional teams have led the strategy of converting to the I4.0 model at Alpha by implementing proofs of concept. These projects cover receiving inspection activities using augmented reality, systems integration (MES, ERP, and BI), automated quality control, and computer vision inspection systems. The prioritization of LM practices at Alpha derives from the organizational strategy. Each year, the headquarters establishes a strategic plan and deploys it in the units using the *Hoshin Kanri* method. To foster and disseminate the LM culture, Alpha has implemented *kaizen* action called *Material Information Flow Chart* (MIFC), which replaces the traditional VSM. Currently, *kaizen* events are implemented in a workshop format with an average duration of five days and directed to specific topics, including MIFC, standardization, and Single Minute Exchange of Die (SMED).

The identification of the CPs implemented at Alpha took place through the verification of the questions with Favorable Response Indexes (FRI) greater than 50%, representing the sum of the percentages obtained in items 4 "agree" and 5 "strongly agree." Thus, of the eleven CPs present in the framework, six were fully implemented, as shown in Table 2. Cronbach's alpha coefficient for this group of questions was 0.6022, demonstrating the consistency of the answers obtained. After prioritizing the PCs with the highest company adherence, the research was directed to the implementation process of these PCs, seeking an understanding of the technical requirements, and the results provided by this strategy. Next, a narrative about the practices evidenced in Alpha will be presented, which was built from the content analysis of the interviews.

Table 2 – Perception of respondents regarding the implementation of PCs at Alpha.

Questions related to CPs	1	2	3	4	5	Favorable Response Indexes (FRI)
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	
	Frequency of responses (%)					
CP1. *Digital Value Stream Mapping.*	**0,00**	**0,00**	**37,50**	**25,00**	**37,50**	**62,50**
CP2. *Real Time performance management through CPS and Big Data*.	**0,00**	**0,00**	**0,00**	**37,50**	**62,50**	**100,00**
CP3. *Predictive maintenance using Big Data and CPS.*	12,50	12,50	37,50	0,00	37,50	37,50
CP4. *Pull system aided by digital controls (e-kanban).*	**12,50**	**0,00**	**12,50**	**50,00**	**25,00**	**75,00**
CP5. *Corrective action using CPS and e-andon.*	12,50	12,50	37,50	0,00	37,50	37,50
CP6. *Inspection and mistake-proofing with advanced robotics and CPS.*	**0,00**	**12,50**	**12,50**	**25,00**	**50,00**	**75,00**
CP7. *Reduction of setup time with the aid of CPS and Big Data Analytics*.	12,50	25,00	25,00	12,50	25,00	37,50
CP8. *Waste elimination through additive manufacturing*.	37,50	12,50	37,50	12,50	0,00	12,50
CP9. *"e-maintenance" activities.*	75,00	12,50	0,00	0,00	12,50	12,50
CP10. *Standardized work aided by Augmented Reality*.	**0,00**	**12,50**	**12,50**	**25,00**	**50,00**	**75,00**
CP11. *Digitization of internal logistics activities.*	62,50	12,50	12,50	0,00	12,50	12,50

Part of the manufacturing processes documentation, including operation sheets, work instructions, control plans, and process maps, is already in electronic format. However, according to Technology Director (TD1), the implementation of **CP1 - *Digital Value Stream Mapping*** could present real-time information not previously detected. The activities are mapped based on the requirements of the Advanced Product Quality Planning (APQP), which is widely used in the automotive industry. Although the development of flowcharts and process maps can identify important characteristics for the control of activities, the use of Big Data and simulation can help identify other less common characteristics (TD1).

According to the opinion of this interviewee, a map with updated information on the process in real-time would be useful to generate data that could be smoothed in a predictive way, as demonstrated in the statement below.

> TD01: *"To increase the process efficiency above 95%, it is necessary to have a system for predicting quality problems instead only identifying failures. It is essential to predict when these failures will happen. It is in this context that we need to expand monitoring and use other analytical tools*."

The implementation of **CP2 - *Real-time performance measurement through CPS and Big Data*** was conducted through a project that integrated the MES, IoT, PLC, BI systems, and cloud. According to the Quality Manager (QM1), before implementing this project, Alpha managed its measurement system through Microsoft Excel®. In 2014 the MES system was specifically implemented to control production. In 2017, this system started to be integrated with BI to monitor various indicators through smartphones, monitors, and screens. In terms of operational excellence, the indicators of setup time, productivity, quality, and OEE stand out.

All stages of the manufacturing process consume some material that must be available at the appropriate time and in quantity needed for production. As explained by the Quality Analyst (QA1), although the replacement of these materials is not yet performed automatically, the partial implementation of **CP4 - *Pull system aided by digital controls*** has allowed the real-time identification of the quantities consumed through MES system, which is fed with the aid of barcode. When the operator removes a certain quantity of specific material from the stock, this operation is registered through bar codes and notes in the MES system. The update of stock levels is performed automatically in the ERP system. From definitions of replacement point and minimum stock for each station, the operator can be informed about the withdrawal of materials.

This inventory control system can work as an alternative to the *kanban* system. The implementation of CP4 required the integration between the MES and ERP systems and the acquisition of printers, labels, and barcode collectors. According to the interviewee's opinion, "*The MES implementation has to be considered a watershed moment.*" (QA1).

The company has two applications of **CP6 - *Inspection and mistake-proofing with advanced robotics and CPS*** with an emphasis on RFID technology. The first application was in the plasma cutting area. Every 5 minutes, the operating system reads the tags installed on the operators' protective equipment and compares it with a register of operators qualified to work in the area. In this way, the machine is released only to the task-enabled operators. One of the significant problems in plasma cutting and welding processes is eventually allocating someone who is not qualified in the function (QM1).

The second application involved the calibration control and Measurement System Analysis. Each equipment has a tag that connects to the machine's PLC for automatic release or blocking of the operation, according to the observed situation (AQ2). It is important to highlight here that the MSA activity aided by CPS was not identified in the literature. According to the opinion of an Engineering Analyst (EA1):

> EA1: *"I think that this issue of blocking activities through an automated system is an excellent gain for quality. I believe that industry 4.0 and all the tools it provides have the potential further to improve production control in the sense of failure prevention."*

Finally, the implementation of **CP10 - *Standardized work aided by augmented reality***, is still undergoing experimentation. One of the challenges to be overcome is the weight of the equipment. However, this restriction can be offset by replacing the glasses with tablets. It is expected that the quality of inspection on receipt of materials can significantly improve, as the technology can optimize the task through 3D images, hologram, and instructional videos (QA2).

Among the most expressive **IT requirements**, systems integration (ERP-MES-CLP-BI), communication protocols, out-tasking, ethernet, and connectivity aspects (IoT) stand out, as well as the possibility of predictive analysis. As explained by the Senior Maintenance Analyst (MA1), information security management included a hierarchy with permission levels. The operator's access to the MES system is limited to monitoring production stages, with no possibility of changes in product variables. Besides, the organization developed the data receiving software (wireless) in partnership with a metrology solutions provider.

The investigation of **automation requirements** revealed that the most cited components regarding architecture for the implementation of CPS include RFID, wireless, Bluetooth technologies, PLCs, sensors, and actuators. Collection and transmission of shop floor data required PLC memory structures available on a server allocated for the CPS application. Thus, the software works as a gateway to capture the PLC memories and make the data possible in hardware resources. It should be noted that the communication by cabling is necessary since the manufacturing process has steps that consume too much electrical energy (plasma and solder), which interferes with wireless communication technologies (QA1).

The analysis of people requirements highlighted online training actions, hiring professionals from the IT area, and knowledge in the programming language, statistics and data analysis, network architecture, software engineering, and understanding of the business. Actions for the development of skills 4.0 involved not only training but also participation in workshops, congresses, and international fairs. Such events are fundamental for acquiring knowledge on cutting-edge technology and new suppliers representing an excellent opportunity to clarify doubts regarding the use of new technologies and equipment (DT1). The skills development strategy at Alpha covers the allocation of people with skills in software engineering, computer science, database, and M2M communication directly in the factory operations (AQ2). It was observed that IT staff acts as a support to the implementation of digitization projects and that this involvement is essential for the success of the projects.

> QM1: *"I needed a lot of training in IT, but when the IT staff joined our team in 2015, it became a revolution. If these people had not come to the process area and helped with the projects, we would not have progressed."*

Finally, the results from the implementation of the CPs declared by the interviewees are consistent with the literature on traditional LM, since they are aligned with the "House of Toyota" model, where the roof is represented by three targets: highest quality, lowest cost, and shortest lead time (Stewart, 2011). In addition to these results, respondents also cited the benefits of implementing CPs as eliminating waste in the process, increasing organizational competitiveness, and real-time information. Figure 2 shows a conceptual map synthesizing the entire narrative that was built from content analysis and codification. The comparison of this concept map with the research framework provides answers to the research questions presented concerning DLM practices in the investigated company.

CONCLUSIONS

The implementation of I4.0 technologies within the scope of operational excellence practices is still developing. The evolution of the LM to DLM approach requires the implementation of CPs between both areas. Although the specific literature on the topic presents some empirical studies combining specific enabling I4.0 technologies with LM practices, examples of the application of frameworks capable of integrating the two themes (LM and I4.0) still represent a research gap.

The present work mitigates this gap by presenting a real case study carried out in a Brazilian company undergoing a digital transformation process. The research framework tested in this study can bring together the managerial elements inherent to DLM in a single and simple structure, which can be used by practitioners and researchers. As answers to the RQ1, the PCs evidenced at Alpha included: CP1 - *Digital Value Stream Mapping*; CP2 - *Real-time performance measurement through CPS and Big*

Data; CP4 - *Pull system aided by digital controls*; CP6 - *Inspection and mistake-proofing with advanced robotics and CPS*; and CP10 - *Standardized work aided by augmented reality*.

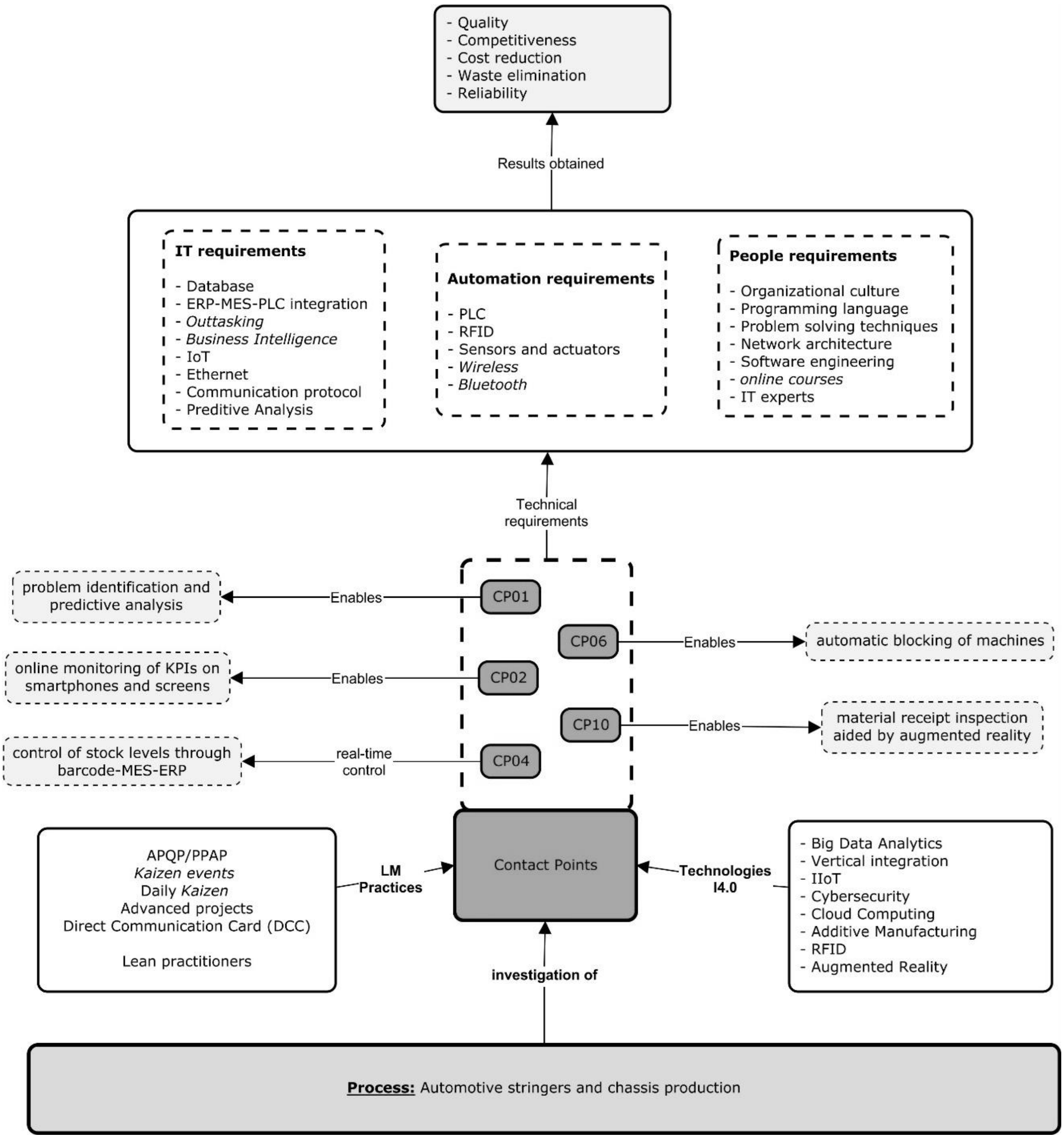

Figure 4 – Conceptual Map.

The results revealed that the implementation of these CPs had demanded specific requirements (RQ2), including IT requirements (integration of MES-ERP-PLC systems, outtasking, and communication architecture), automation requirements capable of connecting sensors, actuators, RFID, and PLC devices, as well as people requirements, with emphasis on digital culture and IT skills. Besides, interviews with Alpha professionals revealed that the results from the implementation of these CPs (RQ3) are in line with the LM theory, as they are aimed at reducing operating costs, eliminating waste, increasing quality, reducing lead time, and real-time information. However, it was also observed that the digitalization of LM practices increased the organizational competitiveness and the reliability of manufacturing processes. Such results evidence that the DLM implementation strategy can go beyond a simple "conversion" to digital manufacturing.

It is also worth noting that the implementation of DLM has managerial implications. The need for significant investments in technology and changes in shop floor routines is an example of these implications. In this context, the importance of multidisciplinary teams involved in I4.0 projects is highlighted. Regarding future research, this study will be extended to other companies, to allow a cross-case analysis and evidence the implementation of other CPs not discussed in this study. The analysis of a single case is the primary limitation research, as well as the impossibility of generalizing the results obtained. However, it is expected that the research framework presented in this paper will be able to be replicated in other studies related to DLM.

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