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Integration of Industry 4.0 and Lean Manufacturing and the Impact on Organizational Performance.

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Dissertation

Master in Economics and Business Administration

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2018

Abstract

The purpose of this study is to analyze the relationship between Lean Manufacturing, Industry 4.0 and business performance. It intends to examine, theoretically, the compatibility and correlations of both themes. Thus, hypothesized potentialities of an integrated approach are evaluated empirically through Portuguese's companies. Data were collected from 212 companies through an on-line questionnaire, which measures the implementation level of Lean Manufacturing and of Industry 4.0.

The findings suggest that Lean Manufacturing and Industry 4.0 present a positive and high correlation. The Industry 4.0 maturity appears as important influencer on Lean Manufacturing maturity, and also presents tips of a mediation effect from Lean Manufacturing to business performance. The impact of Lean Manufacturing, Industry 4.0 and of the integrated approach on performance were statistically non-significant.

Key-words: Lean manufacturing, Industry 4.0, Digitization, Organizational Performance, Assessment Models, Industry 4.0 Implementation approach.

Resumo

O objetivo deste estudo é analisar a relação entre o Lean Manufacturing e a Indústria 4.0 e o desempenho organizacional. Pretende-se examinar, teoricamente, a compatibilidade e as correlações de ambos os temas. Em seguida, as potencialidades hipotéticas dessa abordagem integrada são avaliadas empiricamente através da avaliação de empresas portuguesas. Os dados empíricos foram coletados de 212 empresas através de um questionário online que media o nível de implementação de Lean Manufacturing e da Indústria 4.0.

Os resultados sugerem que o Lean Manufacturing e a Indústria 4.0 apresentam uma correlação positiva e alta. A maturidade da Indústria 4.0 aparece como uma importante influência na maturidade do Lean Manufacturing e também apresenta pistas de possível efeito de mediação do Lean Manufacturing para o desempenho do negócio. O impacto do Lean Manufacturing, da Indústria 4.0 e da abordagem integrada sobre desempenho não apresentou significância estatística.

Palavras-chave: Lean Manufacturing, Indústria 4.0, Digitalização, Desempenho Organizacional, Modelo de Avaliação, Abordagem para Implementação da Indústria 4.0.

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List of Acronyms

ABM - Activity-Based Management

AMT - Advanced Manufacturing Technology

CPS - Cyber Physical System

CFA Confirmatory Factor Analysis

EFA – Exploratory Factor Analysis

HPWS - High Performance Work System

HRM - Human Resource Management

I4.0 - Industry 4.0

ICT - Information and Communication Technology

IoT - Internet of Things

JIT - Just in Time

LM - Lean Manufacturing

RoA - Return on Assets

RoS - Return on Sales

SME – Structural Equation Modeling

SML – Small, Medium and Large companies

TPS - Toyota Production System

TPM - Total Productive Maintenance

TQM - Total Quality Management

1 Introduction

1.1 Context

Since its appearance as a simple and efficient system (Womack, Jones, & Roos, 1990), Lean Manufacturing (LM) has been used by several companies in order to improve operational and financial performances (Camacho-Minano, Moyano-Fuentes, & Sacristán-D□ az, 2013), till it became a paradigm and a source of competitiveness for companies.

LM implementation has not been restricted into shop floor, its applications cover almost every organization's areas (Samuel, Found, & Williams, 2015) and has been adopted in different industrial business (Danese, Manfè, & Romano, 2017) as well in service sectors (Slomp, Bokhorst, & Germs, 2009).

The principles of LM are focused on a value creation system that seeks to offer high added value products and services and to eliminate systematically seven cardinal wastes (Ohno, 1988) that can be accomplished by adopting the "Lean way of Thinking" (Womack & Jones, 1996) and by applying a set of Lean practices and tools (Warnecke & Hüser, 1995). Hines, Holwe, and Rich (2004) demonstrate that the "Lean thinking" has been evolving and in synchronization with it, other processes' improvement programs emerged. Some of these methodologies were used to face the gaps and critics that Lean had faced and ended up with a creation of integrated approaches, such as: Lean Agile, Lean Six Sigma, Lean Sustainability and Lean Automation (Danese et al., 2017).

Industry 4.0 (I4.0), on the other hand invokes the contemporary technological advances that integrate physical objects, their virtual model and services, and coordination (Drath & Horch, 2014), over organizational boundaries to create a smart, inter-connected and agile value chain (Dalmarco & Barros, 2018; Schumacher, Erol, & Sihn, 2016). The theme has assumed a relevant matter in the manufacturing environment.

Recently, governments and industries worldwide launched strategic programs to develop manufacturing capabilities in order to support the growth and take advantage of the new industrial revolution wave (Geissbauer, Vedso, & Schrauf, 2016; Liao, Deschamps, Loures, & Ramos, 2017), also named by digitization. The principles of Industry 4.0 are supported by two essential elements: the Cyber Physical System (CPS) (Kagermann H., Wahlster W., & J., 2013), and the connectivity, widely understood through the internet. (Günther Schuh, Reiner Anderl, Jürgen Gausemeier, Michael ten Hompel, & Wahlster, 2017). Hermann, Pentek, and Otto (2016) announced four design principles about Industry 4.0: interconnection; information transparency by data provision, integration and analytic; autonomy through decentralized decisions; and virtual and physical support. Drath and Horch (2014) reinforce the real-time capability, service orientation, and flexible adaptation/modularity., Kagermann H. et al. (2013) presents the digital integration concept, broke down into three pillars of industry 4.0: horizontal integration; vertical integration; and End-to-End digital integration.

In this environment, the manufacturing system is self-controlled, supported by an innovative platform that assists intelligent products, data and services (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014), and will generate an integrated optimized system by managing a multi-agent system (Almada-Lobo, 2016). Academics and companies affirm that Industry 4.0 has high potential concerning value creation and expect three sources of benefits by implementing it: a reduction on operational costs, an increase of efficiency and additional revenues (Geissbauer et al., 2016; Schumacher et al., 2016)

While I4.0 is part of the strategic and research plans, organizations still face challenges to understand their current situation concerning Industry 4.0 (S. Erol, Jäger, Hold, Ott, & Sihn, 2016) to identify how I4.0 technologies can support their processes (Ganzarain & Errasti, 2016) and to learn about implementation details and possible benefits (Liao et al., 2017)

Besides that, in one perspective, research indicate that organizations with high LM maturity levels are susceptible to achieve better results in the application of other management methodologies (Yang, Hong, & Modi, 2011), including I4.0 (Tortorella & Fettermann, 2017). On the inverse point of view, Sanders, Elangeswaran, and Wulfsberg (2016), argue that LM implementation demands a huge and consistent efforts from the organization and I4.0 can facilitate it and enhance the success rate.

1.2 Research Design

The present study aims to examine the relationship between LM and I4.0 concerning concepts, practices and outcomes. Besides the theoretical analysis, the project investigates, empirically, evidence of the integrated approach of LM and I4.0 on Portuguese's companies.

In order to do so, the study started with the definition of the research questions. After the definition of the research questions, an in-depth literature review tried to answer them. The findings and missing information of the literature review generate five hypothesis which were defined to be tested through a survey research. The work discuss the findings of the literature review and the finding of the survey research. Research overview on Figure 1-1.

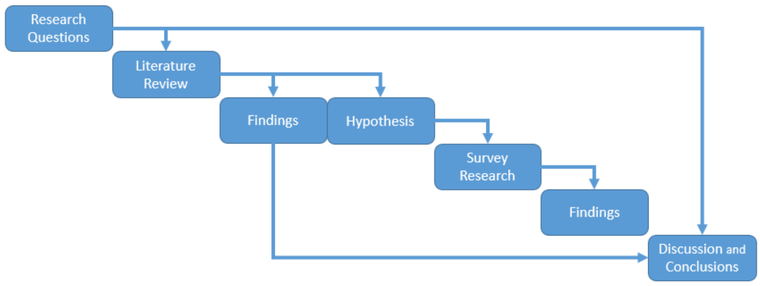


Figure 1-1: Research overview

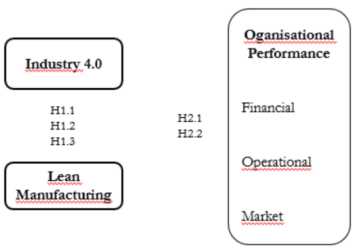
1.2.1 Research Questions

The research investigates the following questions:

1) Are LM and I4.0 compatible?
2) Does a correlation between LM and I4.0 exist?
3) Does the integrated approach of LM and I4.0 enhances business performances?

1.2.2 Summary of the Conceptual Framework and Hypothesis

The conceptual framework and hypothesis defined on later chapters is summarized below:



RESEARCH QUESTION	HYPOTHESIS
1)	-
2)	**H1.1** The correlation between I4.0 and LM is significant and positive. **H1.2** LM experience provides significant contribution on I4.0. **H1.3** I4.0 experience provides significant contribution on LM.
3)	**H2.1** The integraetd approach presents a significant and positive influence on organizational performance. **H2.2**. The integrated approach of LM and I4.0 implies a higher impact on organizational performance compared with the influence of each approach implemented in a stand-alone way.

Figure 1-2: Introduction to the Conceptual Framework and Hypothesis.

1.3 Similar Study

A similar study have been conducted in a similar direction, namely Tortorella and Fettermann (2017). They analyzed I4.0 implementation in regard with LM implementation. Their study was conducted through a survey within 110 valid responses from Brazilian manufacturing organizations. The LM was assessed by 41 questions and I4.0 by 10 I4.0 technologies.

Tortorella and Fettermann (2017) found three important results: companies with higher improvement on operational performances had important association between Industry 4.0 technologies and Lean manufacturing practices; this association can be perceived in organizations independent of their size; and the most organizations with great implementation level of Industry 4.0 technologies conjointly present higher level of Lean manufacturing implementation. They suggests that Industry 4.0 implementation could be facilitated by the Lean Manufacturing involvement.

The novelty attributed to this work regards the different dimensions that it is considered to measure I4.0 and the scope of application, where the present wants to realize the current situation of Portuguese's manufacturing.

1.4 Document Structure

This document contains six sections. The present section is dedicated to introduce the theme and contents of the dissertation. Section 2 presents a literature review. Section 3 indicated the conceptual framework and hypothesis development. Section 4 describes the methodology adopted on research development considering target definition, data collection process, instrument and measures applied. Section 5 presents the survey analysis and findings discussion. Section 6 intends to conclude and expose the limitations of the work.

2 Theoretical Background

This chapter includes a literature review of relevant material about Lean Manufacturing (LM), and Industry 4.0 (I4.0). The major part of the materials used on this section was searched on Scopus and "Web of Science" data bases.

Firstly, this section aims to understand the concepts, principles and applications of each theme and about their integration. In order to prepare the basis to evaluate the potential relationship and impact of this integration, a second moment of the literature review is focused on assessment models of both methodologies.

The literature concerning LM is numerous and covers diverse aspects of management fields. However, I4.0 academic material is in an early phase of development and a few studies have been conducted until today, mainly correlating the theme with LM.

2.1 Lean Manufacturing

2.1.1 Introduction

The term "Lean Manufacturing" emerged to identify the production system that was developed by Eiji, Kiichiro Toyoda and Taichii Ohno from early 1950s through the 1980s in the Japanese automotive industry, in particular at Toyota Motor Corporation (Ohno, 1988; Womack et al., 1990).

The TPS knowledge appeared when Taiichi Ohno shared his workbooks in 1970 that announced the system approach, methods and techniques (Hines et al., 2004) and became widely famous after the publication of the book "The Machine that Changed the World" in 1990, by Womack and Jones, that named the TPS as LM and exalted its efficiency by highlighting its superiority over traditional manufacturing practices (Samuel et al., 2015) in special differentiating itself from Henry Ford's mass production (Behrouzi & Wong, 2011).

2.1.2 Concepts

On its dissemination, the LM has received different definitions and treatments (Danese et al., 2017) In the beginning, Womack and Jones, presented LM as a system focused on waste elimination (Womack et al., 1990), Warnecke and Hüser (1995) defended LM as a system of measures and methods that should be applied all at once. Bicheno (2004) considered LM as a set of tools and techniques.

Others authors identify LM as a philosophy, It is more than just tools and techniques, it is a modus to guiding behavior and tackling challenges. (Hines et al., 2004; Shah & Ward, 2003). A milestone for this approach is the book "Lean Thinking" published in 1996 by James Womack and Daniel Jones and since then, this concept have been recognized by many managers and have been applied beyond many initiatives.(Bhamu & Sangwan, 2014)

The confusion about LM definition could be related with the fact that many dimensions of LM have evolved since its appearance. In fact, Hines et al. (2004) argue that the "Lean thinking" has been evolved, however, maintaining a base of principles. See Table 1.

Phases	1980-1990 Awareness	1990-mid 1990 Quality	Mid 1990-2000 Quality, cost and delivery	2000+ Value system
Literature theme	Dissemination of shop-floor practices	Best practice movement, benchmarking leading to emulation	Value stream thinking, lean enterprise, collaboration in the supply chain	Capability at system level
Focus	JIT techniques, cost	Cost, training and promotion, TQM, process reengineering	Cost, process-based to support flow	Value and cost, tactical to strategic, integrated to supply chain
Key business process	Manufacturing, shop-floor only	Manufacturing and materials management	Order fulfilment	Integrated processes, such order fulfilment and new product development
Industry sector	Automotive – vehicle assembly	Automotive – vehicle and component assembly	Manufacturing in general – often focused on repetitive manufacturing	High and low volume manufacturing, extension into service sectors
Shingo (1981, 1988)	Shingo (1981, 1988) Schonberger (1982, 1986) Monden (1983) Ohno (1988) Mather (1988)	Womack *et al.* (1990) Hammer (1990) Stalk and Hout (1990) Harrison (1992) Andersen Consulting (1993, 1994)	Lamming (1993) MacBeth and Ferguson (1994) Womack and Jones (1994, 1996) Rother and Shook (1998)	Bateman (2000) Hines and Taylor (2000) Holweg and Pil (2001) Abbas *et al.* (2001) Hines *et al.* (2002)

	1980-1990	1990-mid 1990	Mid 1990-1999	2000+
Key gaps	Outside shop-floor Inter-company aspects Systemic thinking Auto assembly only	Mainly auto Human resources, exploitation of workers Supply chain aspects System dynamics aspects	Coping with variability Integration of processes Inter-company relationships Still mainly auto Integrating industries	Global aspects Understanding customer value Low volume industries Strategic integration E-business
Main critics	Carlisle and Parker (1989) Fucini and Fucini (1990)	Williams *et al.* (1992) Garrahan and Stewart (1992) Rinehart *et al.* (1993)	Davidow and Malone (1992) Cusumano (1994) Goldman *et al.* (1995) Harrison *et al.* (1999) Suri (1999) Schonberger and Knod (1997)	Bateman (2000) Christopher and Towill (2001) van Hoek *et al.* (2001)

Table 1: Combined from "The evolution of lean thinking" and "The main gaps and criticisms of lean thinking". (Hines et al., 2004)

The first LM objectives are related to accomplish reduced lead time, lowest costs and best quality (Ohno, 1988). On the early phase it had a prescriptive approach to applying tools, then evolved through a contingency approach (1990), and then got a perspective of system taking attention to people and teamwork, integration features and a focus on customer value creation (2000).

Because of its simplicity and efficacy, LM has become a paradigm and a source of competitiveness for companies. It became not restricted to shop floor implementation, its applications cover almost every organization's areas (Behrouzi & Wong, 2011) such in administrative work (Buzby, Gerstenfeld, Voss, & Zeng, 2002), and supply chains (Ben Naylor, Naim, & Berry, 1999; Simpson & Power, 2005), and has been adopted in different business as service sectors (Slomp et al., 2009) including Health system (Carter et al., 2012; Furman & Caplan, 2007).

Observing the LM movement, it is possible to identify others process improvement programs emerging. They all have a lot in common: origins, aims, tools and techniques; however they differ in some aspects as focus, scope and investment. For example: Theory of constraints, Total Quality Management, Total Productive Maintenance, Business Process Management, World Class Manufacturing (Hines et al., 2004; Samuel et al., 2015).

Some of these methodologies were used to face the gaps and critics that LM had faced and was presented as an integrated approach, such as: Lean Agile, Lean Six Sigma, Lean Sustainability and Lean Automation. (Danese et al., 2017).

On this perspective, the value creation arises by two guidelines: In a strategic level, by offering product and service with characteristics valued by the customer; and in an operation level focused on waste reduction, by focusing on lead time, cost and quality (Hines et al., 2004).

The identification and promotion of value creation are sustained by the principles of the Lean thinking that support all applications through an organization. It is based on five key features: specify value for each product; identify the value stream; make the value flow without interruptions; let the customer pull value from the producer; and pursue perfection (Womack & Jones, 1996).

Ohno (1988) identifies 7 cardinal wastes to be eliminated: transport or conveyance; motion or movement; waiting or delay; overproduction; defect; inventory; and overprocessing.

In addition to pursue the waste elimination, the basic approach of Lean is a continuous improvement process by integrating the pillars: Just-in-time; Built in quality (Jidoka); Motivated people (People & Teamwork); Standardized work; Stability; Heijunka; Visual management; 5S and Kaizen.

Based on those principles and pillars, academics and practitioners present different bundles to LM. However, none diverge significantly from each other.(Doolen & Hacker, 2005; Fullerton & Wempe, 2009; Shah & Ward, 2007; Yang et al., 2011). The bundles are defined to associate the lean practices and impacted areas over the companies (Shah & Ward, 2003).

Shah and Ward (2003) combined 22 individual practices into four lean bundles and assume that the practices associated to production flow were joined on JIT bundle, the TQM bundle grouped practices linked to continuous improvement and products and process quality and the activities related to work-force management, as engagement, problem solving, autonomy, flexibility, team organization and development are themes related to HRM bundle.

Doolen and Hacker (2005) developed a map with 29 practices and six bundles: Manufacturing Equipment and Processes, Shop-Floor Management, New Product Development, Supplier Relationships, Customer Relationships and Workforce Management.

2.1.3 Tools, Techniques and Applications

The literature is plenty of lean tools and techniques and frequently new ones emerge or are updated, some of them are listed on **Error! Reference source not found.**. Many researchers affirm that LM achieve better results when a diverse set of manufacturing tools are applied, even if they have concurrent emphasis. (Shah & Ward, 2003) However, Pavnaskar, Gershenson, and Jambekar (2003) emphasize the importance to apply the appropriate tools to get better results and therefore propose a classification scheme to serve as a link between manufacturing waste problems and lean manufacturing tools.

There are available on the literature different methodology that helps practitioners to better identify the waste and the practice or tool to be applied. Pavnaskar et al. (2003) presented a classification scheme that focused on internal opportunities and it was organized based on three concepts: manufacturing problems, types of manufacturing wastes and the Lean manufacturing tools. Taylor and Brunt (2001) *apud* Pavnaskar et al. (2003) with a supply chain approach correlating seven value stream mapping tools with the seven cardinal wastes.

2.2 Industry 4.0

2.2.1 Introduction

The term "Industrie 4.0" was announced in 2011 when the Industry-Science Research Alliance launched an strategic initiative plan oriented to German manufacturing industry wich outlined an overall combination of information and communication technology (ICT) and industrial environment (Günther Schuh et al., 2017). The fundamentals of this initiative have been published in 2013 on the final report of the I4.0 working group (Kagermann H. et al., 2013).

The recommendation for implementation to the German Government was decisive to the rapid communication of Industry 4.0 concepts (Lasi et al., 2014). After 2013, there was an impressive growth in the number of publications and conferences related to the theme, passing from five papers and five conferences to 121 and 63 in 2015, respectively (Liao et al., 2017).

Focusing on increasing level of automation, mass customization and business processes network (Bley, Leyh, & Schäffer, 2016), Industry 4.0 invokes the contemporary technological advances that integrate physical objects, their virtual model and services, and coordination (Drath & Horch, 2014), over organizational boundaries to create a smart, inter-connected and agile value chain (Schumacher et al., 2016).

Industry 4.0 designates itself as an industrial revolution presumptive (Drath & Horch, 2014). While third industrial revolution was based on electronics and information technologies for accomplish the automation of single equipment and processes, Industry 4.0 aims to integrate all the physical agents on the value chain creating an end-to-end digital ecosystem (Geissbauer et al., 2016).

Despite some authors mention that is still early to ensure that Industry 4.0 is a revolution, Kagermann H. et al. (2013) affirms that based on a technological viewpoint, the industry sector is going through a new revolution phase. Drath and Horch (2014) argue that the title of revolution, concerning Industry 4.0, is more about the ability to cope with challenges, by creating the new horizon of business models, services, and individualized demands than a technical feature.

Lasi et al. (2014) describes the term "Industry 4.0" as a future project that is emerging by two advancement's forces: a technology-push in industrial practice and a remarkable need for changes due to changing operative framework conditions. Meanwhile, Drath and Horch (2014) consider that Industry 4.0 is already being done and the innovation lies in how to arrange existing technologies in a new way.

In fact, the theme has assumed a relevant matter in the manufacturing environment. Many companies has it at the core of strategic and research development (Geissbauer et al., 2016) and in some industrialized countries, the value creation is already structured towards the "so-called Industry 4.0" (Stock & Seliger, 2016).

Recently, governments and industries worldwide launched strategic programs to develop manufacturing capabilities in order to support the counties growth and take advantage of the new industrial revolution wave (Liao et al., 2017), details on Appendix G.

The new revolution, also named by digitization, has approaches over the world identified by various names (Sanders et al., 2016). This mixture of terms and initiatives that have been emerged in the world have caused a misunderstanding of Industry 4.0, that was potentialized by an overambitious marketing. (Drath & Horch, 2014).

Industry 4.0 is often confused with simple application of Internet of Things (IoT) or Cyber Physical System (CPS) and also with the movement into IoT called "Industrial IoT" that has similar technological approach of Industry 4.0 and is sponsored by the Industrial Internet Consortium (ICC)[1]. (Günther Schuh et al., 2017)

In general, companies in Japan and Germany are the most engaged with the digitization of their processes in the value chain (Geissbauer et al., 2016). Regarding the academic production, the institutions from Germany, China, Spain, Austria and USA are most involved in publications (Liao et al., 2017).

The expectations of the level of Industry 4.0 implementation are similar in the entire world (EMEA, the Americas and Asia Pacific). The intention is so expressive that if even half of it is met, the new configuration will essentially change the competitive landscape and change the settled industries. (Geissbauer et al., 2016)

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[1] http://www.iiconsortium.org/iic-i40-joint-work.htm

2.2.2 Concepts

Günther Schuh et al. (2017) define Industry 4.0 as "real-time, high data volume, multilateral communication and interconnectedness between cyber-physical systems and people" (p. 10).

Hermann et al. (2016) announced four design principles about Industry 4.0: Interconnection; Information transparency by data provision, integration and analytics; Autonomy through decentralized decisions; and virtual & physical support. Others reinforce the real-time capability, service orientation, and flexible adaptation/modularity.

These principles are supported by two essential basis of the Industry 4.0: the Cyber Physical System (CPS) (Kagermann H. et al., 2013), and the connectivity, widely understood through the internet. (Günther Schuh et al., 2017)

The CPS is composed by a computational level, network and physical objects with embedded system that monitor, coordinate, control and integrate systems by a computing and communication core (Rajkumar, Lee, Sha, & Stankovic, 2010). Lee, Bagheri, and Kao (2015) present an architecture divided into five levels, 'Connection Level', 'Conversion Level', 'Cyber Level', 'Cognition Level', and 'Configuration Level'. Illustration on Figure 2-1.

Wagner, Herrmann, and Thiede (2017) emphasize the data acquisition and data processing; the machine to machine communication (M2M); and the human-machine interaction (HMI) and Drath and Horch (2014) emphasize three components: the physical objects; its data models; and services based on the available data.

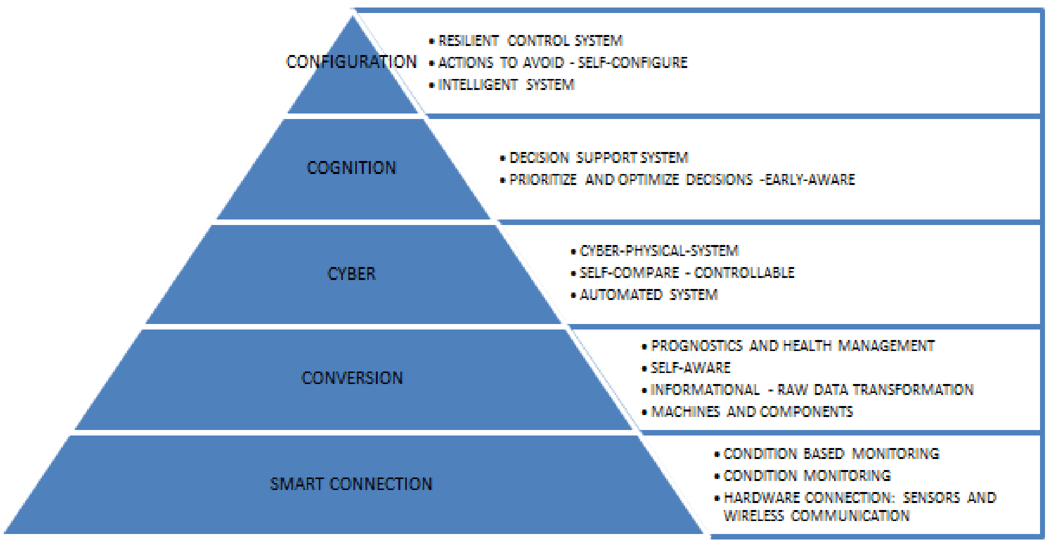

Figure 2-1: Industry 4.0 - CPS architecture (5C). Adapted from (Lee et al., 2015; Qin, Liu, & Grosvenor, 2016)

Within this context, the concepts of communication are vital (Leyh, Martin, & Schäffer, 2017). Components, equipment, factories and products furnished with automation instruments will progressively be connected through the Internet network or a private network (Drath & Horch, 2014) wich permit CPS to work autonomously (Kolberg & Zühlke, 2015).

Related to connectivity, The "Industrie 4.0 Working Group" mentions that the Internet of Things and Services (IoT and IoS) have the capacity to allow the design of smart environments (Kagermann H. et al., 2013) and It is widely recognized and settled as a interlinked communication network (Leyh et al., 2017).

In addition to the CPS and IoT approaches and Industry 4.0 principles, Kagermann H. et al. (2013) presents the digital integration concept, broken down into three pillars of industry 4.0: "Horizontal Integration through value networks"; "Vertical Integration and networked manufacturing systems"; and "End-to-End Digital Integration of engineering across the entire value chain".

Almada-Lobo (2016) pointed out the importance of cloud computing and advanced analytics into Industry. Indeed, "Identifying and gathering the right data, deploying it for the right purposes and effectively analyzing it will be critical to make the right Industry 4.0 decisions." (Geissbauer et al., 2016)

Stock and Seliger (2016) present a Macro and a Micro perspective that cover the integration features of Industry 4.0., Figure 2-2. The Macro view put cross-linked product life cycles as central element of the value creation networks. The micro emphasizes the vertical integration within smart factories.

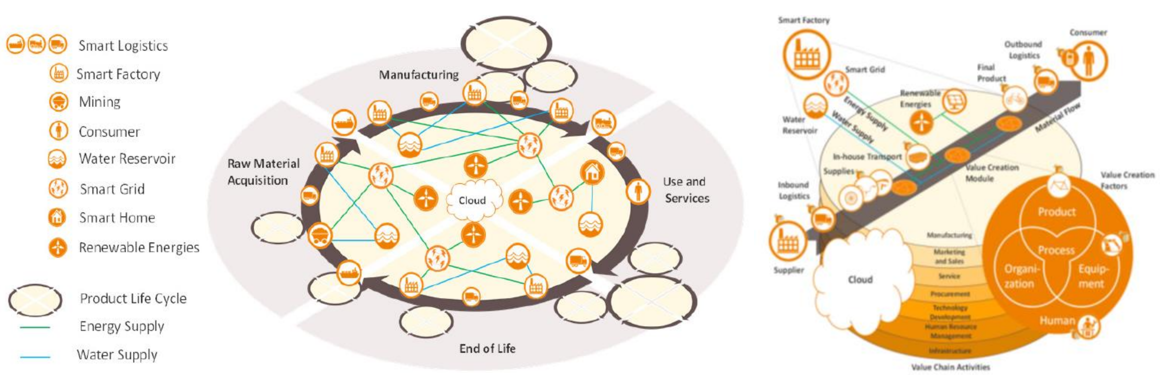

Figure 2-2: Macro and a Micro perspective that cover the integration features of Industry 4.0. Adapted from (Stock & Seliger, 2016)

All the elements of the value chain, whether internal or external are interconnected in a network and sharing information during the entire life cycle, covering suppliers and other stakeholders. The vertical integration goes along different aggregations' levels from product, equipment, production line, factory and includes different areas of organization as marketing, procurement, planning, engineering, human resource, etc.

In this environment, the manufacturing system is self-controlled, supported by an innovative platform that assists intelligent products, data and services (Lasi et al., 2014), and will generate an integrated optimized system by managing a multi-agent system (Almada-Lobo, 2016).

This value creation configuration, the "smart, networked world", involves the smart product that is processed by a smart machine according an optimized plan made in real-time by a smart planner. These operations are referred to a smart factory that is supplied by smart grids in the field of energy and have the material flow accomplished by the smart logistics (Kolberg & Zühlke, 2015; Stock & Seliger, 2016).

Companies that would implement Industry 4.0 applications have to accomplish some basic requirements, as: the Investment protection, stability, data privacy and cybersecurity (Drath & Horch, 2014).

The final report of the Industry 4.0 working group points eight priority areas for action in order to successfully implement Industry 4.0: "Standardization and Reference Architecture"; "Managing Complex Systems"; "Delivering a Comprehensive Broadband Infrastructure"; "Safety and Security"; "Work Organization and Design"; "Training and Continuing Professional Development"; "Regulatory Framework"; and "Resource Productivity and Efficiency" (Kagermann H. et al., 2013).

While I4.0 is part of the strategic plan and investigations, organizations face challenges to understand their current situation concerning Industry 4.0 (S. Erol et al., 2016) to identify how the I4.0 technologies can support their process (Ganzarain & Errasti, 2016) and miss implementation details and possible benefits (Liao et al., 2017)

2.2.3 Technologies and Applications

Advancements on technological features have been the main conductor of Industrial revolutions and the source of productivity enhancement. In the digitization era, the adoption of nine basics technologies has support the Industry 4.0 implementation: "additive manufacturing", "advanced robotics", "augmented reality", "big data and analytics", "cloud computing", "cyber security", "horizontal and vertical system integration", "the industrial internet", and "simulation". (Rubmann M. et al., 2015)

The applications of these technologies implies both in management practices and technical questions (Sanders & Wulfsberg, 2015). Some opportunities are proposed by Geissbauer et al. (2016) and explore the integration features, examples on Figure 2-3.

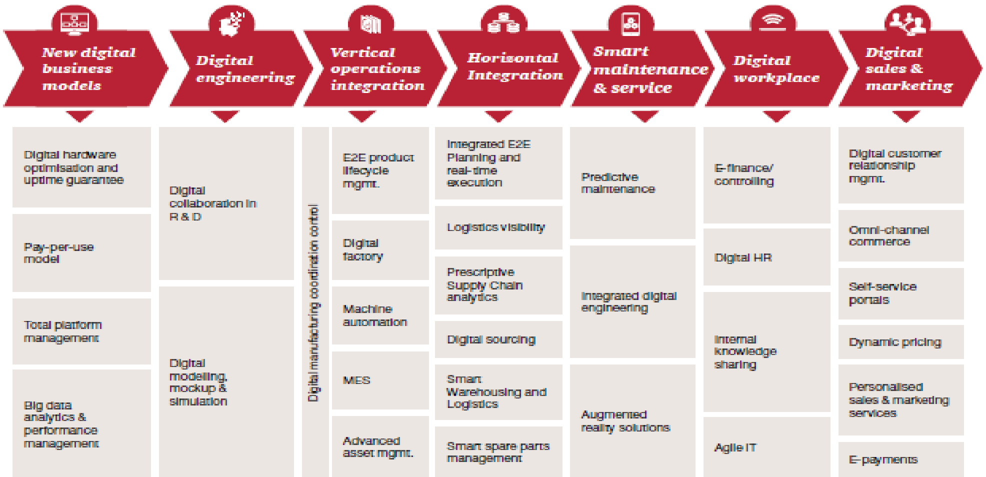

Figure 2-3: Industry 4.0 - Opportunities along vertical and horizontal operations. (Geissbauer et al., 2016)

Industry 4.0 has high potential concerning value creation and expect three sources of benefits by implement it: a reduction on operational costs, an increase of efficiency and additional revenues (Geissbauer et al., 2016; Schumacher et al., 2016).

Günther Schuh et al. (2017) affirm that "the chief economic potential of Industrie 4.0 lies in its ability to accelerate corporate decision-making and adaptation processes" and presents how the technologies can support this agility model, Figure 2-4.

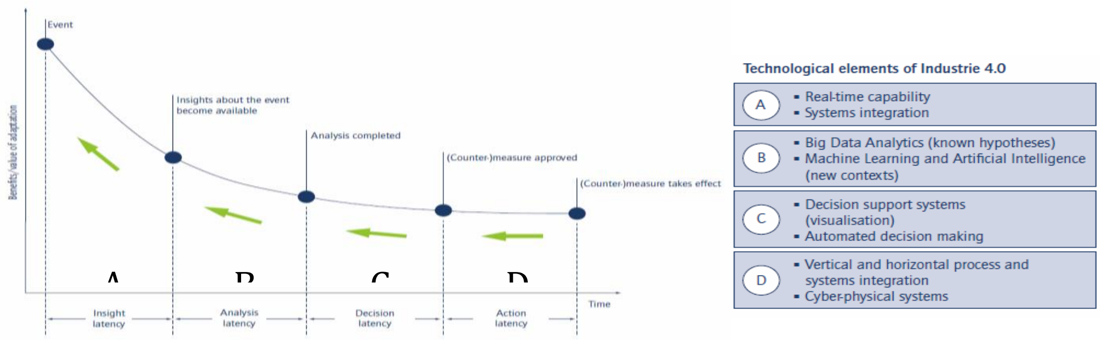

Figure 2-4: Corporate adaptation processes and Technological Elements. Adapted from (Günther Schuh et al., 2017)

2.3 Assessment Models

The focus of this section is to identify the LM and I4.0 assessment models available in the literature, checking the decisive factors and measures concerning LM, I4.0 and organizational performance and their correlation.

2.3.1 Lean Manufacturing Assessment

Despite the LM has been widely implemented over the world, its assessment are not clearly defined and it is in a continuing development. (Camacho-Minano et al., 2013) In fact, different methods to evaluate the level of lean influence in a company are available in the literature. Danese et al. (2017) point out basically two directions of analysis: the degree of lean implementation and the analysis of lean outcomes.

Authors have been adding contextual variables to the existing models (Camacho-Minano et al., 2013), considering that several factors interfere both in the level of implementation (Shah & Ward, 2003) and in the level of outcomes (Qi, Zhao, & Sheu, 2011).

The contextual factors varies from company size (Doolen & Hacker, 2005), cultural aspects (Chavez et al., 2015; Kull, Yan, Liu, & Wacker, 2014), environmental complexity and dynamism (Azadegan, Patel, Zangoueinezhad, & Linderman, 2013), demand behavior (Bortolotti, Danese, & Romano, 2013), management practices (Bortolotti, Boscari, & Danese, 2015) or industrial market (Cooney, 2002).

2.3.1.1 Lean Manufacturing Implementation

On the pack of qualitative assessment, the objective is to evaluate the level of lean adoption of a company. It can be measured for a specific tool or a specific bundle (represented by a set of tools) or can be focused to analyze the overall Lean implementation (lean as a system). (Bonavia & Marin, 2006; Camacho-Minano et al., 2013; Danese et al., 2017).

In general, the methodologies that assess the level of a LM implementation combine both tactical and strategic factors (Doolen & Hacker, 2005) and is usually applied through a checklist (Camacho-Minano et al., 2013).

The literature review of lean implementation assessment emphasizes four works and their literature base is summarized on Table 2.

Authors	Description
Sanchez and Pérez (2001)	Assessment model according to the most common lean production principles. Based on six groups: Elimination of zero value activities, Continuous improvement, Multifunctional teams, JIT production and delivery, Integration of suppliers and information exchange.
Shah and Ward (2003)	"This research study was based on an annual survey of manufacturing managers in 1999 by publishers of Industry Week. The survey included questions on the level of implementation of 22 different lean practices, including practices related to JIT, TPM, TQM, and HRM"
Doolen and Hacker (2005)	An overall structure integrating the multiple dimensions of a lean enterprise. Six impact areas: manufacturing equipment and processes, shop floor management, new product development, supplier management, customer relations, and workforce management. 29 practices and activities of LM that support the impact areas. Six additional survey items were included at the end of the survey to provide demographic information on both the company and the respondent.
Shah and Ward (2007)	The assessment model is based on 10 dimensions: "Supplier feedback", "Just in Time delivery", "Supplier Development", "Customer involvement", "Pull production", Continuous flow", "Setup time reduction", "Statistical process control", "Employees involvement", "Employees involvement". It considers 48 questions.
Singh, Garg and Sharma (2010)	Developed a leanness index based on a study of an Indian auto component industry. It is calculated by scores of five parameter: Supplier Issues, investment priorities, Lean practices, Various wastes and Customer issues. Fuzzy methodology.

Table 2: Literature Review - Lean implementation assessment.

On their work, Doolen and Hacker (2005) reviewed seven assessment instruments and five research surveys and developed a model to assess both the quantity and the level of implementation of lean practices in an organization. Their model evaluates 29 practices linked to six impact areas: manufacturing equipment and processes, shop floor management, new product development, supplier management, customer relations, and workforce management.

Singh, Garg, and Sharma (2010) treat Lean as a multi-dimensional approach that involves a collection of management practices. Their study was based on a review of 11 measurement models and seeks to create a model to calculate a unique index that aggregate different dimensions of LM, the leanness, by the score of five parameters: supplier issues, investment priorities, LM practices, various wastes and customer issues.

Doolen and Hacker (2005) cited factors that could interfere in the applicability of LM practices, such as: "economic conditions", "demand uncertainty", "high-mix", "low-volume", "rigid organizational structures" and aspect of "human resources management". And they also concluded that the average use and degree of use of LM practices is positively correlated with organizations size. (Doolen & Hacker, 2005; Sânchez & Pérez, 2001)

2.3.1.2 Lean Manufacturing Outcomes

Regarding the assessment of Lean outcomes, two points should be analyzed: organizational performance and social outcomes (Danese et al., 2017). The effects of LM on companies can be evaluated across financial (Yang et al., 2011), operational (Bonavia & Marin, 2006; Chavez et al., 2015; Shah & Ward, 2007), and marketing (Yang et al., 2011) areas. The social outcomes are related to work environment and employees topics and will not be part of this study.

Camacho-Minano et al. (2013) raised information of diverse Lean assessment studies application and observed the measures used on the models they presented, ranging from context, operational and financial and then analyzed if practices of five bundles were correlated with them. The Table 3 shows the quantity of papers analyzed.

		TQM		JIT		ABM		HPWS		TPM	
Number of papers		57	47.9%	33	27.7%	10	8.4%	5	4.2%	1	0.8%
Type of indicators	Only financial	11	19.3%	6	18.1%	2	20.0%	0	0.0%	0	0.0%
	Financial & operational	46	80.7%	27	81.9%	8	80.0%	5	100%	1	100%
Contextual factors	Yes	22	38.6%	16	48.5%	8	80.0%	5	100%	1	100%
	No	35	61.4%	17	51.5%	2	20.0%	0	0.0%	0	0.0%

Table 3: Papers according to mode of assessment of lean practices. Adapted from (Camacho-Minano et al., 2013)

Concerning TQM bundle, Relation to financial performance – Positive 33 of the 57 papers (57.9%) demonstrated a positive correlation with financial performance and seven papers were not significant (12.3%). 69.8% of the papers related to JIT practices demonstrated positive correlation with financial performance and 15.1% were not significant. The ABM bundle presented a positive relation on 70% of papers and 10% were not significant. TPM has just one paper that is positive correlated with financial perform. The HPWS bundle was represented by 5 papers which 3 were positively correlated with financial perform.

Authors	Description
Yang et a. (2011)	309 samples of the diverse manufacturing firms; Analyze relationship of LM, environmental management practices and organization performance. Measurement items selected from the IMSS database;
Fullerton et al. (2009)	Data collected from 121 US manufacturing executives ; This study contributes to our understanding of the relationships among lean manufacturing practices, utilization of NFMP measures, and firm profitability.
Fullerton et al. (2014)	Survey data from 244 U.S. manufacturing firms. The purpose of this study is to shed insights on lean management accounting practices (MAP), financial control essential for internal decision making on lean organizations.

Table 4: Literature Review - Lean outcomes assessments

Yang et al. (2011) concluded on their study that LM practices are significantly correlated with market and financial performances. Moreover, they affirm that LM enhances other management practices approach (the environmental management). And also it indicates that the contextual factors, as firm size, locations and GDP per capita influence both the LM implementation level and market and financial performance.

Fullerton and Wempe (2009) confirmed that shop-floor employee involvement influence the success of lean implementation. Additionally, they showed that the operational measures have important effect on financial outcomes.

Fullerton, Kennedy, and Widener (2014), observed that the extent of LM is positively related to simplified and strategically aligned Management Accounting Practices and the use of visual boards. The use of visual performance measures is positively related to operations performance and then into financial performance. Table 5 lists the most used indexes

OPERACIONAL	MARKET	FINANCIAL
Inventory level	Market share	Return on sales (ROS)
Equipment downtime	Turnover	Return on assets (ROA)
On-time delivery		Net sales
Scrap; Rework; Product Quality		Overall firm profitability
Lot sizes; Lead Time		Costs of goods sold
Setup times Customer complaint		Total Assets
Labor productivity		Inventory - Raw Materials and WiP
Queue times and move times		Finished Goods
Cycle efficiency; Throughput time		Transportation Cost

Table 5: Lean Assessment - Outcomes - Index most used. (Bayou & de Korvin, 2008; Behrouzi & Wong, 2011; Camacho-Minano et al., 2013; Fullerton et al., 2014; Fullerton & Wempe, 2009; Yang et al., 2011)

2.3.2 Industry 4.0 Assessment

Similar to Lean Manufacturing approach, Industry 4.0 has different dimensions that can be measured to evaluate its level of implementation. Lichtblau et. al (2015) proposed a I4.0 readiness check based on six dimensions. Schumacher et al. (2016) suggested a nine dimensions model for assessing Industry 4.0 maturity. Ganzarain and Errasti (2016) presented a maturity model as a process of change based on three stages: envision, enable and enact. Tortorella and Fettermann (2017) focused on practices and technologies and evaluated the degree of uses of 10 technologies to assess the level of Industry 4.0 implementation. The most known maturity index is proposed by Acatech study "Industry 4.0 Maturity Index – Managing the digital transformation of companies" (Günther Schuh et al., 2017). Further information on Table 6.

Model	Authors	Description
I	Ganzarain and Errasti (2016)	Applied on a representative sample of SMEs in the Basque Country. Three stage maturity model in SME's towards industry 4.0: envision, enable and enact. Industry 4.0 challenges and the diversification dynamic. Four strategic perspectives: market, product, process, and value network.
II	Schumacher et al. (2016)	The framework was based on Becker's step-by-step process for the development of maturity models and considered 72 works on maturity models for further analyses A total of 62 items distributed into nine organizational dimensions.
III	Günther Schuh et al. (2017) Acatech Study	It is based on the "Production and Management Framework" and aims to guide the organization through a transformation into a learning, agile company. It assesses the organization from a structure, processes and development perspectives. The path covers six evolutive stages related to four key areas of five corporate processes.
IV	Tortorella and Fettermann (2017)	A questionnaire that aims to measure the degree of adoption of the Industry 4.0 technologies, For that, 10 questions were formulated according to different technologies grouped into 3 different application areas: Process, Development/ reduction in time to market and Product/ new business models as suggested by Brazilian National Confederation of Industry (2016).
V	Lichtblau et. al (2015) IMPULS (2015) Industry 4.0 Readiness	The model comprise six dimensions: "Smart Strategy and organization"; "Smart Factory"; "Smart Operations"; "Smart Products"; "Data-Driven services"; and "Employees". It assess the I4.0 Readiness level of a company through 24 questions and characterize the company with three general questions (sector, # employess, and annual revenue). It classify companies on six levels: "Outsider", "Beginner", "Intermediate", "Experienced", "Expert" and "Top performer".
VI	PwC (2016) Industry 4.0 – Self Assessment	The PwC self assessment model is composed of five dimensions: "Business Model, Product & Services Portfolios"; "Market & Customers"; "Value Chain & Processes"; "IT Architeture"; and "Compliance, Legal, Risk, Security and Tax". The questionnaire present a section for respondent characterization (Industry sector, Region, Country and Annual Revenue) and 33 specific questions for I4.0 mautirity evaluation that is translated in four levels: "Digital Novice"; "Vertical Integrator"; "Horizontal Collaborator" and "Digital Champion".
VII	Akdil et al. (2018)	The proposed maturity model has three dimensions: Smart Products and Services; Smart Business Process; Strategy and Organization. It consist of 68 questions that measure the maturity level in 4 stages: "Absence"; "Existence"; "Survival" and "Maturity".

Table 6: Literature Review - Industry 4.0 implementation assessment.

The model I is based on the strategic framework of (Selim Erol, Schumacher, & Sihn, 2016) and aims to deal with Industry 4.0 challenges and the diversification dynamics. There are four strategic perspectives: market, product, process, and value network and five maturity scale (Ganzarain & Errasti, 2016).

Ganzarain and Errasti (2016) applied the model on a representative sample of SMEs in the Basque Country and concluded that, regarding the diversification, the majority companies do not have Industry 4.0 insert on their culture, and pointed out an essential demand of support to develop an individual vision and project planning for Industry 4.0 implementation.

Schumacher et al. (2016) developed a maturity model based on others existing models and tools. The authors examined 72 works on maturity models, highlighting IMPULS – Industrie 4.0 Readiness (2015), Empowered and Implementation Strategy for Industry 4.0 (2016), Industry 4.0 / Digital Operations Self-Assessment (2016), The Connected Enterprise Maturity Model (2014) and Reifegradmodell (2015).

The model II goes beyond the technological focus and includes different organizational features. It has a total of 62 items distributed into nine organizational dimensions: "Products", "Customers", "Operations" and "Technology", "Strategy", "Leadership", Governance, "Culture" and "People". It demonstrate that organizations can take strategic insights by executing a self-assessment (Schumacher et al., 2016).

The model III, the maturity index, evaluates four structural areas of a company based on six steps of transformation. The four structural areas are: resources, information systems, culture and organizational structure. The six levels of implementations is divided into two groups, the first two represent the basic requirement of Industry 4.0 implementation (computerization and connectivity) and the others four stages are "Visibility" (related to data collection), Transparency (linked data availability and analysis), "Predictive capacity" (concerned to future scenarios simulations), and "Adaptability" (related to autonomous degree). This evaluation is made on five individual functional areas: of development, production, logistics, services and marketing & sales (Günther Schuh et al., 2017).

The study of Tortorella and Fettermann (2017) was conducted through a survey within 110 valid responses from Brazilian manufacturing organizations. The survey was divided into four groups: Q1 identifies contextual variables; Q2 assesses the Lean Manufacturing implementation based on Shah and Ward (2007) that focus on 41 practices; Q3 measures the adoption level of 10 Industry 4.0 technologies as indicated by Brazilian National Confederation of Industry (2016); and Q4 used to identify the operational performance improvement in last three years.

The model V is proposed by Lichtblau et. al (2015) and is available for self check in an online version[2]. The tool measures the I4.0 Readiness degree of a company assessing topics as Strategy, Innovation, IT System, ICT and factory Infrastructure, data usage, employee skills, data driven fields and other.

The model VI is available on an online survey[3] that allows companies to conduct a self-assessment of their I4.0 maturity level. The questions are based on a likert scale with specific definition of the highest and minimum score for each question.

Besides the aspects of strategy, organization and production system, the model VII covers different processes of the business considering marketing, sales, finance, procurement, logistics, and other. On its publication, it presents a case on the retail sector.

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[2] https://www.industrie40-readiness.de/?lang=en
[3] https://i4-0-self-assessment.pwc.nl/i40/landing/

3 Conceptual framework and hypothesis: Lean Manufacturing and Industry 4.0 integration

A few studies have been carried out until today relating to Lean Manufacturing and Industry 4.0. Almost all of them try to figure out the inter-link of both themes.

The compatibility of LM and I4.0 integration has been faced a skepticism through two main dilemmas. The first dilemma concerns to the fitness of LM to work on context of highly volatile customer demand and non-repetitive environment (Buer, Strandhagen, & Chan, 2018; Sanders, K. Subramanian, Redlich, & Wulfsberg, 2017). The second dilemma discusses that while LM focus on simplicity and production in series, I4.0 increases complexity and is indicated to conditions of customized products with short life cycles. (Mora, Gaiardelli, Resta, & Powell, 2017; Satoglu, Ustundag, Cevikcan, & Durmusoglu, 2018)

Despite these questioning, it is believed that there is a positive relationship between them. Indeed, Dombrowski, Richter, and Krenkel (2017) realized that the LM principles and tools have been used in 260 I4.0 use cases analyzed at the "Plattform Industrie 4.0" [4].

The literature addresses the relations of LM and I4.0 from different perspectives. These panoramas helped to organize this section in four topics: 1) LM as the basis for I4.0; 2) I4.0 enable of LM; 3) I4.0 as a complement of LM and the integrated approach as an evolution of LM. 4) I4.0 and LM integrated approach enhances manufacturers' performance.

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[4] Plattform Industrie 4.0 is a platform used by companies, their employees, trade unions, associations, science and politics from Germany, who wants to contribute with the competitiveness increase through I4.0 solution. It aims to identify all relevant trends and developments in the manufacturing sector and to combine them to produce a common overall understanding of Industrie 4.0. https://www.plattform-i40.de

3.1 Lean Manufacturing as the Basis for Industry 4.0

Comparing the characteristics of LM and I4.0, it is possible to realize the resemblance of them. The five principles of LM cited by Womack et al. (1990) added with the "People" principle suggested by Hines et al. (2004) seem to be close related with the core competences of I4.0 cited by Bitkom e.V. (2016) see Table 7.

Lean Principles Womack and Jones (1990) *added by Hines et al. (1994)	**Industry 4.0 Core Competences** Bitkom (2017)
Value Proposition	
Value Stream	Horizontal Integration
Flow	End-to-End
Pull	Vertical Integration
Perfection	Continual development of cross-sectional technologies
People*	New social infrastructure for work
	Architectures
	Security of Network System
	Legal Framework

Table 7: LM principles and I4.0 core competences.

Regarding the "value creation" principle, Hines et al. (2004) emphasises the focus of LM on reducing internal wastes and on enhancing customer perceived value of products or service. These characteristics are not defined as a pillar in the I4.0 principles, however it is evident that I4.0 also seeks for value creation through operational efficiency, cost reduction and quality assurance (Geissbauer et al., 2016), and also exploring opportunities on creating new business models (Müller, Kiel, & Voigt, 2018).

Through this first principle the LM aims to guarantee a match between customers' need and the offer of products and services. It intends to satisfy customers' need and avoid unnecessary complexity and features that does not create value. Divers techniques can be applied at this moment as QFD, Voice of the customer, Kano modeling, Value Curves (Customers, Proposition and Business Model), Value Stream, etc.

Both approaches, I4.0 and LM, present similarities and chase continuous improvement of processes and products in order to satisfy customers with reduced non-value added charges.

One point of attention in the implementation of I4.0 is the BUZZ effect and the lack of proven results. Many of the decisions to implement I4.0 solutions happen top down and often the use cases are implemented because of the obligation and loss the focus of the value creation objective.

In this way the LM philosophy can be a basis for identifying problems and opportunities for improvement and then supporting the selection of technologies and systems that best answer the problem and thus ensuring value creation to the business.

Moreover, the LM journey have already learned with the transitions phases from the practices dissemination, best practice movements, benchmark emulation, value stream thinking and capability at system level. (Hines et al., 2004)

The first five core competences of I4.0 listed above – "Horizontal Integration", "End-to-End", "Vertical Integration", "Continual development of cross-sectional technologies", "Social Infrastructure for work" – are well matched with the last five principles of LM listed above – " Value Stream", "Flow", "Pull", "Perfection", "People". All of these principles were explained on section 2.1. Here it will be discussed the alignment of them.

The aspects of integration is not a novelty for Lean. Smeds (1994):

> *"Low costs and high quality are already taken for granted, and increasing attention is now being paid to the element of time. Faster product development and shorter lead times in procurement, production and distribution are the critical competitive factors of today. The integration of business operations within and even between industrial enterprises has much innovation potential in this respect. Through integration, business operations can be streamlined, which not only shortens lead times, but also gives radically new "lean" options for the enterprises' strategies and organizational structures […] In integration, a co-evolutionary process is going on between organizations and technology."*

Åhlström (1998) suggested that the vertical information system is a supporting principle of your Lean implementation framework:

> *"Vertical information systems contribute to Japanese manufacturing companies' success at involving employees in manufacturing improvement (Cole et al., 1993). A high amount of business information is distributed to employees, who receive training to understand the information. Japanese managers then empower employees to act on the information."*

According to Hines et al. (2004), the integration features initiated to be part of LM around the year 2000, by integrating processes and the value chain. Indeed Warnecke and Hüser (1995) discussed the necessity of Lean production to not only thinks to vertical linked organization but also through a horizontal integration with decentralization characteristics, see Figure 3-1.

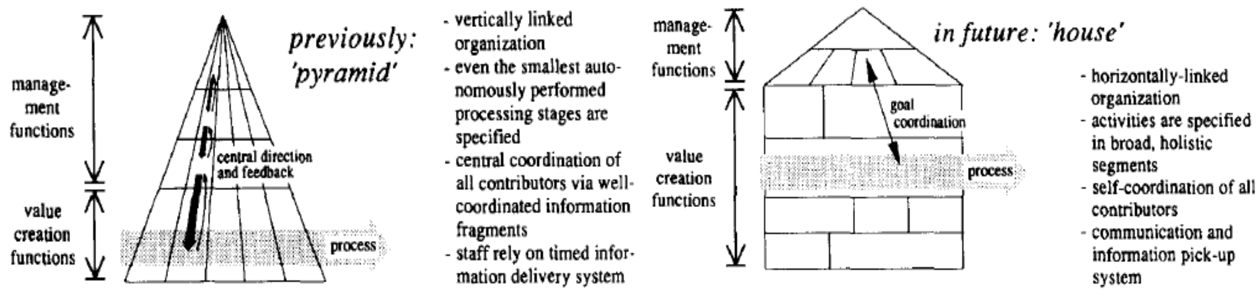

Figure 3-1: Adapted from Warnecke and Hüser (1995) - Interplay of organization, information and value creation.

The LM principles cover the integration of processes, flexible and self-regulated production units that includes manufacturing technologies and autonomous operators with multi skills (Smeds, 1994). It is argued that companies with integrated processes could have a greater facility to implement I4.0 because, in addition to already having part of the work done (mapping processes, identification of partners and relevant infos), it will present a culture in this sense.

The competence of "Continuous development of cross-sectional technologies" emphasizes the need to improve the basic infrastructure of I4.0, addressing aspects such as the systems & network (interoperability, bandwidth, scalability, etc.); microelectronic systems (sensors, actuators and embedded systems); security of information and operations; the standardization of syntax and semantics (object representation and information models); and the importance of data analysis (Bitkom e.V., 2016).

The approach presented here focus on how LM as a philosophy and as a set of techniques of continuous improvement can support organizations on I4.0 implementation and improve technological aspects.

The most obvious support from LM lies in the evolution of these new technologies that can be guaranteed by the principle of continuous improvement through incremental improvements. They are close related to the operational part, which can be through new uses of existing technologies or in the improvement of these technologies.

Indeed, manufacturers have already taken advantage on combining LM and advanced manufacturing technologies (AMTs), by making regular improvement directly on job routines and by developing solutions from local creativity and tests (Upton & McAfee, 2000).

However, the I4.0 implementation has been seen as a top down decision and responsible to achieve disruptive improvements. On this context, LM can support with its strategic part, in particular with its principle 1 - "Value creation" - in the identification and selection of technologies that add value to the business and in the idealization and development of new technologies.

> *"Much research on the implementation of advanced manufacturing technologies (AMTs) indicates that even though their introduction appears to be a strategic leap, principles of continuous improvement can be important in determining success" (Upton & McAfee, 2000).*

All of these features are fully aligned with I4.0 and will add value to the development of data analysis, knowledge generation, systems with feedforward and self-optimization, and others solutions in the context of I4.0.

The topic "social infrastructure for work" addresses concerns about the change on how employees will work together, taking into account the new ways of collaboration and the interaction with machines and intelligent systems and about the aspects of technology acceptance and working practices, focusing also on work structure, work force development and equipment/workplace design. (Bitkom e.V., 2016)

Since new information systems have been improved, Upton and McAfee (2000) suggested that managers will need to encourage the involvement of employees on the development process of new tools and to ensure that their organization has the necessary skills in order to take advantage from employees' knowledge and gain the commitment of them to success implement, maintain and modify new systems.

Smeds (1994) argues that manufacturing changes towards "Lean enterprise" required a radical techno-organizational change, which implied new structures, strategy and culture.

LM as BPC as a way of thinking could help the manufacturing transformation for I4.0 implementation. Satoglu et al. (2018) agrees with the potential benefit that companies experienced with Lean could take advantage of for the change through I4.0:

> *… erroneous and prejudiced habits and waste-accustomed behaviors of employees about working method is a critical problem to be addressed in the design of manufacturing systems. In this context,*

the strategy should be to change the process of thought of people after altering their behavior with the help of a business discipline which does not distress people. Therefore, Lean Management System including work standardization and visual control is suggested to achieve this strategy.

The other three core competence of I4.0 – "Architectures", "Security of Network System" and "Legal Framework" are topics most related with IT features and may be the factors that most distinguish LM from I4.0.

It relies to the creation of a reference model that should be able to implement the fundamental ideas of I4.0: vertical and horizontal integration and end-to-end solutions. It means the design of system and establishment of protocols and standards that take care about the aspect of the networking of production resources; of the technical, administrative and commercial data collected within the entire value stream; and about the extended and dynamic network created beyond individual factory locations. (Bitkom e.V., 2016)

Despite these last three core competences topics are more related to technical domain, LM can also contribute positively within it. Indeed, in the context of ERP implementation Powell, Alfnes, Strandhagen, and Dreyer (2013) argues that LM and ERP are complementary approaches. In special due to LM methodologies and techniques that requires accurate data and simplify data integrity and planning processes. Moreover, Wallace and Kremzar (2001) *apud* Powell et al. (2013) considers LM as an element of extreme value for the ERP.

It is important to analyze the other six design principles for I4.0 implementation: interoperability, virtuality, real-time capability, decentralization, service orientation and modularity. (Hermann et al., 2016)

It is important to remember that a force that drives LM pursue a self-organization behavior within a structure developed in direction of the simple co-ordination of the fundamental business processes in the value chain (Smeds, 1994). The LM supports production's control by using a set of self-regulated techniques. (Wang, Zhao, WAN ZG, & Jian, 2016).

Both approaches, LM and I4.0, consider managing large systems with a decentralized structures counting on small modules of less complexity (Kolberg & Zühlke, 2015)

LM also has the principle of "Autonomation", also called as pre-automation by Shigeo-Shingo, which is a kind of automation - that assist and depends of human intervention - that implements supervisory functions through machines in order to detect abnormal conditions/operations (Ohno, 1988, p. 58).

Regarding the interoperability is common to find many industrial projects that connect automation and information technology. And in this context again, the experience of implement JIT systems are rending easier for companies to adopt these technologies, due to the capabilities of sharing information timely and accurately (Buer et al., 2018), simplifying and organizing processes.

The value orientation summed up with robust and waste-free processes taken by companies experienced with LM makes the digitalization process easier (Buer et al., 2018; Sanders et al., 2016). Moreover, although poorly coordinated and inefficient processes can be automated or digitally supported, the process itself will remain inefficient and therefore Lean processes are an excellent basis for Industry 4.0 implementation[5] (Kaspar & Schneider, 2015).

The guidelines of "first organize, then invest" or "first process and then technology" is an example of how LM can contributes to I4.0 implementation, by ensuring that the I4.0 solutions support the process of value creation instead of generate wastes[6] (Kaspar & Schneider, 2015). Technology will not always contribute for performance improvements, and sometimes can only bring complexity to the system (Satoglu et al., 2018).

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[5] Zwar lassen sich auch schlecht aufeinander abgestimmte und ineffiziente Prozesse automatisieren oder digital unterstützen, der Prozess an sich wird aber ineffizient bleiben. Das vorhandene Produktivitätspotenzial wird nicht realisiert und die Kosten der Automatisierungslösung sind oft um ein Vielfaches höher. Die Gestaltung durchlaufzeitoptimierter, synchronisierter und robuster Prozesse stellt somit eine hervorragende Basis für Industrie 4.0 Maßnahmen dar. Denn der Einsatz von Technologien und IT soll nicht dem Selbstzweck dienen, sondern ein Hilfsmittel sein und muss sich immer an der erreichten Prozessverbesserung messen lassen (Kaspar & Schneider, 2015)

[6] Dadurch trägt Lean wesentlich dazu bei, Komplexität zu reduzieren. Dabei gilt die Leitlinie „erst organisieren, dann investieren“ beziehungsweise „erst Prozess dann Technik“. So wird sichergestellt, dass die Technologie den wertgenerierenden Prozess unterstützt anstatt Verschwendung zu erzeugen [8]. Dieser Grundsatz lässt sich auch auf das Zusammenwirken von Lean und Industrie 4.0 übertragen. Lean schafft durch Komplexitätsreduzierung, die Verringerung von Verschwendung sowie kontinuierliche Verbesserung unter Einbeziehung der Mitarbeiter die Grundlage. Darauf bauen die (informations-)technischen Lösungen einer Industrie 4.0 auf (Kaspar & Schneider, 2015).

Another LM principle that is worthwhile to consider is the "*doing what is needed, how it is needed, when it is needed",* mainly in the context of Big Data, *"provide the information that is needed, when it is needed, where it is needed, and in the right format*". (Cattaneo, Rossi, Negri, Powell, & Terzi, 2017)

The basic LM tools considered as essential for successful I4.0 implementation are value stream mapping standardization, Kanban and SMED. They are most related with ERP implementation, modularity and interoperability, Plug&Play solutions, batch sizes reduction and data management (Powell et al., 2013; Sanders et al., 2017; Satoglu et al., 2018; Staufen, 2016).

Because of all the findings analyzed above it is coherent to agree with one of the approaches for the relationship between LM and I4.0 that argues LM as the base for I4.0. Indeed, Croatian manufacturing industries considers that besides the importance of LM on increasing competitiveness, LM is a prerequisite to the progress on I4.0 solutions (Veza, Mladineo, & Gjeldum, 2016). The same scenario is found in China, where manufacturing companies consider LM as the basis for smart manufacturing (Wang et al., 2016).

In Germany, Staufen (2016) conducted a survey with 179 industrial companies and found that 73% of respondents have relevant level of LM implementation, and 27% have already gained experience in Industry 4.0 projects, suggesting that advanced lean experience paves the way for entry into Industry 4.0.[7]

On that context, lean thinking seems to be a logical enabler of I4.0 (Cattaneo et al., 2017). Due to the mastery of process cleanness, transparence and standardization, LM appears as good option to reduce complexity and decrease the risk of I4.0 implementation. (Kolberg & Zühlke, 2015). With LM, the infrastructure for digital management is easier built. (Wang et al., 2016). LM is far to disappear, it is become more relevant on I4.0 initiatives (Sanders et al., 2017).

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[7] Schlanke Prozesse bilden das Fundament für Industrie 4.0. Knapp jedes fünfte Unternehmen (18 Prozent) hat bisher ausschließlich einen kontinuierlichen Verbesserungsprozess eingeführt, 41 Prozent haben darüber hinaus auch ihre gesamte Wertschöpfung bereits nach den Lean-Prinzipien ausgerichtet und weitere 15 Prozent haben diese auch schon auf die indirekten Bereiche ausgedehnt. Den nächsten Schritt – die komplette Ausrichtung von Strategie und Organisation an der Lean-Philosophie – haben bisher erst 17 Prozent der Befragten vollzogen. Von den Unternehmen, die bereits Erfahrungen mit Industrie-4.0-Projekten gesammelt haben, tun dies jedoch schon 27 Prozent. Dies lässt den Schluss zu, dass fortgeschrittene Lean-Erfahrungen den Einstieg in Industrie 4.0 deutlich ebnen (Staufen, 2016).

3.2 Industry 4.0 as Enabler of Lean Manufacturing

On the other perspective, it is expected that the adoption of I4.0 solutions helps companies to overcome difficulties of LM management and to achieve high level of LM maturity with less effort. (Sanders et al., 2016)

The I4.0 with its new ways of ICT uses are attuned with LM principles and its applications are helping to stabilize LM processes and to support LM practices (Wagner et al., 2017).

Buer et al. (2018) present some Lean practices that have been benefited with I4.0 solutions: "Andon", "Heijunka", "Just-in-time deliveries", "Kanban", "Man-machine separation", "One piece flow", Poka Yoke", "SMED", "Standardised work", "Statistical process control", " Takted production", "Total Productive maintenance", "Values Stream Mapping", "Waste reduction", "5S", "Kaizen"and "People and Teamwork".

Sanders et al. (2017) calculated two measures that evaluate how a LM tool is benefited from I4.0 principles and that evaluate how supportive is the I4.0 principles to the LM tools. See Table 8.

		Industry 4.0 Design Principles					
	Beneficiary Coefficient	Real- Time Capability	Decentrali-zation	Modularity	Interoperability	Service Orientation (SOA and IoS)	Virtualization
Supporting Coefficient		6.6	6.1	3.1	6.2	4.7	6.1
Lean Management Tools							
Kaizen (PDCA)	5.3	10	5	0	10	0	7
TPM	9.5	10	10	7	10	10	10
Standardization	2.8	5	0	0	7	0	5
Forms of wastes	7.3	10	10	7	5	5	7
5S	2.5	5	7	0	3	0	0
TQM	4.7	7	7	0	7	0	7
Kanban (JIT/Pull)	7.0	10	10	5	10	0	7
Takt Time	-8.0	-7	-10	-10	-7	-7	-7
Value Stream Mapping	4.7	10	5	0	3	0	10
Heijunka (Smooting)	7.7	10	7	5	7	10	7
Autonomation	7.0	5	10	3	10	7	7
Andon	4.0	5	7	0	5	0	7
Poka Yoke	4.7	3	8	3	7	0	7
SMED	6.0	10	3	5	10	3	5

Legend										
	Value	10	7	5	3	0	-3	-5	-7	-10
	Degree of influence	Full support	High support	Moderate support	Limited support	No impact/ neutral	Limited hinderance	Moderate hinderance	High hinderance	Full hinderance
	Range	9.1 to 10.0	6.1 to 9.0	3.1 to 6.0	0.1 to 3.0	0	0.1 to 3.0	-3.1 to -6.0	-6.1 to -9.0	-9.1 to -10.0

Basic lean tool for Industry 4.0

Table 8: Interdependence Matrix - LM Tools and I4.0 principles. (Sanders et al., 2017)

One measure is the "Beneficiary coefficient" which assesses the degree of benefit that each LM tool is benefitted from all the I4.0 design principles. The second measure reflects the other side, accounting the level of influence of each design principle of I4.0 on LM tools.

The value of each cell that intercept one design principle of I4.0 and one LM tool reflects the level of interaction of each other. The cells in blue represent basic lean for I4.0. The green color represents high degree of influence and the red one full hindrance.

On Sanders evaluation, all design principles are capable to influence LM tools, with "Real-Time Capability" and "Interoperability" that most impact. On LM tools perspective, "TPM", "Heijunka (Smoothing)", "Forms of waste", "Kanban" and "Autonomation" are the most influenced by I4.0 design principles.

Almost all of LM tools on showed above scored with a medium-up beneficiary coefficient, only "5S" demonstrated low degree of interaction and "Takt-Time" presented a negative relationship.

Sanders et al. (2016) presented a perspective of how to cope with challenge in implementing LM using I4.0 solutions, on appendix H. The barriers presented involve 10 dimensios of LM proposed by Shard and Ward (2007): supplier feedback, JIT, supplier development, customer involvement, pull production, continuous flow, set up time reduction, Total productive maintenance, statistical process control and employee involvement.

The I4.0, in terms of the use of ICT in an integrated way combined with real-time capability through systems is improving traditional LM practices, improving productivity, and assuring low levels of waste generation (Sanders et al., 2016).

The appearance of I4.0 does not hide LM, instead, I4.0 implementation is helping manufacturer to increase the maturity level of LM (Roy, Mittag, and Baumeister (2015) *apud* Buer et al. (2018)). It can also be understood by the statement of Powell et al. (2013), that links LM and ERP implementation:

> *"Companies have been building environments in which they take advantage of lean production practices facilitated by developments in information technology for quite some time [...] it was observed first-hand that the ERP implementation process can act as a catalyst for the implementation of lean practices, as many of the tasks are the same or similar, or they support each others application."*

Warnecke and Hüser (1995) argued that the ICT system in the future should provide data within the framework of the relevant manufacturing process and should support the continuous improvement processes. Indeed, it had happened, Powell et al. (2013) pointed out some features of ICT/ERP that support and potentialize the Lean characteristics, see Table 9.

ERP characteristics that benefit Lean Manufacturing
Support customer relationship management;
Automate necessary non-value adding activities (e.g. backflushing);
Enable process-modelling to support standard work processes;
Support information sharing across the supply chain;
Create synchronized and streamlined data flow (internal and external);
Support line balancing and demand and production levelling;
Provide decision support for shop floor decision making;
Support Kanban control;
Provide a system to support root-cause analysis and follow-up of quality problems;
Provide highly visual and transparent operational measures;
Implement standard procedures;
Access real-time data;
Integrate business processes;
Improve process transactions, and keep a historical of these transactions.

Table 9: ERP characteristics that benefit Lean Manufacturing. Adapted from (Powell et al., 2013)

Another factor that implies in benefit to LM is that monotonous, routines and non-skilled activities are automated, changing the nature of work and improving employees satisfaction (Sanders et al., 2016)

Today the intelligent manufacturing, through its technological solutions, reinforces the LM practices by making them more efficient and easier, and permits companies to reach higher level of LM implementation (Mora et al., 2017; Wang et al., 2016).

3.3 Industry 4.0 as a Complement of Lean Manufacturing. The Integrated Approach as an Evolution of Lean Manufacturing.

Although LM is widely used by organizations, it is criticized about its effectiveness on achieving good results depending on specific situations, especially regarding flexible production systems and the industrialization of customized and complex products within a context of volatile demand (Kolberg & Zühlke, 2015; Sanders et al., 2017).

Regarding this critics of LM, Mora et al. (2017) argues that Industry 4.0 can complement LM, mainly helping companies to deal with shorter product lifecycles, customized demands, and reduced lead times. This position is also supported by Buer et al. (2018) who discussed the necessity of I4.0 integration into a LM framework that one may rise LM systems' flexibility.

Mrugalska and Wyrwicka (2017) advise practioners to implement IT integration through value stream (including production system, customers and suppliers) by using CPS in order to overcome the flexibility issues. "With advanced information and communication systems in place along with a lean operating structure, an industry has the potential to expand into new horizons at ease" (Sanders et al., 2016).

In addition, digital transformation contributes with real-time information that support decision making, bringing agility, communication improvement, empowerment and commitment of people and helping the operationalization of the strategic and tactical plan (Becker, Delfino, R., Huber, & Lacopeta, 2018).

At the same time that I4.0 solutions, as advanced manufacturing technologies (AMT), new system architecture and CPS are presented as complement for LM, It is also questioned about its compatibility. Some "traditional" lean people are discouraged to use technology because they interpret it as harmful to labor force. However, the majority accepts the use of technology on LM systems in case of value creation and as a support on workstations (Mora et al., 2017).

Indeed, the I4.0 technologies have potentiality to overcome some of the criticisms and to reinforce the LM. Satoglu et al. (2018) discuss the interaction between Lean Production and Industry 4.0 and highlights the possible benefits of waste elimination provided by the Industry 4.0 technologies, Table 10.

	Additive manufacturing (3-D printing)	Augmented reality	Simulation & virtualization	Adaptive robotics	IoT	Data analytics	Cloud computing
Transportation		√	√	√		√	
Motion		√		√			√
Waiting	√		√	√	√	√	√
Inventory	√				√	√	
Unnecessary processing	√		√	√			√
Overproduction	√				√	√	
Defectives	√	√	√	√	√	√	

Table 10: Seven wastes and advanced Industry 4.0 technologies.

With similar arguments, the literature addresses the use of automation as a concern for the I4.0 and LM integration. Nevertheless, LM does not ban the use of automation and rather, their combination exist and often is positive (Kolberg & Zühlke, 2015; Sanders et al., 2017).

Indeed, in the early 1990s a new concept linked to LM emerged indicating the integration of automation technology and LM (Kolberg & Zühlke, 2015). It started with solutions putting together LM techniques, mechanical and electrical systems (Satoglu et al., 2018), and later considering information and communication technology (Kolberg, Knobloch, & Zühlke, 2017) it and was called by Lean automation. However, it had been asleep until the buzz of I4.0.

It can indicate that some applications integrating the concepts of I4.0 and LM already exist. Sanders et al. (2016) considers I4.0 as an advancement of automation on production system and points out the relevance of it for LM since LM beginning. Mrugalska and Wyrwicka (2017) are more ambitious and present the concept of I4.0 factory as an evolution of LM that passes from the automation and computerization to a real integration and virtualization of the processes.

Regarding these concepts, the Chinese plan "Made in China 2025" presents the concept of "Lean Intelligent Production System (LIPS)" that is based on the integration of LM and the I4.0 fundaments and is designed to be implemented by Chinese factories as the basis for intelligent manufacturing (Wang et al., 2016)

It is known that the use of ICT is a basic element of I4.0 (Leyh et al., 2017). In the same way, authors consider that ICT, in special ERP system, should be considered as part of LM toolbox (Powell et al., 2013).

The integration would increase the objective of low cost, high quality and lead-time. Moreover, it would bring more options to improvements on time spent, flexibility and new business model.

The aspects of vertical and horizontal integration present a lot of potential of innovation and performance improvements (Smeds, 1994). The new ICT technologies enable better relationship between partners, improving the collaboration, synchronization and keeping an effective and continuous partners' feedback (Sanders et al., 2016).

Workstations equipped with CPS reinforce the decentralized structures, giving flexibility and autonomy to modules to act according to the availability, cycle times and demand in order to optimize capacity utilization and guarantee a continuous flow. (Kolberg & Zühlke, 2015)

Through I4.0 solutions, LM concepts and techniques can be supported and expanded (Leyh et al., 2017; Satoglu et al., 2018). The different consequences of I4.0 implementation that strengthens the LM practices presented on **Error! Reference source not found.** by Sanders et al. (2016) could be seen as possible evolutions referring to the LM´s dimensions. Indeed, traditional LM tools have already been improved with the use of technologies (Mora et al., 2017).

The CPS, by its IoT and auto-regulated devices with communication capabilities, supports the Just-In-Time dimension, increasing the visibility and the accuracy of information, permitting route optimization and reliability on logistic processes. With this capability, a continuous control can be executed and thus assist schedule process through a pull system perspective. In addition, with the CPS systems, the decentralized perspective increases the flexibility through low time to changeovers and improve the continuous flow dimension.

Indeed, the combination of SMED technique with Plug and Play technology and the modular work station based on standardized physical and IT interfaces exposed the capacity of implementing efficient and flexible production lines as in the *SmartFactoryKL* project (Kolberg & Zühlke, 2015).

The network created by virtual environment enables a cooperation of a diversity of partners that are able to share resources and information, improving their relationship and the supplier development.

The big data environment and edge analytics creates on equipment the capabilities of self-monitoring promoting the predictive maintenance, anticipating breakdowns, process variability, quality issues and then increasing the level of the total productive maintenance dimension. Still in this context, the products are also embedded with technologies thus equipment and product information, together, can establish a more robust process control.

In the work environment of Industry 4.0, smart operators are equipped with smart devices as tablets, smart watches or smartphones that support the decentralized decision-making actions and the continuous feedback processes, increasing the empowerment and enhancing the employee involvement dimension. The uses of smart devices support both managers and subordinates in daily activities by giving real time and contextualized information in a friendly way, what improves speed, performance, coordination and management of actions.

Besides the improvement on technological applications, it is observed that the practitioners' mindset encompass the lean philosophy and the digital thinking. Indeed, Smeds (1994) affirmed that technological integration has to co-exist with organization transformation, in terms of strategy, structures, practices and also by new integrative thinking.

The majority of studies discuss the data-driven momentum, the challenge of how to take advantage of the ocean of data and about the alignment of LM and Digital thinking through information disposal, JIT, zero defects, the holistic vision of systems that includes a global strategy including suppliers, customers, employees and focus on the value creation, efficiency, learning and knowledge creation over a continuous improvement process (Cattaneo et al., 2017; Mrugalska & Wyrwicka, 2017; Sanders et al., 2017)

Mckinsey's study about LM reinforce the power of continuous improvement culture and argues that the new digital tools are giving scale, even across business, of the LM tools which have year by year rendered the industries more efficient. (Becker et al., 2018)

Kupper, Heidemann, Strohle, Spindelndreier, and Knizek (2017) observed, in a survey with about 750 production managers, that only 5% of manufacturing comapnies have high level of maturity of I4.0 and LM today. The survey indicates that the importance of I40 will increase in the next years and LM presents high level of importance today with little reduction for the next years. Both concepts will be relevant by 2030 and will determine the next level of operational excellence.

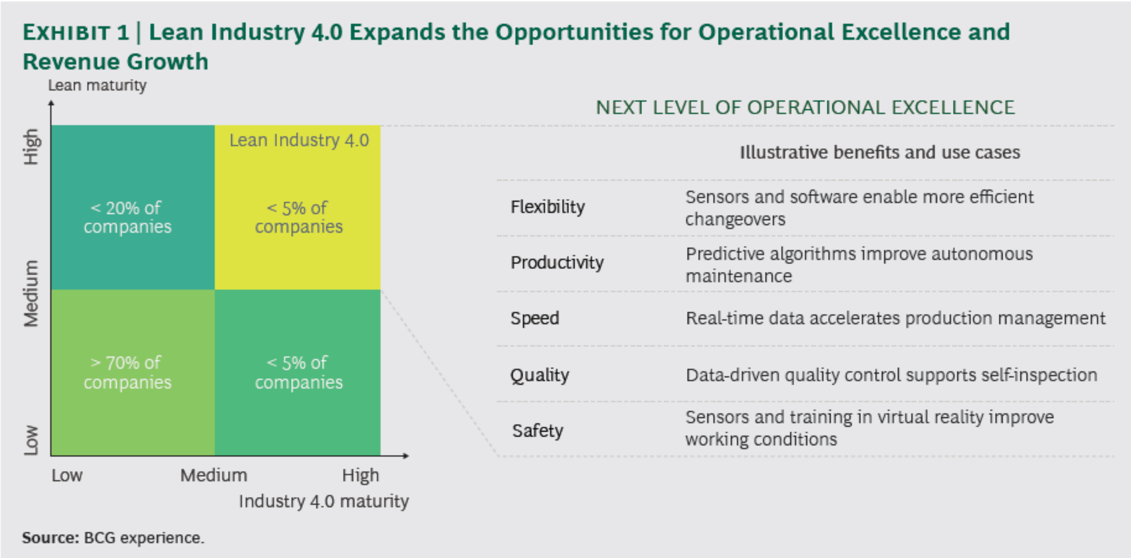

Figure 3-2: Lean Industry 4.0 Expands the Opportunities for Operational Excellence and Revenue Growth. (Kupper et al., 2017)

The LM journey evidences the LM's ability to evolve and to learn from criticism and from new industrial contexts and demands. Some movements have occurred by combining LM principles and tools with others methodologies and techniques as Six Sigma, Theory of Constraints TOC, Agility, etc (Hines et al., 2004).

Kaspar and Schneider (2015) defend that LM and I4.0 pursues similar objectives and have concepts based on decentralized control. They consider that I4.0 will not displace LM and argue that both are complementary defending that lean processes can be further optimized by means of innovative technologies, indicating that an integrated approach is an evolution.[8] Actually, it is possible to look at I4.0 as an evolution of LM that will support all of its principles and even enhances its capacities and results (Mrugalska & Wyrwicka, 2017; Sanders et al., 2017; Wang et al., 2016).

[8] Lean und Industrie 4.0 verfolgen im Kern ähnliche Ziele und setzen auf dezentrale Steuerungskonzepte. Zwar sind die Vorgehensweise und die eingesetzten Mittel teilweise andere, doch können sich diese beiden Konzepte oftmals sinnvoll ergänzen. Industrie 4.0 wird Lean nicht verdrängen, sondern ergänzen. Es handelt sich vielmehr um eine Evolution, als eine Revolution. Wie das vorgestellte Praxisbeispiel zeigt, können bereits schlanke Prozesse mittels innovativer Technologien aber durchaus weiter optimiert werden(Kaspar & Schneider, 2015).

3.4 Industry 4.0 and Lean Manufacturing Integrated Approach Enhances Lean and Organizational Performance

Buer et al. (2018) presented a resume of studies that relate potential operational performance benefits on integrating I4.0 and LM. The performance dimensions affected by the integration are: Cost, Flexibility, Productivity, Quality, Inventory and Reliability. The Table 11 shows the studies evaluated with the indication of the Authors and Performance dimensions.

	Conceptual research			Empirical research				
Performance dimension	Ghi and Rossetti (2016)	Jayaram (2016)	Sanders, Elangeswaran, and Wulfsberg (2016)	Kolberg, Knobloch, and Zühlke (2017)	Kolberg and Zühlke (2015)	Ma, Wang, and Zhao (2017)	Wagner, Hermann, and Thiede (2017)	Wang et al. (2016)
Cost			X			X		
Flexibility			X	X	X	X		X
Productivity			X					X
Quality	X	X						
Reduced inventory				X	X		X	
Reliability						X	X	

Table 11: Studies evaluating the performance benefits of integrating Industry 4.0 and Lean Manufacturing. (Buer et al., 2018)

Kupper et al. (2017) highlights five benefits of the integrated approach: “Flexibility” through sensors and software that enable changeovers that are more efficient; “Productivity” through predictive algorithms; “Speed”, by the use of real-time data; “Quality” by new ways of doing quality control and self-inspections; and “Safety” that are improved by the use of sensors and training in virtual reality.

Riezebos and Klingenberg (2009) noted that companies who implemented IT-based production systems supported by LM principles could achieve better results in productivity, avoid expending large amount of capital and thus increasing the return of investment.

The LM also demonstrate to improve the results of AMTs implementation. Khanchanapong et al. (2014) *apud* Buer et al. (2018) presented that the integration of both granted a synergistic impact on performance better than optimizing either concepts isolated.

Regarding I4.0, Kupper et al. (2017) indicates that the integrated approach with LM has the potential to increase manufacturers’ performance by achieving a 40% reduction in conversion costs in a period maximum of ten years, which is better than the sum of the results obtained applying each methodology alone.

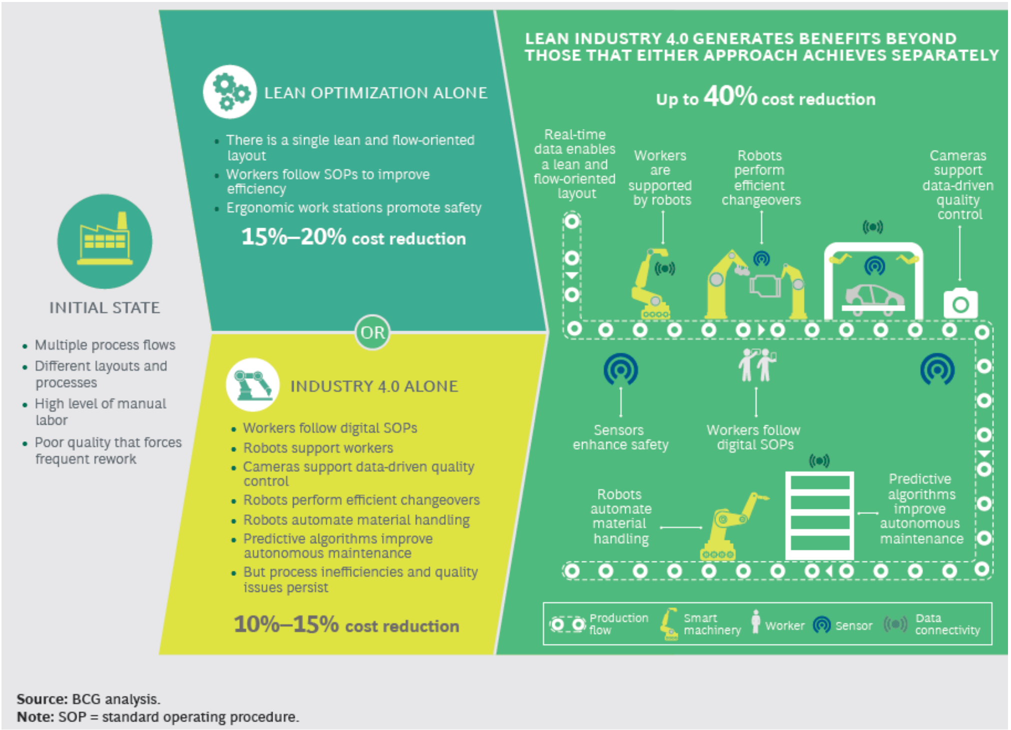

Figure 3-3: With an integrated approach, LM and I4.0 are mutually enabling. (Kupper et al., 2017)

The processes with value creation orientation and uncharged of wastes developed by LM on companies enable I4.0 solutions to be built upon efficient processes. And It combined with the end-to-end approach, with visibility in real time and a dynamic structure that permits optimized decision making and high level of resource productivity and efficiency of I4.0 (Mrugalska & Wyrwicka, 2017), results in a reasonable value to organizations. (Sanders et al., 2017)

Besides the idea of mutual facilitation of both concepts on Figure 3-3, Kupper et al. (2017) affirms that the integrated approach of LM and I4.0 will raise the bar of organization performance:

> *"Manufacturers seeking to optimize their operations need to understanding the interplay between traditional lean management and Industry 4.0. […] in most cases, the integrated application of Lean management and Industry 4.0 – which we call Lean Industry 4.0 is the most effective way to reach the next level of operational excellence."*

Based on the present section, one can notice that, theoretically, LM and I4.0 are absolutely compatible and present strong convergence and complementarity. Although some studies consider the presence of both concepts in a set of use cases and the publication of the potential benefits of the integrated approach there is no empirical evidence of these benefits.

Taking into account all the information discussed on the present section, it is possible to state five different propositions and postulate hypothesis to be tested in the sequence of this work:

- H1.1 The correlation between I4.0 and LM is significant and positive.
- H1.2 LM experience provides significant contribution on I4.0.
- H1.3 I4.0 experience provides significant contribution on LM.
- H2.1 The LM and I4.0 integrated approach presents a significant and positive influence on organizational performance.
- H2.2. The integrated approach of LM and I4.0 implies on a higher impact on organizational performance compared with the influence of each approach implemented in a stand-alone way.

4 Methodology

The literature announces the possibility of mutual benefits with the integrated approach between LM and I4.0 that can boost agility, efficiency, autonomy and changes on business models. In order to examine the relationship of both themes, this research work carried out a survey through Portuguese's companies.

This method was selected because, at first, it is appropriate to study the relationship between concepts, at second it intends to collect information of several organizations when the information requested are not available on open databases.

In terms of literature review, the investigation focused on the fundamental aspectcs of each theme, LM and I4.0, in order to figure out the coherence of their integration and considers also the findings of few studies that either mention any type of integration between LM and I4.0 at the conceptual, maturity or applied cases.

The research was conducted using different terms such as Lean production, Lean management, Lean thinking, Digitalization, Digital transformation, etc. Preference was given to papers published in renowned journals that are available on databases as Scopus, Web of Science and Sciencedirect. However, due to the lack of abundance of academic works with high impact on this topic, it has been considered publications from renowned consultants, consortiums, and centers of innovation, observing their relevance and credibility.

The survey intends to get evidence from industries in order to confirm what was interpreted from theoretical analysis. Overall, it is expected a high correlation between I4.0 practices and LM practices. Moreover, it is expected to learn how LM tools and I4.0 technologies are most used and understand their integration and consequences in terms of organizational performance. Regarding the impact, it is supposed to meet high correlation between LM implementation and organizational performance and even better results through companies with I4.0 integrated approach. However, it is expected a low degree of adoption of I4.0.

The survey practice is detailed on the following subtopics and was based on Forza (2002) method. The data was analyzed with the support of the softwares AMOS and SPSS.

4.1 Target Sample and Data Collection

The target of this study is the active manufacturing companies established in Portugal, with revenues greater than 2 Million Euros or 10 or more employees in 2017 (small medium and large sized enterprises) and classified with primary code of NACE Rev 2[9] between 10 to 32. The population of these companies is 30010 according to SABI[10].

Managers and administrators of 3448 industrial companies were contacted by mail with an invitation to participate of the research. Out of 260 responses, 212 are usable (48 presented problems with missing values (>5% of items), or signals of non-engagement, interpreted by answers with standard deviation close to zero) representing 6,1% of response rate, representing 107 small, 94 medium and 11 large companies. The sample summary is on **Error! Reference source not found.**.

4.2 Instruments, Measures and Model Specification

The survey is divided in three sections. The first part includes organization and respondent's demographic questions. The second section is the Lean implementation assessment. The last section is the Industry 4.0 assessment.

The first part was defined based on previous literature review and comprises: firm size based on numbers of employee (Doolen & Hacker, 2005), sales volume, firm location (Yang et al., 2011), respondent positions (Fullerton et al., 2014) and industry sector (Cooney, 2002). It was also requested the fiscal identification number (NIF) of each company what was useful to collect official information, as the performance's index.

Regarding the LM assessment model, it was used the model proposed by Shah and Ward (2007) that assesses the level of LM implementation by evaluating 10 bundles which is presented on section 2.3.1. The model was chosen due to its validity in the academic environment. It provides further information through the items and has an easy way to be used.

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[9] NACE Rev 2 is a statistical classification of economic activities in the European Community defined by Eurostat, the Statistical Office of the European Communities.

[10] SABI is a Database with complete financial analysis information of Portuguese and Spanish companies with a history of annual accounts up to 25 years. It was accessed with the license of Economics Faculty of Porto University. https://sabi.bvdinfo.com

Lastly, the I4.0 assessment model used is based on questions of Acatech study model, PwC self-assessment, IMPULS assessment, Schumacher et al. (2016), Akdil, Ustundag, and Cevikcan (2018), considering some concepts of technology adoption and absorptive capacity (Huang, Bhattacherjee, & Wong, 2018; Lin, 2014; Nieto & Quevedo, 2005).

The I4.0 assessment model determine a maturity level based on the evaluation of 12 dimensions summing a total of 88 Likert Scale questions. The Table 12 presents the dimensions and topics covered.

Dimension	Details
Strategy, Management and Leadership	Measure de level of Knowledge and Competences about I4.0 of managers; their degree of involvement and support on I4.0 initiatives; I4.0 implemetnation management; and people responsibility.
Execution	Evaluate the scope and status of I4.0 implementation.
Collaboration and Partnership	Evaluates the existence of a relationship with partners for the development of digitalisation
Receptive for change Organisational	Evaluate the posture of the organisation concerning training; process and product innovation; crossdepartment activities and knowledge management.
Receptive for change People	Evaluate the posture of employees concerning changes, learning, acceptance of new methods and technologies and improvement process proposals.

Dimension	Details
Resource digitization and Automation	Evaluate if the resources (Product, Assets, Plants) have advanced digital skills and the automation scope on production process.
Decentralization	Measure the existence of interaction between production systems. (M2M, M2S, S2S)
Data Use	Evaluate the forms of Data Collection, Storage, Processing and Usability.
Systems	Measure the existence of systems as ERP, CRM, WMS, MOM, MES, PPS, SCM
Basic Technologies	Communication Network; Cloud computing; Data Analytics and Cyber Security.
Others I4.0 Technologies	Evaluate the implementation plan concerning others technologies: Artificial Intelligence; Simultation; Collaborative Robot; Aumented Reality; Embeded System; Additive Manufacturing; and Mobile Devices.
Integretation	Assess the level of vertical and horizontal integration and the visibility on supplychain.

Table 12: Industry 4.0 assessment – Dimensions and topics covered.

The construction of this questionnaire initiated by the selection of appropriated questions regarding the theoretical literature review. After that, the questions were adjusted to present similar scales, with the care of ensuring that the language was appropriated to the target respondent (industrial professionals, mainly managers and executives), and also with the care that the questions were almost uncorrelated and that the alternatives on closed questions were mutually exclusive. A pilot test was conducted with three academics and two industry experts to guarantee that the questions were clear and had been interpreted equally.

In addition to the activities described on the paragraph below, an Exploratory Factor Analysis (EFA) was executed in order to guarantee that the dimensions were correctly defined. The results demonstrated that the instrument gauge the dimensions as the finding of the literature.. The final instrument is presented on Table 12 and the EFA is described on Appendix A.

All the questions used on LM and I4.0 questionnaires are available on appendix B. They will be treated here by their shortening name (Topic, number and subtopic). All of them are based on the Likert scale where in general "1" indicate no implementation and "5" complete implementation.

The Organizational performance comprises indicators of Operational, Market and Financial measurements, see Table 13. The information was collected from SABi database using the NIF of each company. Thus an index is calculated as the average of the variation of 2017-2016 and of 2017-2015 results. The measures are represented in a Likert Scale in terms of level of improvement or worsening. The scale is based on 10 interval of equal percentiles (10% of observations).

Operational	Market	Financial
Operational Cost	Sales (Turnover)	Net Income
Material Cost	Market share	Return on Assets (ROA)
Stock Turnover		Margin - Profitability

Table 13: Measures of organizational and LM performances.

The operational performance is measured by operations cost, material cost and stock turnover. The market performance is rationalized by the measures of sales and market share. The financial performance is evaluated by net income, return on assets and margin. The metrics of each index are available on appendix C.

Despite of the coherence of I4.0 and the literature validity of LM measuring instruments, it was conducted another EFA in order to identify a reduced, simple, model of both instruments. The LM assessment was condensed in three dimensions defined by 9 observed variables while the I4.0 assessment model was downsized to 7 dimensions measured by 24 observed variables. The performance measurement was restricted, on this first analysis, to ROA, Margin and Operational Costs. A Confirmatory Factor Analysis (CFA) was conducted to verify the validity of each measuring instrument. The CFAs of both I4.0 and LM instruments are on Appendix D.

The final construct model is represented on Figure 4-1. Both, the LM and I4.0 factors are conceptualized as a second-order construct and with multidimensional measurement.

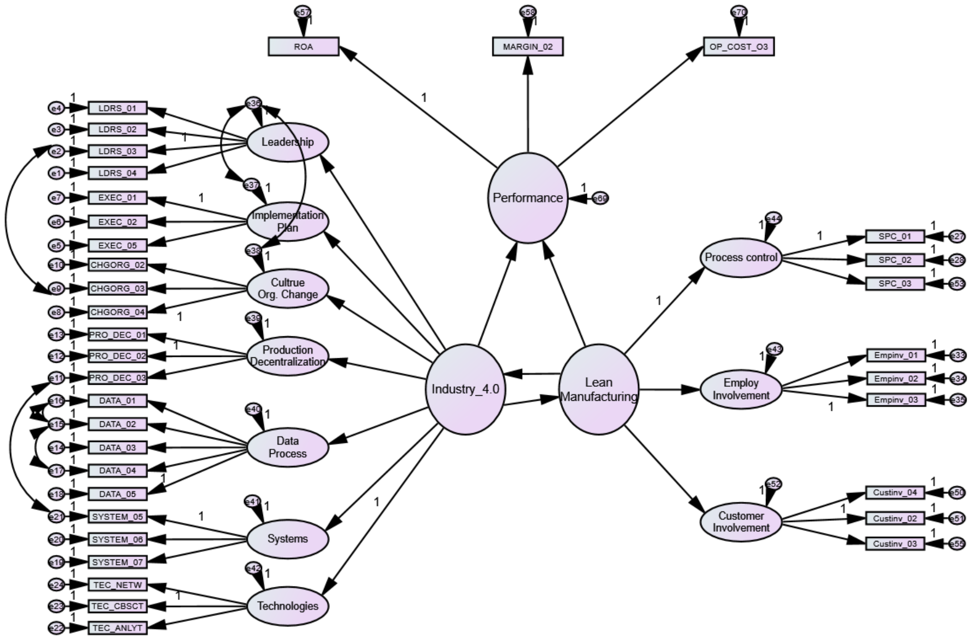


Figure 4-1: Composition of Lean Manufacturing maturity measure.

In this model, the organizational performance is measured as the regression of ROA, Margin and Operational Cost distinct factors. As indicated by the signs associated in the path, I4.0 is represented as a multidimensional construct with Leadership, Implementation Plan, Culture, Production Decentralization, Data Process, Systems and Technologies. LM is represented by Process Control, Employee Involvement and Customer Involvement factors.

4.3 Assessing Validity and Reliability

The test of the complete model is a critical stage before conducting any evaluation of the structural model. The assessment of the measurement model is done in terms of validity and reliability. (Forza, 2002) The methodology used on that work is based on Anderson and Gerbing (1988) that suggest a two-step approach to conduct a hypothesis test. First, the model is tested concerning scale reliability and construct validity. The second step evaluate the structural relationship.

4.3.1 Respondent Profile and Biases

The main recipients of the survey were managers and directors of operational areas, profiles responsible for more than 50% of responses. Summary of respondents profile on Table 14

Attendant Profile	Frequency	%
Administração / Chief Executive	38	18%
Diretor Operações / Industrial / Fábrica / Produção / Qualidade / Manutenção	59	28%
Diretor Financeiro /Administrativo / Compras / RH	17	8%
Engenharia	9	4%
Gerente de Operações / Industrial / Fábrica / Produção / Qualidade / Manutenção	54	25%
Gerente Financeiro /Administrativo / Compras / RH	6	3%
Técnico Industrial / Logística / Administrativo	29	14%
Total	212	100%

Table 14: Respondent profile.

The survey was responded in one unique step by each attendant, thus the Harman's single factor test using confirmatory factor analysis (CFA) was used to evaluate the response bias.

4.3.2 Reliability

The most widely used method to test reliability is the Cronbach coefficient alpha. It is the most used index of internal consistency in OM survey research (Forza, 2002)

Reliability Statistics

LEAN MANUFACTURING									
Statistical Process Control (SPC)		Employee Involvement		Customer Involvement		Performance		OVERALL	
Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens
0,819	3	0,765	3	0,718	3	0,886	3	0,896	36

INDUSTRY 4.0													
Leadership		Execution		Culture Org. Change		Decentralized Production		Data		Systems		Technologies	
Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens	Cronbach	N. of Itens
0,871	4	0,888	3	0,847	3	0,882	3	0,935	5	0,843	3	0,852	3

Table 15: Reliability test - Cronbach alpha. Calculated in SPSS.

The responses demonstrated to be reliable as the threshold for the alpha is 0.6 or higher.

4.3.3 Construct Validity – Convergent and Discriminant Validity

Besides the validity of the individual instruments, the statistic of goodness-of-fit indicates a reasonable model. $\chi_{(576)}^{2}$: 765,23; GFI: 0,841; CFI:0,960 RMSEA: 0,039 and p-value: 0,000.

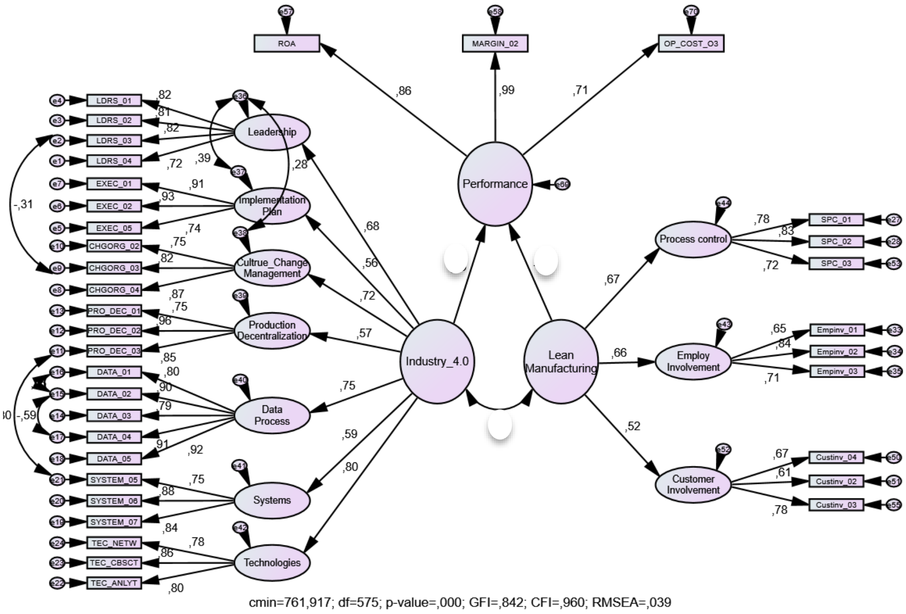


Figure 4-2: Structural Model Estimation

As it is possible to see on Figure 4-2, the majority of the standardized factors loading of the model is above 0.80, only 6 below 0.7 and a minimum of 0.52 Therefore, it is possible to consider the convergent validity of the model.

It leads to concluded that Leadership, Implementation Plan, Culture, Production Decentralization, Data Process, Systems and Technologies are potential determinants for I4.0 maturity. The Process Control, Employee Involvement and Customer Involvement are factors with strong indication of LM maturity. The Organizational performance is well charged by ROA, Margin and the Operational Cost Indicator.

The validity check ensures that the model in case is measuring the exactly concept expected and the reliability check demonstrates that the model has stability and consistency in measurement. (Forza, 2002).

Besides the SEM, general analysis and statistics were used to bring additional information, specially related to means. These alternative analysis comprise I4.0 Maturity, LM Maturity and Organizational Performance.

The I4.0 and LM maturity were calculated computing the data collect on survey with the regression on Equation 1 and Equation 2 respectively. The maturities will be presented as a standardized value (as a percentage of the maximum punctuation that a company could achieve on each equation - having score of 5 on all questions).

$$\boldsymbol{I4.0}\ \textbf{Maturity} = (\boldsymbol{\beta_1} * \boldsymbol{Leadership} + \boldsymbol{\beta_2} * \boldsymbol{Implementation_{PLan}} + \boldsymbol{\beta_3} * \boldsymbol{Cult_{CHNMNG}} + \boldsymbol{\beta_4} * \boldsymbol{Prod_{Decentralization}} + \boldsymbol{\beta_5} * \boldsymbol{Data_{Process}} + \beta_6 * \boldsymbol{Systems} + \beta_7 * \boldsymbol{Technologies})$$

Equation 1: I4.0 Maturity Equation.

$$\boldsymbol{LM\ Maturity} = (\emptyset_1 * \boldsymbol{Process\ Control} + \emptyset_2 * \boldsymbol{Employee\ Involvement} + \emptyset_3 * \boldsymbol{Customer\ Involvement}$$

Equation 2: LM Maturity Equation.

Where, B and $\emptyset$ are the standardized coefficient of SME analysis for the unobserved exogenous variables Industry 4.0 and Lean Manufacturing, indicated on the second factors models on Appendix D. Each variable of equations (maturity dimensions) is estimated in terms of the regression of their indicators (observed variables on survey).

The organizational performance is the same as the used on SEM analysis, obtained from SABI, using the fiscal identification information of each company.

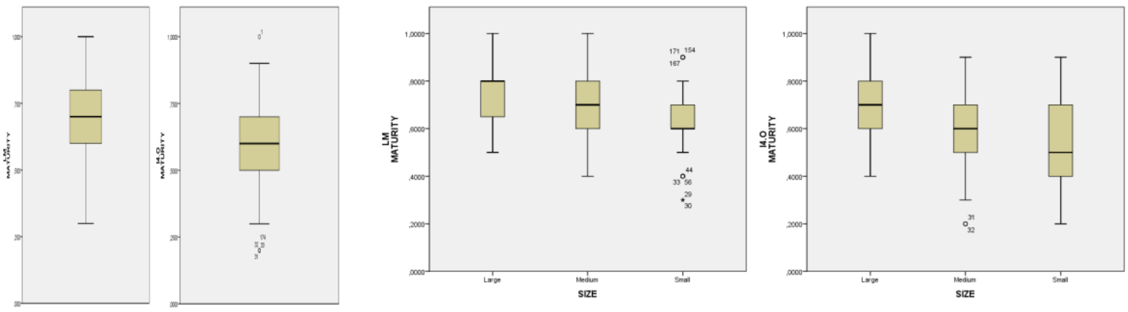
5 Data Analysis and Discussion

The present section mixes a SEM analysis with general statistics methods in order to test the hypothesis of this research and discuss interesting points and general findings of the sample data related with LM, I4.0 and organizational performance.

5.1.1 Preliminary Analysis

Regarding the descriptive analysis of the survey data it is possible to observe that the respondents companies present an average of LM Maturity of 66% and I4.0 maturity of 57%. Both averages seem to be higher on large companies and decrease in medium and small sized companies. The LM maturity presents more stability than the I4.0 maturity.

These results were expected as LM is an approach consolidated for years while I4.0 is an emergent practice. Descriptive analysis is reported on Table 16.



Descriptive Statistics

	LM MATURITY						I4.O MATURITY					
	N	Amplitude	Mínimo	Máximo	Média	Desvio Padrão	N	Amplitude	Mínimo	Máximo	Média	Desvio Padrão
ALL	212	0,70	0,30	1,00	0,66	0,13	212	0,80	0,20	1,00	0,57	0,16
SMALL	107	0,60	0,30	0,90	0,64	0,12	107	0,64	0,23	0,87	0,53	0,16
MEDIUM	94	0,61	0,39	1,00	0,67	0,13	94	0,69	0,20	0,89	0,59	0,15
LARGE	11	0,49	0,47	0,96	0,73	0,14	11	0,59	0,37	0,96	0,69	0,17

Table 16: Survey descriptive analysis - First impressions of Portuguese manufacturing regarding LM and I4.0 maturities.

The overall model used on SEM analysis, on Figure 5-1, demonstrates that the characteristics of "Leadership", "Implementation Plan", "Culture", "Production Decentralization", "Data Process", the use of "Systems" and "Technologies" are potentials determinants for I4.0 maturity. The "Process Control", "Employee Involvement" and "Customer Involvement" are factors with strong indication of LM maturity. The integrated Path of both concepts are plausible and could be linked to "Organizational performance" that is measured, on this case, by a "ROA", a "Margin" and an "Operational Cost" indicators.

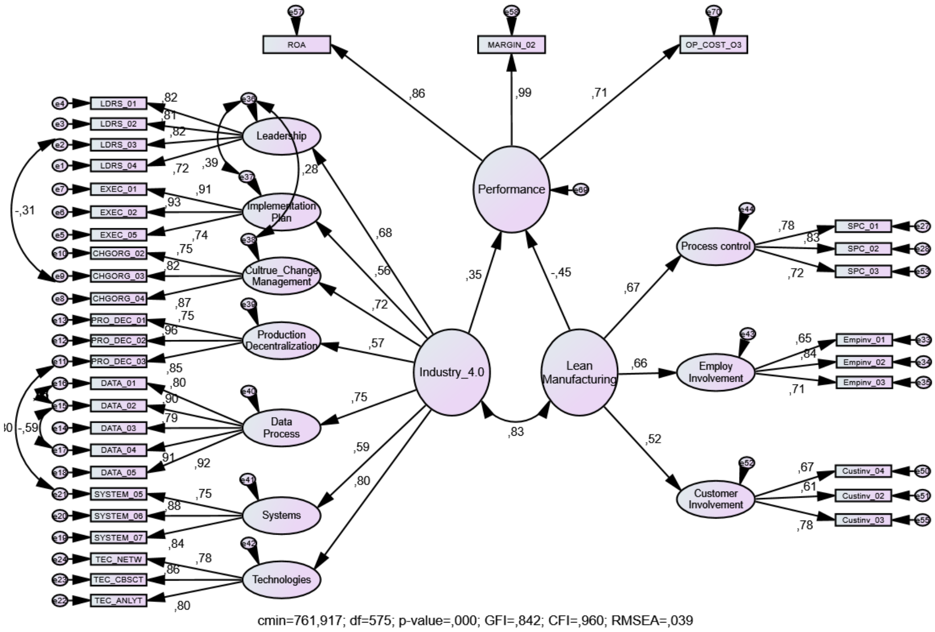


Figure 5-1: Estimated Model - Standardized factors loading.

The factors loading of I4.0 demonstrated to be statistically strong, with C.R. higher than 6, a p-value close to 0, and explaining 84% of the I4.0 measure variance. All of them presents a positive effect on determining I4.0 maturity, highlighting "Technology" measure. See Table 17.

Regression Weights: (Group number 1 - Default model)								
Relation			**Estimate (Standardized)**	**Estimate (Untandardized)**	**S.E.**	**C.R.**	**P**
Leadership	<---	I4.0	0,683	0,704	0,093	7,6	***
Implementation Plan	<---	I4.0	0,564	0,76	0,111	6,827	***
Culture - Org. Change	<---	I4.0	0,717	0,718	0,089	8,102	***
Decentralization	<---	I4.0	0,57	0,659	0,093	7,077	***
Data Process	<---	I4.0	0,747	0,94	0,106	8,859	***
Systems	<---	I4.0	0,593	0,84	0,121	6,954	***
Technology	<---	I4.0	0,8	1			

Table 17: Regression weights statistics - I4.0 factors.

The LM maturity presents lower factors loading compared with I4.0 variable. However, all of them are significant with highest value assigned by "Process Control" dimension. The variance accounted by its endogenous variables is about 60%, details on Table 18.

Regression Weights: (Group number 1 - Default model)							
Relation			**Estimate (Standardized)**	**Estimate (Untandardized)**	**S.E.**	**C.R.**	**P**
SPC	<---	LM	0,668	1			
EMPINV	<---	LM	0,656	0,67	0,117	5,708	***
CUSTINV	<---	LM	0,52	0,398	0,089	4,452	***

Table 18: Regression weights statistics - LM components.

Regarding the impact on performance, both I4.0 and LM factors do not present statistical significance, see Table 19. The factors loading of both effect present a p-value higher than 0,05. This result was not expect by the author, however it could be plausible.

Indeed, there are several arguments that can support this result. The main one is related with the difficulty to attribute the organizational results to few conditions. Also, it is not to exclude the possibility of data treatment error.

Regression Weights: (Group number 1 - Default model)							
Relation			**Estimate (Standardized)**	**Estimate (Untandardized)**	**S.E.**	**C.R.**	**P**
Performance	<---	I4.0	0,353	1,096	0,801	1,368	0,171
Performance	<---	LM	-0,45	-1,648	1,04	-1,585	0,113

Table 19: Regression weights statistics - I4.0 and Lm Impact on Performance.

Despite of statistical insignificance, it can be observed that I4.0 presented a positive effect on performance, instead LM. The negative factor loading of LM on Performance can reinforce the criticism about the LM efficiency. Indeed several cases of companies that do not achieved expected results through LM implementation were mentioned on section 2.1 and 2.3.1.2.. The coefficient of I4.0 could give a clue to the idea of beneficial consequences of I4.0 on organizational performance for further researches.

5.1.2 Hypothesis tests

5.1.2.1 H1.1: The correlation of I4.0 and LM is significant and positive.

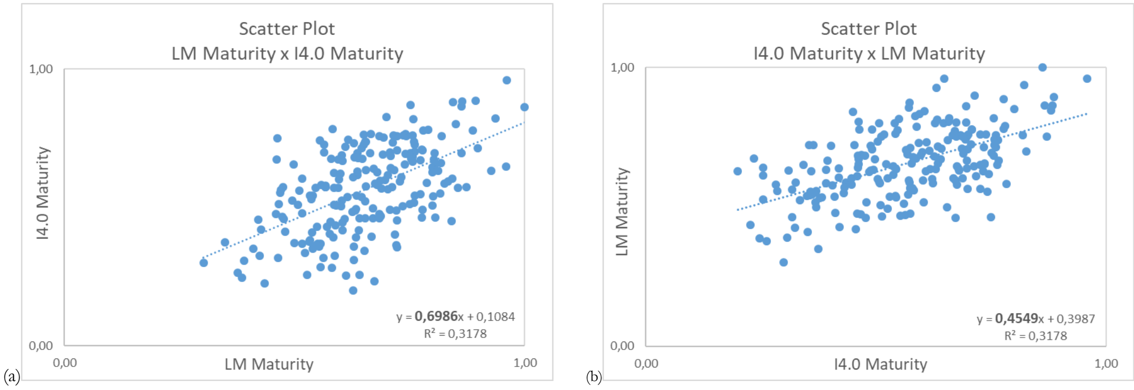
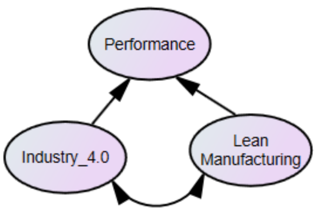


Figure 5-2: Scater Plot - (a) LM x I4.0 Maturity (b) I4.0 x LM Maturity

Through the graph analysis on Figure 5-2 it is possible to realize that I4.0 and LM are positively correlated. Moreover, the average impact of a variation on I4.0 Maturity implies in higher variation on LM than the inverse effect.

Regarding the results of the estimated model it is possible to identify a high correlation between LM and I4.0. The correlation's score almost reached the maximum permitted to validate the structure model (<,90), see Table 20. A value of 0,83 confirms the hypothesis H1.1 that suggests a positive and high relationship of I4.0 and LM



Correlations: (Group number 1 - Default model)

Relation			Estimate
I4.0	<-->	LM	0,828

Covariances: (Group number 1 - Default model)

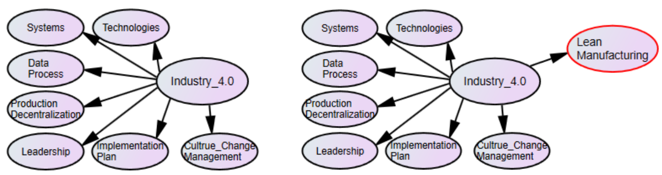
Relation			Estimate	S.E.	C.R.	P
I4.0	<-->	LM	0,588	0,108	5,451	***

Table 20: I4.0 and LM correlation.

To interpret the influence of one concept to another, it was conducted a comparison of the original model of each concepts (Constrained model) and the model with the addition of one concept as an endogenous variable that influences the other. (Unconstrained model).

5.1.2.2 H1.2: LM experience provides significant contribution on I4.0.

This hypothesis was defined to verify the coherence and strength of the belief that LM is the the basis for I4.0



		χ^2	Df	GFI	CFI	RMSEA	p-value	Explained Variability on I4.0
Unconstrained	LM <--- I4.0	641,115	478	0,853	0,962	0,040	0,000	0,840
Constrained	I4.0 alone	320,588	239	0,894	0,977	0,04	0,000	0,880

Relation			Standardized Regression Weights		Regression Weights			
			Estimante Constrained	Estimante Unconstrained	Estimate	S.E.	C.R.	P
LM	<---	I4.0		0,574	0,094	6,081	***	***
Leadership	<---	I4.0	0,667	0,702	0,092	7,602	***	***
Implementation	<---	I4.0	0,579	0,756	0,111	6,817	***	***
Cult_CNGORG	<---	I4.0	0,701	0,716	0,088	8,107	***	***
Decentralization	<---	I4.0	0,544	0,655	0,093	7,052	***	***
Darta	<---	I4.0	0,741	0,94	0,106	8,881	***	***
Systems	<---	I4.0	0,611	0,615	0,093	6,579	***	***
Technology	<---	I4.0	0,82	1				

Overall Model	χ^2	Df	p-value
Unconstrained (I4.0 with LM as endogenous variable)	641,115	478	0
Constrained I4.0 stand alone	320,588	239	0
Difference	**320,527**	**239**	**0,000**

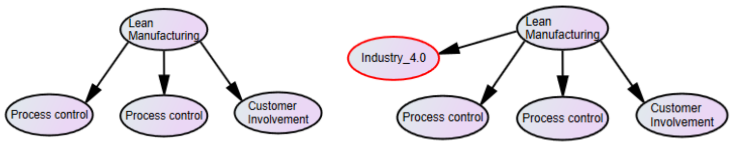
Table 21: Evaluation of the LM maturity influences on I4.0 maturity.

The LM maturity as an endogenous variable on I4.0 model accounts a significant and positive standardized factor loading of 0,574. However, it appears as the worst factor loading of the new construct, causing also a degradation on the model fit. The new model presents different characteristics from the primer, as confirmed by the test of $\chi 2$ difference. As observed on Table 21, the model fit decreases in terms of GFI, CFI and total variance explained on I4.0 is a reduced a little.

Thus, it is possible to conclude that exists a positive influence of LM on I4.0 maturity, however other factors are more important than LM influences.

5.1.2.3 H1.3: I4.0 experience provides significant contribution on LM.

This hypothesis is based on the literature findings that mention I4.0 as an enabler of LM. It is supported on the fact that I4.0 facilitates the implementation and dissemination of LM techniques and also reduces efforts to maintain them. Thus, increases LM maturity.



		χ^2	Df	GFI	CFI	RMSEA	p-value	Explained Variability
Unconstrained	I4.0 <--- LM	641,115	478	0,853	0,962	0,040	0,000	0,570
Constrained	LM alone	55,150	24	0,948	0,949	0,078	0,000	0,400

Relation			Standardized Regression Weights		Regression Weights			
			Estimante Constrained	Estimante Unconstrained	Estimate	S.E.	C.R.	P
I4.0	<---	LM		0,826	1			
SPC	<---	LM	0,535	0,655	0,841	0,157	5,373	***
EMPINV	<---	LM	0,713	0,677	0,645	0,124	5,215	***
Customer	<---	LM	0,599	0,517	0,365	0,085	4,276	***

Overall Model	χ^2	Df	p-value
Unconstrained (LM with I4.0 as endogenous variable)	641,115	478	0
Constrained LM stand alone	55,15	24	0
Difference	**320,527**	**239**	**0,000**

The I4.0 as an endogenous unobserved variable on LM construct presented a high regression weight. In fact, it came out as the most important contributor to LM factor, with a factor loading of 0,826. The new path model demonstrated a better goodness of fit, with growth on CFI and explained variability of LM and a reduction on RMSEA. In that way, it is logical to confirm the hypothesis H1.3.

5.1.2.4 H2.1: The integrated approach of LM and I4.0 presents a significant and positive influence on organizational performance.

As it was discussed on section 5.1.1, the coefficients attributed to explain the relation of the factors LM and I4.0 with Organizational Performance presented a p-value higher than 0,05 not supporting statistical significance to take conclusion of their loading.

5.1.2.5 H2.2: The integrated approach of LM and I4.0 implies on a higher impact on organizational performance compared with the influence of each approach implemented in a stand-alone way.

Despite the test pointed out a non-statistical significance of the effects of I4.0 maturity and LM maturity variables on Performance, the analysis here will focus on the mutual influence of the LM and I4.0 maturity on Organizational Performance.

In order to evaluate this hypothesis, a mediation test was conducted to account the direct and indirect effect of both variable on Performance. The hypothesis will be validated if the total effect of LM and I4.0 integrated path on Organizational performance is higher than the direct effect of each approach in stand-alone implementation.

First, it was tested the LM mediation from I4.0 to Organizational performance. The Table 22 shows the three scenarios which it was possible to compute the direct effect of I4.0 on Performance, the indirect effect of I4.0 on Performance through LM and the result of the complete effect (Direct + Indirect) of I4.0 on Performance.

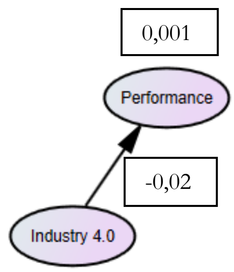
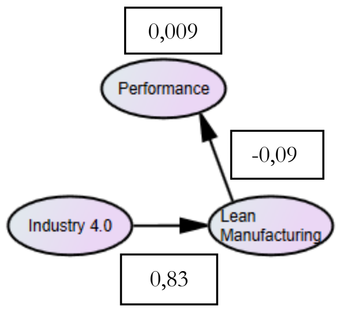
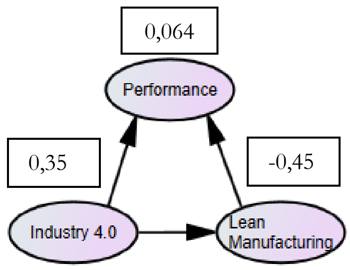
<table>
<tr><th>Direct Effect</th><th>Indirect Effect
(Performance <-- LM <-- I4.0)</th><th>Direct and Indirect Effects</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

Table 22: LM mediation representation.

The stand-alone implementation of I4.0 seems to present a negative effect, with a factor loading of -0,02, however, with a p-value of 0,768, see Table 23. Besides the coefficient close to zero, the p-value indicates that this relation is practically invalid. This condition can be explained by the fact the I4.0 is on its early phase of implementation in Portugal and companies yet does not know how to take advantage of it. Furthermore, experts suggest that the benefits of I4.0 will indeed be felt in the medium term.

As already mentioned, I4.0 maturity has a positive effect on LM maturity of 0,82. The LM Maturity, with indirect effect of I4.0 resemble to present a negative consequence on Performance in order of 0,09.

Models	Relations			Standardized Weight	Estimate	S.E.	C.R.	P
Direct Effect	Performance	<---	I4.0	-0,023	-0,06	0,203	-0,295	0,768
Indirect Effect (Performance <-- LM <-- I4.0)	LM	<---	I4.0	0,818	0,574	0,094	6,098	***
	Performance	<---	LM	-0,093	-0,357	0,318	-1,123	0,262
Indirect and Direct Effects	LM	<---	I4.0	0,828	0,591	0,095	6,219	***
	Performance	<---	LM	-0,45	-1,701	1,079	-1,577	0,115
	Performance	<---	I4.0	0,353	0,952	0,698	1,364	0,173

Table 23: Estimates statistics - LM mediation Analysis.

Here it would be important to conduct a Sobel test in order to evaluate the significance of the indirect effect. Because of the relation of LM and I4.0 variables on Performance were indicated as statistical non-significant, the results of Sobel test should also fail. Indeed, the test of the indirect effect of I4.0 on Performance going through LM showed a Sobel statistic less than 1,96, see Table 24, what it does not confirm the presence of this indirect effect.

	Test statistic	p-value
Sobel test:	1.104	0.269
Aroian test:	1.090	0.275
Goodman test:	1.119	0.263

Table 24: Sobel test: indirect effetct of I4.0 on Performance through LM.

It is also observed that the effect of I4.0 on Performance increases when considering the LM mediation. Moreover, it passes from a negative to a positive influence. It is possible to see that the p-value of I4.0 coefficient on Performance improves from 0,768 to 0,173.

Besides the Sobel test result, the test of $\chi 2$ difference with a p-value = 0,129 indicates that there is no accentuated difference on model level, but it may be a difference at the path level. Indeed, the major difference on the model is on the explained variability of Performance that increases from 0,009 to 0,064, see Table 25.

Models	χ^2	Df	GFI	CFI	RMSEA	p-value	Explained Variability on Performance
Direct Effect	416,372	310	0,878	0,973	0,04	0	0,001
Indirect Effect (Performance <-- LM <-- I4.0)	764,265	576	0,841	0,96	0,039	0	0,009
Indirect and Direct Effects	761,917	575	0,842	0,96	0,039	0	0,064

Overall Model	χ^2	Df	p-value
Indirect Effect (Performance <-- LM <-- I4.0)	764,2	576	
Indirect and Direct Effects	761,9	575	
Difference	**2,3**	**1**	**0,129**

Table 25: LM mediation model evaluation.

Thus, the analysis indicates an inexistence of indirect effect of I4.0 on Performance through LM factor.

Regarding the I4.0 mediation analysis, the Table 26 shows three scenarios which it was possible to compute the direct effect of LM on Performance, the indirect effect of LM on Performance through I4.0 and the result of the complete effect (Direct + Indirect) of LM on Performance.

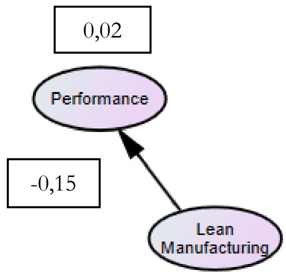
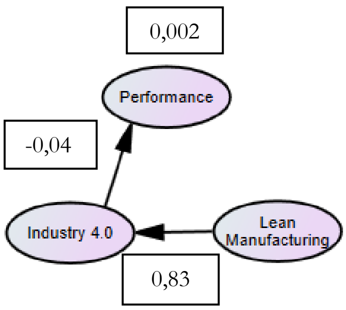
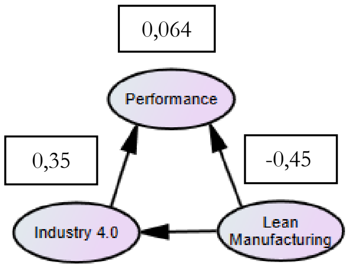
Direct Effect	Indirect Effect (Performance <-- I4.0 <-- LM)	Direct and Indirect Effects
		

Table 26: Estimates statistics - I4.0 mediation analysis.

The factor loading of direct effect of LM on performance indicates a negative influence of 0,15. It could support the LM criticism regarding its inability to face with current manufacturing challenges, or regarding their implementation issues. The indirect effect of LM on Performance through I4.0 seems to present an improvement, but still negative.

Models	Relations			Standardized Weight	Estimate	S.E.	C.R.	P
Direct Effect	Performance	<---	LM	-0,15	-0,688	0,443	-1,553	0,121
Indirect Effect (Performance <-- I4.0 <-- LM)	I4.0	<---	LM	0,827	1,19	0,221	5,38	***
	Performance	I4.0	LM	-0,041	-0,11	0,206	-0,537	0,591
Indirect and Direct Effects	I4.0	<---	LM	0,828	1,161	0,214	5,421	***
	Performance	<---	I4.0	0,353	0,952	0,698	1,364	0,173
	Performance	<---	LM	-0,45	-1,701	1,079	-1,577	0,115

Table 27: Estimates statistics - I4.0 mediation analysis.

The test of the indirect effect of LM on Performance going through I4.0 showed a Sobel statistic less than 1,96, see Table 28, what does not confirm the presence of this indirect effect.

	Test statistic	p-value
Sobel test:	0.534	0.593
Aroian test:	0.525	0.599
Goodman test:	0.543	0.586

Table 28: Sobel test: indirect effetct of LM on Performance through I4.0.

The differences on model fit indicates that there is difference between both models.

Models	χ^2	Df	GFI	CFI	RMSEA	p-value	Explained Variability on Performance
Direct Effect	74,58	50	0,948	0,976	0,048	0,014	0,02
Indirect Effect (Performance <-- I4.0 <-- LM)	765,233	576	0,841	0,96	0,039	0	0,002
Indirect and Direct Effects	761,917	575	0,842	0,96	0,039	0	0,064

Overall Model	χ^2	Df	p-value
Indirect Effect (Performance <-- I4.0 <-- LM)	765,233	576	0
Indirect and Direct Effects	761,900	575	0
Difference	**3,333**	**1**	**0,068**

Table 29: Sobel test: indirect effetct of LM on Performance through I4.0.

The test of $\chi 2$ difference with a p-value = 0,068 indicates that the complete model with mediations presents a better model fit. Despite of Sobel test to reject the possibility of indirect effect, it actually seems to exist. Probably the non-significance of LM<--Perf and I4.0<--Perf disturbed the results.

Because of Sobel test results, it is not possible to consider the existence of indirect effects of both, LM and I4.0 through each other on Organizational Performance. Hence, it is not desirable to confirm, statistically, the hypothesis H2.2.

However, the results demonstrated that the possibility of indirect effect's existence is not at all excluded, mainly regarding the I4.0 mediation. The main issue is that the non-significance of LM and I4.0 factors loading to Performance calls into question all the analysis.

Details of the analysis conducted on the present section are available on Appendix E and Appendix F.

Arguments to answer the first research question " Is the integrated approach of I4.0 and LM compatible?" , is found at all subsection of the conceptual framework. However, it is remarkable the similarities discussed on section 3.1 through the Lean principles and Industry 4.0 core competences and their common objective on value creation. Indeed the concepts and practices related to "Value Stream", "Flow", "Pull", "Perfection" and "People" of LM are well connected with the view of Horizontal and Vertical integration, continuous development and social infrastructure core competences of I4.0. Both approaches, I4.0 and LM, present similarities and chase continuous improvement of processes and products in order to satisfy customers with reduced non-value added charges.

The second research question "Does exist a correlation between I4.0 and LM?" is already answered at the introduction of the section 3. Indeed the literature has addressed different kinds of relationship of LM and I4.0. Briefly, the literature present on one perspective LM as the basis for I4.0 and in on another perspective the literature suggests that I4.0 can address some LM issues and then improve it.

In fact, the survey analysis confirmed the three hypothesis concerning LM and I4.0 mutual influences. The correlation between both was expected, however, its intensity (0,83) confirmed that there is no doubt of its compatibility and potential benefits.

The H1.2 is most related with the influence of LM maturity on I4.0 maturity. The survey analysis demonstrated that a positive impact of LM on I4.0 is plausible. Theoretically, academics pointed different reasons for it, such as: the change management experience; the lean thinking, the focus on creating integrated and organized processes with high level of standardization, transparency and simplicity; the capabilities of sharing information timely and accurately; and the ability to work on technical features, as in context of ERP, AMT and Automation implementation.

The H1.3 concerns the influence of I4.0 on LM maturity. The literature behind that hypothesis is based on two different perspectives. The first one looks to the I4.0 as a solution to overcome difficulties of LM management, to stabilize LM processes and to support LM practices. The other argues that I4.0 can complement LM by addressing market requests that is not filled by LM competences.

Indeed, the survey analysis presented evidence to believe in a high influence of I4.0 on LM. Besides the two possibilities of origin of this influence, it is important to mention that it could indicate that academics, who thinks that LM will disappear, could be wrong.

LM implementation, perhaps paralyzed by one company or another, could now gain momentum again. Some manufacturers believe that Industry 4.0 is a rebirth of Lean Management's principles as the process thinking gains relevance again. In addition, they are certain that technology-oriented 4.0 industry thinking fits with Lean's philosophy of value-oriented flow and thus the approaches complement each other perfectly (Staufen, 2016).[11]

[11] In die vielleicht bei dem einen oder anderen Unternehmen ins Stocken geratene Lean-Umsetzung könnte nun wieder in Schwung kommen. Denn vier von fünf Befragten (82 Prozent) meinen, dass Industrie 4.0 eine Renaissance für Lean-Management-Prinzipien bedeutet, da das prozessuale Denken wieder mehr Gewicht bekommt. Und nicht nur die Unternehmen, die im Bereich Industrie 4.0 bereits Erfahrungen haben, sind sich zudem absolut sicher, dass das technikorientierte Industrie-4.0-Denken hervorragend mit der am Wertstrom orientierten Lean Philosophie zusammenpasst und sich die Ansätze bestens ergänzen (Staufen, 2016).

6 Conclusion and Limitations

This research presented LM and I4.0 as two approaches that can be perfectly integrated. First, it was noticed from the literature review that the concepts, practices and goals of both approaches are compatible. Moreover, integrated applications have already been implemented.

Different associations of LM and I4.0 were identified on the literature. This work analyzed them from 3 different perspectives: "LM as the basis", "I4.0 as an enabler of LM", "I4.0 as a complement of LM and the integrated approach of LM and I4.0 as an evolution" and also analyzed the potential impact of the integrated approach on organizational performance.

Besides the theoretical research, a survey research was conducted to verify 5 hypothesis concerning LM and I4.0 integration. Three of them were related with the mutual effect of LM and I4.0 Maturity. The results indicate a high correlation between them. I4.0 appears as the main contributor on the LM regression. LM presented a positive influence on I4.0, however with lower intensity. These findings present an empirical evidence of LM and I4.0 correlation, moreover a score of 0,83 indicates that both approaches are almost inseparable.

No evidence was obtained to support the hypothesis of positive effect of both approaches on company's performance. Neither it was possible to verify if the integrated approach implies in higher performance than the results obtained by implementation of each methodology isolated.

Another contribution of this work was the development of a reliable and valid I4.0 assessment model. A model based on 12 dimensions were constructed and tested within a sample of 212 respondents.

It is important to highlight four limitations on the study. The non-statistical significance of LM and I4.0 factors loading on Organizational Performance was a constraint that should be exceeded in order to continue the analysis.

Despite of discussing possibilities of causality, the present study does not meet the requirements to do it. Besides statistical validation issues, the data analyzed were collected in a single moment. The evolution (difference in temporal space) between the variables has not been verified.

Although the survey has obtained responses from a reasonable sample size (212), it would be ideal to have at least 300 observations due to the size of the questionnaire.

The author is not specialist on SEM analysis, neither on AMOS software uses. The present study was developed at the same time as the author studied about the topics.

7 Future Directions:

- To Improve and to publish the I4.0 assessment model;
- To execute a 2^{nd} round of present study in order to collect more data and to initiate a temporal analysis;
- To report an Detailed analysis of Portuguese manufacturing regarding LM and I4.0 aspects correlating it with financial and operational performances. Could be done by cluster analysis identifying and explaining their Financial structural profile; Performance historic/behavior;
- To develop a framework for I4.0 Implementation considering an integrated approach with LM, indicating a best practices list of methodologies, techniques and technologies uses.

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Appendix A – Industry 4.0: Scale Developing and Validation.

1. INSTRUMENT DEVELOPMENT
- Topics selection through theoretical and literature review
- Questions selection through literature review
- Interview and pretest with with three academics and two industry experts

3. SAMPLE DOMAIN
- The same as this work.
- Portuguese comapanies
- More than 2Mi in tiurnove or 10 or more employees in 2017 (Small, medium and large sized enterprises)
- Manufacturing companies classified with primary code of NACE Rev 2[1] between 10 to 32
- Ideal Respondents: Directors and manager of any fiel of Operations or Administrators

2. Exploratory Factor Analysis with 88 items
- Data cleaning (Missing Values, Unengagement and Outliers)
- Sample size: 212.
- Preliminary convergent and divergent validity assessment.
- EFA with Maximum Likelihood approach and Promax rotation method with Kappa = 4.

- 25 itens eliminated.
- 12 dimensions well defined, similar to theoretical proposal.
Factors, loading and Cronbach listed on table below.

4. Confirmatory Factor Analysis
- Developped only for a reduced model and described on the Methodology section of this work.

Teste de KMO e Bartlett

Medida Kaiser-Meyer-Olkin de adequação de amostragem.		,896
Teste de esfericidade de Bartlett	Aprox. Qui-quadrado	9703,809
	gl	1953
	Sig.	,000

Variância total explicada (12 Fatores): 61,37%
Há 134 (6,0%) resíduos não redundantes com valores absolutos maiores que 0,05.

Matriz de padrão[a]

	Fator											
	1	2	3	4	5	6	7	8	9	10	11	12
STRG_16_MNG			,597									
LDRS_1_KCIS			,904									
LDRS_2_KCIS			,825									
LDRS_3_KCIS			,954									
LDRS_4_KCIS			,688									
LDRS_5_KCIS			,772									
PEOP_1_RESP			,588									
PEOP_2_RESP			,610									
STRG_7_EXEC				,842								
STRG_8_EXEC				,827								
STRG_11_EXEC				,626								
STRG_12_EXEC				,903								
STRG_13_EXEC				,829								
CULT_1_COLampPART										,394		
CULT_3_COLampPART										,455		
CULT_4_COLampPART										,552		
CULT_5_COLampPART										,656		
CULT_6_CHNG_ORG								,576				
CULT_7_CHNG_ORG								,612				
CULT_8_CHNG_ORG								,753				
CULT_9_CHNG_ORG								,957				
CULT_11_CHNG_PEOP							,770					
CULT_12_CHNG_PEOP							,758					
CULT_13_CHNG_PEOP							,718					
ICT_1_AUT												
ICT_2_DIG						,808						
ICT_3_DIG						,946						
ICT_4_DIG						,737						
ICT_5_DIG						,433						
ICT_7_DEC									,641			
ICT_8_DEC									,985			
ICT_9_DEC									,874			
ICT_10_DATA	,739											
ICT_11_DATA	,852											
ICT_12_DATA	,825											
ICT_13_DATA	,870											
ICT_14_DATA	,977											
ICT_15_DATA	,600											
ICT_16_DATA	,621											
ICT_17_SYS		,351										
ICT_18_SYS		,324										
ICT_20_SYS		,627										
ICT_21_SYS		,791										
ICT_22_SYS		,787										
ICT_23_SYS		,853										
ICT_24_SYS		,702										
ICT_25_SYS		,855										
ICT_27_SYS		,507										
TECH_3_NETW											,686	
TECH_4_CLOUD											,362	
TECH_5_CBSCRT											,765	
TECH_6_ANALYT											,728	
TECH_PEOP_AVG_COMP_TRN					,409							
TECH_2_EMBDSYS					,457							
TECH_7_AI					,611							
TECH_8_SIMUL					,799							
TECH_9_COLROB					,498							
TECH_10_AR					,558							
TECH_11_ADDMAN					,501							
TECH_12_MOBDVC					,357							
INT_1_VER												,777
INT_2_HOR												,831
INT_3_VIS												,337

Método de Extração: Máxima Verossimilhança.
Método de Rotação: Promax com Normalização de Kaiser.

a. Rotação convergida em 9 iterações.

Appendix B – Survey Questions

Lean Manufacturing Assessment questions

Question shortening	Question
Suppfeed_01	Relacionadas com os Fornecedores [Os nossos fornecedores visitam as nossas fábricas]
Suppfeed_02	Relacionadas com os Fornecedores [Nós visitamos as fábricas dos nossos fornecedores]
Suppfeed_03	Relacionadas com os Fornecedores [Damos aos nossos fornecedores feedback sobre a qualidade e o desempenho da entrega]
Suppfeed_04	Relacionadas com os Fornecedores [Esforçamo-nos para estabelecer um relacionamento de longo prazo com os nossos fornecedores]
SuppJIT_01	Relacionadas com os Fornecedores [Os fornecedores estão diretamente envolvidos no processo de desenvolvimento de novos produtos]
SuppJIT_02	Relacionadas com os Fornecedores [Os nossos principais fornecedores entregam na nossa fábrica numa base just-in-time (na altura agendada - nem adiantado, nem atrasado – e na quantidade solicitada)]
SuppJIT_03	[Temos um programa formal de certificação de fornecedores]
Suppdevt_01	Relacionadas com os Fornecedores [Discutimos questões estratégicas da nossa empresa com os nossos fornecedores chave]
Suppdevt_02	Relacionadas com os Fornecedores [Tomamos medidas ativas para diminuir o número de fornecedores em cada categoria de produto/consumíveis]
Suppdevt_03	Relacionadas com os Fornecedores [Os nossos principais fornecedores gerem o nosso inventário (relativo ao componente que fornecem)]
Suppdevt_04	[Os nossos fornecedores estão contratualmente comprometidos a reduções anuais de custos]
Suppdevt_05	[Os nossos principais fornecedores estão localizados nas proximidades da nossa fábrica]
Custinv_01	Relacionadas com os Clientes [Estamos em contacto estreito com os nossos clientes]
Custinv_02*	Relacionadas com os Clientes [Os nossos clientes visitam as nossas fábricas]
Custinv_03*	Relacionadas com os Clientes [Os nossos clientes providenciam feedback sobre a qualidade e o desempenho de nossa entrega de produtos]
Custinv_04*	Relacionadas com os Clientes [Os nossos clientes estão direta e ativamente envolvidos nas ofertas atuais e futuras de produtos da nossa empresa]
Custinv_05	Relacionadas com os Clientes [Os nossos clientes partilham informações com o departamento de marketing sobre as procuras atuais e futuras]
Custinv_06	Relacionadas com os Clientes [Realizamos questionários de satisfação do cliente]
Pull_01	Relacionadas com os Processos [As decisões de produção são tomadas apenas após a chegada de uma encomenda ou necessidade de produto intermédio (i.é, a produção é "puxada" pela expedição de produtos acabados)]

Pull_02	Relacionadas com os Processos [Usamos Kanbans (cartões), ou outros sinais para programação e controlo da produção]
Flow_01	Relacionadas com os Processos [Os produtos são classificados/organizados tendo em conta as semelhanças de processo produtivo]
Flow_02	Relacionadas com os Processos [O ritmo de produção está directamente ligado à taxa de procura de clientes]
Flow_03	Relacionadas com os Equipamentos [O equipamento é agrupado para produzir um fluxo contínuo de famílias de produtos, e portanto as famílias de produtos determinam o layout da fábrica]
Setup_01	Relacionadas com os Trabalhadores [Os nossos trabalhadores são treinados para reduzir o tempo necessário para o arranque (set-up) do equipamento]
Setup_02	[As máquinas na nossa fábrica apresentam baixos tempos de preparação (set-up)]
SPC_01*	Relacionadas com os Equipamentos [Utilizamos técnicas estatísticas para reduzir a variabilidade do processo produtivo]
SPC_02*	Relacionadas com os Equipamentos [Gráficos que mostram as taxas de defeitos são usados como ferramentas na área de produção]
SPC_03*	Relacionadas com os Equipamentos [Usamos diagramas do tipo espinha de peixe para identificar as causas dos problemas de qualidade]
SPC_04	Relacionadas com os Equipamentos [Realizamos estudos acerca da capacidade dos processos produtivos antes do lançamento do produto no mercado]
SPC_05	[Os nossos equipamentos/processos na área de produção estão atualmente a ser controlados utilizando uma ferramenta do tipo controlo estatístico da qualidade de processo]
Empinv_01*	Relacionadas com os Trabalhadores [Os trabalhadores da produção são fundamentais para as equipas de resolução de problemas]
Empinv_02*	Relacionadas com os Trabalhadores [Os trabalhadores da produção participam ativamente em programas de sugestões de melhoria dos produtos/processos]
Empinv_03*	Relacionadas com os Trabalhadores [Os trabalhadores da produção são submetidos a treinos multifuncionais]
TPM_01	Relacionadas com os Equipamentos [Dedicamos uma parte de cada dia para atividades de manutenção de equipamento planeadas]
TPM_02	Relacionadas com os Equipamentos [Temos registos rigorosos de todas as atividades relacionadas com a manutenção de equipamentos]
TPM_03	Relacionadas com os Equipamentos [Afixamos os registos de manutenção de equipamentos na área de produção para partilha ativa com os funcionários]

Industry 4.0 Assessment Questions

Question shortening	Question
LDRS_01*	A gestão de topo está interessada em implementar a digitalização
LDRS_02*	A gestão de topo tem o conhecimento necessário para tomar decisões acerca da implementação da digitalização.
LDRS_03*	A gestão de topo monitoriza a implementação da estratégia de digitalização.
LDRS_04*	Os recursos necessários para a implementação da digitalização são disponibilizados pela gestão do topo (recursos financeiros, humanos etc.).
LDRS_05	Qual é o nível de envolvimento e suporte da gestão de topo para a implementação da digitalização?
MNG_01	A empresa tem um plano estratégico para aumentar o nível de digitalização do negócio.
MNG_02	A implementação da digitalização é compatível com a estratégia, a missão e a visão da empresa.
MNG_03	As iniciativas de digitalização são 2s e implementadas de maneira coordenada entre as várias áreas da organização.
P_RESP_01	Como avalia as afirmações abaixo acerca da responsabilização dos colaboradores na implementação da digitalização? [Os colaboradores sentem-se responsáveis pela implementação da digitalização?]
P_RESP_02	Como avalia as afirmações abaixo acerca da responsabilização dos colaboradores na implementação da digitalização? [Os níveis hierárquicos formalmente definidos respondem por um objetivo específico de implementação da digitalização na avaliação de desempenho dos seus elementos?]
STKINFL_01	Em que grau as seguintes partes interessadas influenciam a sua empresa na implementação da digitalização? [Cliente e Consumidores]
STKINFL_02	Em que grau as seguintes partes interessadas influenciam a sua empresa na implementação da digitalização? [Competidores]
STKINFL_03	Em que grau as seguintes partes interessadas influenciam a sua empresa na implementação da digitalização? [Fornecedores]
STKINFL_04	Em que grau as seguintes partes interessadas influenciam a sua empresa na implementação da digitalização? [Governo/Legislação]
EXEC_01*	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Investigação e Desenvolvimento]
EXEC_02*	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Manufatura]
EXEC_03	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Compras]
EXEC_04	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Logística]
EXEC_05*	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Marketing e Vendas]
EXEC_06	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Pós vendas e Serviços]
EXEC_07	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Tecnologia da Informação]
EXEC_08	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Contabilidade e Finanças]

EXEC_09	Em que áreas de atividade, a empresa realizou ou pretende realizar investimentos relativos à implementação da digitalização? [Recursos Humanos]
PEOP_COMP_01	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Infra-estrutura de ICT]
PEOP_COMP_02	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Tecnologia de automação]
PEOP_COMP_03	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Desenvolvimento de aplicações e sistemas]
PEOP_COMP_04	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Computação na nuvem]
PEOP_COMP_05	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Análise de dados]
PEOP_COMP_06	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Inteligência artificial]
PEOP_COMP_07	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Simulação]
PEOP_COMP_08	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Realidade aumentada]
PEOP_COMP_09	Que conhecimento e competências têm os colaboradores sobre os requisitos para a implementação da digitalização da empresa? [Manufatura aditiva]
COL_PART_01	Como avalia as relações/parcerias/colaborações para o desenvolvimento das iniciativas de digitalização com os parceiros abaixo? [Universidades e centros de investigação]
COL_PART_02	Como avalia as relações/parcerias/colaborações para o desenvolvimento das iniciativas de digitalização com os parceiros abaixo? [Forncedores de Tecnologia]
COL_PART_03	Como avalia as relações/parcerias/colaborações para o desenvolvimento das iniciativas de digitalização com os parceiros abaixo? [Consultores]
COL_PART_04	Como avalia as relações/parcerias/colaborações para o desenvolvimento das iniciativas de digitalização com os parceiros abaixo? [Outros Fornecedores]
COL_PART_05	Como avalia as relações/parcerias/colaborações para o desenvolvimento das iniciativas de digitalização com os parceiros abaixo? [Clientes]
CHG_ORG_01	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspetiva da empresa)? [A empresa investe em capacitação/treino dos colaboradores.]
CHG_ORG_02*	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspetiva da empresa)? [A empresa investe em inovação de processos e produtos.]
CHG_ORG_03*	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspetiva da empresa)? [A empresa incentiva e implementa iniciativas inter-departamentais.]
CHG_ORG_04*	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspetiva da empresa)? [A empresa considera a gestão do conhecimento uma alta prioridade.]
CHG_PEO_01	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspectiva dos colaboradores)? [Quando ocorrem mudanças na organização, os gestores tentam geri-las mais do que queixar-se das mesmas.]
CHG_PEO_02	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspectiva dos colaboradores)? [Os colaboradores esforçam-se para aprender]
CHG_PEO_03	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspectiva dos colaboradores)? [Os colaboradores sugerem novas ideias e criam novas soluções]
CHG_PEO_04	Como avalia as afirmações abaixo a respeito da abertura à inovação e disposição para mudar (na perspectiva dos colaboradores)? [Os colaboradores aceitam com facilidade as mudanças (novos métodos de trabalho e uso de novas tecnologias)]
AUT_DIG_01	Qual é o nível de abrangência da automatização dos equipamentos e sistemas de produção?

AUT_DIG_02	Qual o nível de adaptabilidade das máquinas de produção para atender às mudanças dos requisitos de produção (ao nível de volume e tipo de produto)?
AUT_DIG_03	Os recursos (máquinas, linhas de produção, fábricas e produtos) possuem competências digitais avançadas? [Máquina]
AUT_DIG_04	Os recursos (máquinas, linhas de produção, fábricas e produtos) possuem competências digitais avançadas? [Linha/Célula]
AUT_DIG_05	Os recursos (máquinas, linhas de produção, fábricas e produtos) possuem competências digitais avançadas? [Fábrica]
AUT_DIG_06	Os recursos (máquinas, linhas de produção, fábricas e produtos) possuem competências digitais avançadas? [Produto]
PRO_DEC_01*	Como avalia o nível de implementação de iteração dos sistemas de produção? [M2M - Machine-to-Machine]
PRO_DEC_02*	Como avalia o nível de implementação de iteração dos sistemas de produção? [M2S - Machine-to-System]
PRO_DEC_03*	Como avalia o nível de implementação de iteração dos sistemas de produção? [S2S - System-to-System]
DATA_01*	Como avalia as afirmações abaixo acerca da recolha, processamento e armazenagem dos dados? [Os dados são recolhidos automaticamente]
DATA_02*	Como avalia as afirmações abaixo acerca da recolha, processamento e armazenagem dos dados? [Os dados são recolhidos em tempo real]
DATA_03*	Como avalia as afirmações abaixo acerca da recolha, processamento e armazenagem dos dados? [Os dados são armazenados em uma base única (Fonte única e confiável para os usuários)]
DATA_04*	Como avalia as afirmações abaixo acerca da recolha, processamento e armazenagem dos dados? [Os dados são processados de forma automática]
DATA_05*	Como avalia as afirmações abaixo acerca da recolha, processamento e armazenagem dos dados? [Os dados são processados em tempo real]
DATA_06	Como avalia as afirmações abaixo sobre o processamento dos dados recolhidos? [Os utilizadores confiam nos sistemas de informação e nas informações disponibilizadas]
DATA_07	Como avalia as afirmações abaixo sobre o processamento dos dados recolhidos? [As informações são disponibilizadas de forma amigável, sem necessidade de tratamento posterior]
SYSTEM_01	Quais são os sistemas de informação em utilização na empresa? [ERP – Enterprise Resource Planning]
SYSTEM_02	Quais são os sistemas de informação em utilização na empresa? [MES – Manufacturing Execution System or MOM - Manufacturing Operations Management]
SYSTEM_03	Quais são os sistemas de informação em utilização na empresa? [SCADA – Supervisory Control And Data Acquisition]
SYSTEM_04	Quais são os sistemas de informação em utilização na empresa? [PLM – Product Lifecycle Management]
SYSTEM_05*	Quais são os sistemas de informação em utilização na empresa? [PDM – Product Data Management]
SYSTEM_06*	Quais são os sistemas de informação em utilização na empresa? [PPS – Production Planning System]
SYSTEM_07*	Quais são os sistemas de informação em utilização na empresa? [WMS – Warehouse Management System]
SYSTEM_08	Quais são os sistemas de informação em utilização na empresa? [CRM – Customer Relationship Management]
SYSTEM_09	Quais são os sistemas de informação em utilização na empresa? [SCM – Supply Chain Management]
SYSTEM_10	Quais são os sistemas de informação em utilização na empresa? [CAD – Computer-Aided Design]

SYSTEM_11	Quais são os sistemas de informação em utilização na empresa? [Document management]
SYSTEM_12	Quais são os sistemas de informação em utilização na empresa? [Outro...]
TEC_SENS	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Sensores e atuadores inteligentes]
TEC_EMBDS	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Sistemas Embarcados (ex. IoT)]
TEC_NETW*	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Redes de Comunicação]
TECH_CLOUD	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Computação na nuvem]
TECH_CBSCRT*	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Segurança de Dados]
TEC_ANLYTC*	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Análise de dados]
TEC_AI	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Inteligência artificial]
TEC_SIMUL	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Simulação]
TEC_COLROB	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Robôs colaborativos]
TEC_AR	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Realidade aumentada]
TEC_ADDMAN	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Manufatura Aditiva]
TEC_MOBDVC	Quais são as tecnologias que estão a ser consideradas na estratégia da digitalização da empresa? [Dispositivos móveis (APP)]
INT_VERT	Como avalia o nível de integração da cadeia de valor da organização? [Integração Vertical (entre departamentos)]
INT_HOR	Como avalia o nível de integração da cadeia de valor da organização? [Integração Horizontal (com clientes e fornecedores)]
INT_VISIB	Como avalia a visibilidade da cadeia de abastecimento de ponta a ponta da organização (exemplo: dados de localização, capacidade, stock e operações)?

	Questions elimiated due construct incoherence or low loading on EFA 1.
	Questions eliminated on the second round of EFA, withboth models, I4.0 and LM.

* Question used on the final construct.

Appendix C – Metrics of Performance Measures

OPERATIONAL

$$Operational\ Cost = \frac{Turnover - EBITDA}{Turnover}$$

Equation 3: Operational Cost

$$Cost\ of\ goods\ sold = \frac{Cost\ of\ goods\ sold\ and\ consumption\ material}{Turnover}$$

Equation 4: Cost of goods sold

The Stock Turnover was collected directly from SABi.

MARKET

$$Market\ Share = \frac{Turnover}{\sum Turnover\ of\ active\ companies\ with\ the\ same\ CAE}$$

The Sales Turnover was collected directly from SABi.

FINANCIAL

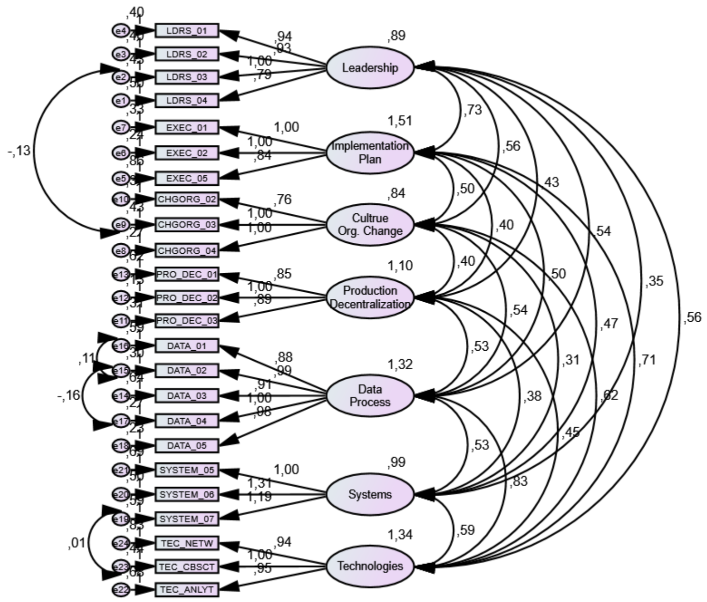
The Net Income and Return on Assets were collected directly from SABi.

$$Margin = \frac{EBIT(1-t)}{Turnover}$$

Appendix D – CFA Construct Validty: I4.0 and LM Instruments

Industry 4.0 1st order

Teste de KMO e Bartlett		
Medida Kaiser-Meyer-Olkin de adequação de amostragem.		0,889
Teste de esfericidade de Bartlett	Aprox. Qui-quadrado	3665,048
	gl	276
	Sig.	0,000



cmin=317,003; df=227; p-value=,000; GFI=,895; CFI=,975; RMSEA=,043

Correlations: (Group number 1 - Default model)

Relation			Estimate
LDRSP	<-->	IMPL_PL	0,628
LDRSP	<-->	CULT_CNGMGN	0,642
LDRSP	<-->	Decentralization	0,438
LDRSP	<-->	DATA_PROCESS	0,494
LDRSP	<-->	SYSTEMS	0,374
LDRSP	<-->	TECHNOLOGY	0,512
IMPL_PL	<-->	CULT_CNGMGN	0,445
IMPL_PL	<-->	Decentralization	0,306
IMPL_PL	<-->	DATA_PROCESS	0,357
IMPL_PL	<-->	SYSTEMS	0,385
IMPL_PL	<-->	TECHNOLOGY	0,499
CULT_CNGMGN	<-->	Decentralization	0,417
CULT_CNGMGN	<-->	DATA_PROCESS	0,513
CULT_CNGMGN	<-->	SYSTEMS	0,341
CULT_CNGMGN	<-->	TECHNOLOGY	0,588
Decentralization	<-->	DATA_PROCESS	0,439
Decentralization	<-->	SYSTEMS	0,362
Decentralization	<-->	TECHNOLOGY	0,369
DATA_PROCESS	<-->	SYSTEMS	0,465
DATA_PROCESS	<-->	TECHNOLOGY	0,622
SYSTEMS	<-->	TECHNOLOGY	0,515
e19	<-->	e23	0,016
e15	<-->	e17	-0,561
e15	<-->	e16	0,259
e2	<-->	e9	-0,307

Standardized Regression Weights: (Group number 1 - Default model)

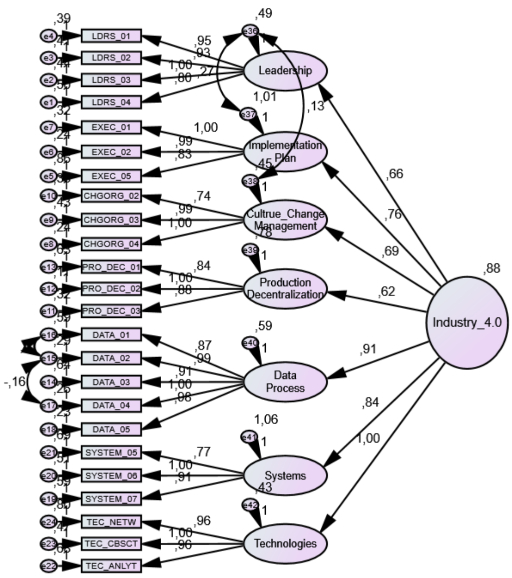
Relation			Estimate
LDRS_4_KCIS	<---	LDRSP	0,724
LDRS_3_KCIS	<---	LDRSP	0,82
LDRS_2_KCIS	<---	LDRSP	0,812
LDRS_1_KCIS	<---	LDRSP	0,815
STRG_11_EXEC	<---	IMPL_PL	0,743
STRG_8_EXEC	<---	IMPL_PL	0,929
STRG_7_EXEC	<---	IMPL_PL	0,906
CULT_9_CHNG_ORG	<---	CULT_CNGMGN	0,87
CULT_8_CHNG_ORG	<---	CULT_CNGMGN	0,815
CULT_7_CHNG_ORG	<---	CULT_CNGMGN	0,753

Relation			Estimate
ICT_9_DEC	<---	Decentralization	0,86
ICT_8_DEC	<---	Decentralization	0,947
ICT_7_DEC	<---	Decentralization	0,75
ICT_24_SYS	<---	SYSTEMS	0,703
ICT_23_SYS	<---	SYSTEMS	0,836
ICT_22_SYS	<---	SYSTEMS	0,878
TECH_6_ANALYT	<---	TECHNOLOGY	0,799
TECH_5_CBSCRT	<---	TECHNOLOGY	0,865
TECH_3_NETW	<---	TECHNOLOGY	0,764

Relation			Estimate
ICT_12_DATA	<---	DATA_PROCESS	0,796
ICT_11_DATA	<---	DATA_PROCESS	0,903
ICT_10_DATA	<---	DATA_PROCESS	0,795
ICT_13_DATA	<---	DATA_PROCESS	0,912
ICT_14_DATA	<---	DATA_PROCESS	0,921

The average standardized factor loading is 0,83 with a minimum of 0,703. Estimated correlations between the factors are not excessively high, the highest is 0,63.

Industry 4.0 2nd Order



cmin=345,199; df=241; p-value=,000; GFI=,887; CFI=,971; RMSEA=,045

Standardized Regression Weights: (Group number 1 - Default model)

Relation			Estimate
LDRSP	<---	I4.0	0,666
IMPL_PL	<---	I4.0	0,578
CULT_CNGMGN	<---	I4.0	0,694
Decentralization	<---	I4.0	0,548
DATA_PROCESS	<---	I4.0	0,743
SYSTEMS	<---	I4.0	0,608
TECHNOLOGY	<---	I4.0	0,818
LDRS_04	<---	LDRSP	0,725
LDRS_03	<---	LDRSP	0,815
LDRS_02	<---	LDRSP	0,806
LDRS_01	<---	LDRSP	0,82

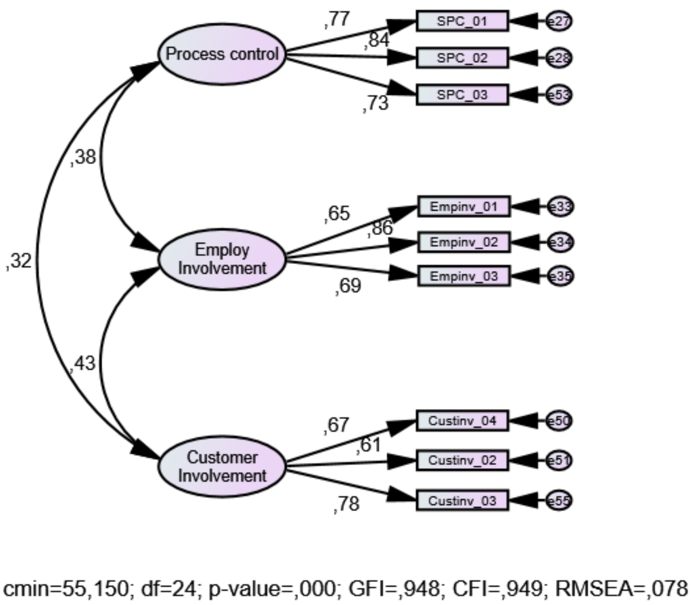
Relation			Estimate
EXEC_05	<---	IMPL_PL	0,743
EXEC_02	<---	IMPL_PL	0,927
EXEC_01	<---	IMPL_PL	0,908
CHGORG_04	<---	CULT_CNGMGN	0,884
CHGORG_03	<---	CULT_CNGMGN	0,815
CHGORG_02	<---	CULT_CNGMGN	0,747
PRO_DEC_03	<---	Decentralization	0,855
PRO_DEC_02	<---	Decentralization	0,954
PRO_DEC_01	<---	Decentralization	0,747

Relation			Estimate
DATA_03	<---	DATA_PROCESS	0,796
DATA_02	<---	DATA_PROCESS	0,904
DATA_01	<---	DATA_PROCESS	0,794
DATA_04	<---	DATA_PROCESS	0,913
DATA_05	<---	DATA_PROCESS	0,92
SYSTEM_07	<---	SYSTEMS	0,839
SYSTEM_06	<---	SYSTEMS	0,877
SYSTEM_05	<---	SYSTEMS	0,767
TEC_ANLYT	<---	TECHNOLOGY	0,802
TEC_CBSCT	<---	TECHNOLOGY	0,859
TEC_NETW	<---	TECHNOLOGY	0,777

The average standardized factor loading is 0,79 with a minimum of 0,548. Estimated correlations between the factors are not excessively high, the highest is 0,63.

Lean Manufacturing 1st order

Teste de KMO e Bartlett		
Medida Kaiser-Meyer-Olkin de adequação de amostragem.		0,761
Teste de esfericidade de Bartlett	Aprox. Qui-quadrado	634,044
	gl	36
	Sig.	0,000



Standardized Regression Weights: (Group number 1 - Default model)

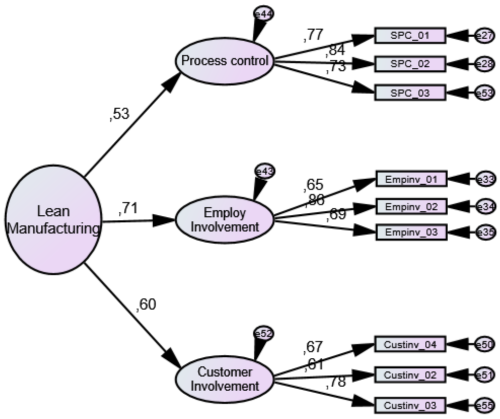
Relation			Estimate
SPC_01	<---	SPC	0,771
SPC_02	<---	SPC	0,837
Empinv_01	<---	EMPINV	0,654
Empinv_02	<---	EMPINV	0,865
Empinv_03	<---	EMPINV	0,686
Custinv_04	<---	Customer	0,669
Custinv_02	<---	Customer	0,606
SPC_03	<---	SPC	0,727
Custinv_03	<---	Customer	0,781

Correlations: (Group number 1 - Default model)

Relation			Estimate
SPC	<-->	EMPINV	0,381
SPC	<-->	Customer	0,32
EMPINV	<-->	Customer	0,427

The average standardized factor loading is 0,73 with a minimum of 0,606. Estimated correlations between the factors are not excessively high, the highest is 0,42.

Lean Manufacturing 2nd order



cmin=55,150; df=24; p-value=,000; GFI=,948; CFI=,949; RMSEA=,078

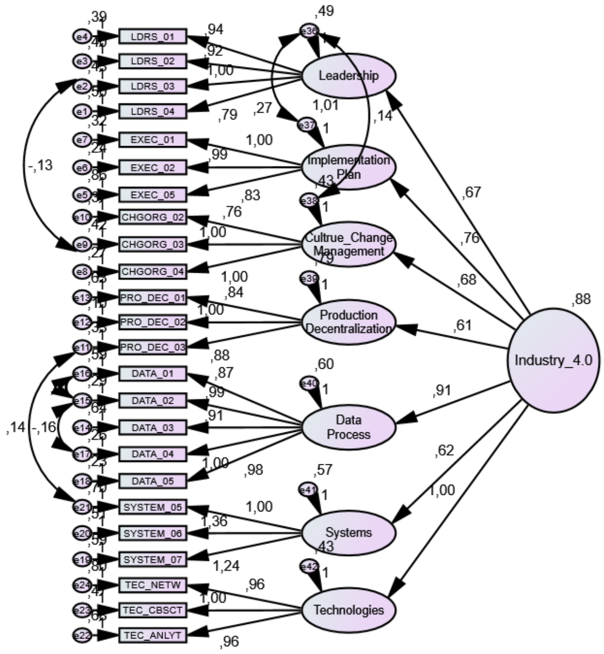
Standardized Regression Weights: (Group number 1 - Default model)

Relation			Estimate
SPC	<---	LM	0,535
EMPINV	<---	LM	0,713
Customer	<---	LM	0,599
SPC_01	<---	SPC	0,771
SPC_02	<---	SPC	0,837
Empinv_01	<---	EMPINV	0,654
Empinv_02	<---	EMPINV	0,865
Empinv_03	<---	EMPINV	0,686
Custinv_04	<---	Customer	0,669
Custinv_02	<---	Customer	0,606
SPC_03	<---	SPC	0,727
Custinv_03	<---	Customer	0,781

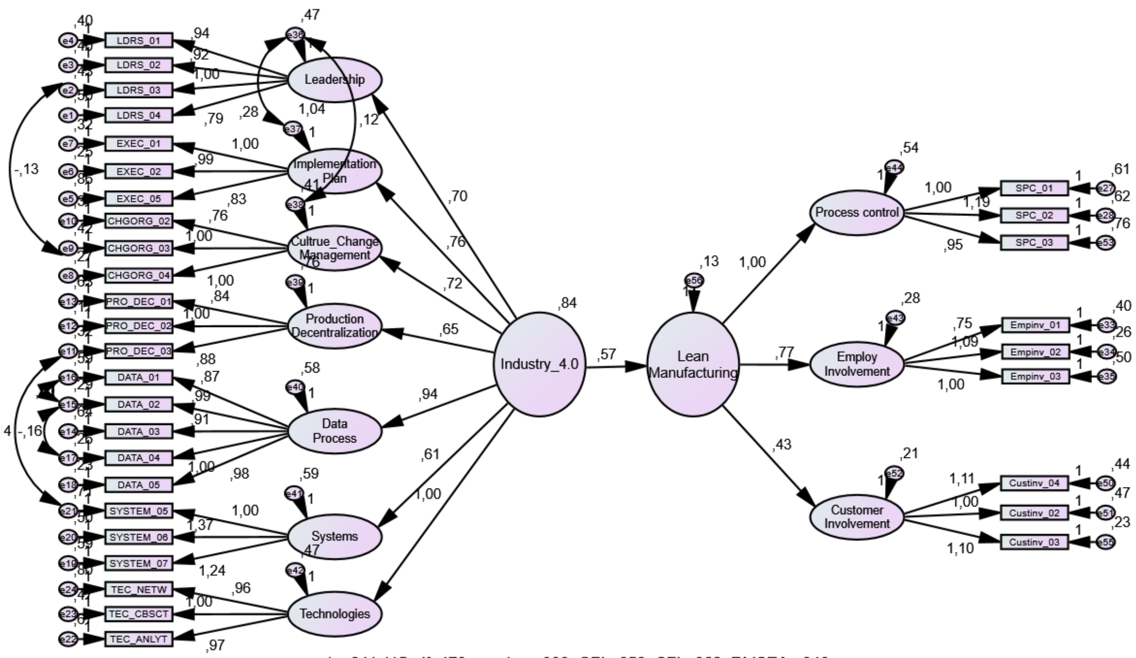
The average standardized factor loading is 0,70 with a minimum of 0,535. Estimated correlations between the factors are not excessively high, the highest is 0,42.

Appendix E – Supported Method to Test H1.

Influence of Lean Manufacturing on Industry 4.0 Maturity

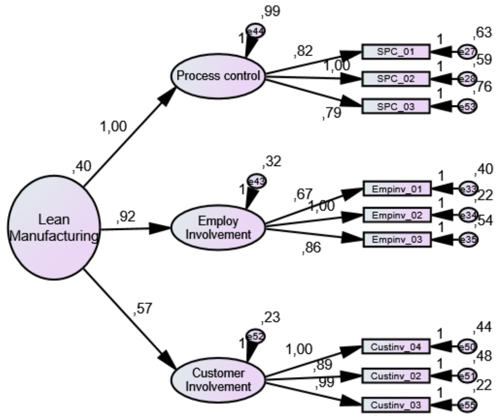


cmin=320,588; df=239; p-value=,000; GFI=,894; CFI=,977; RMSEA=,040

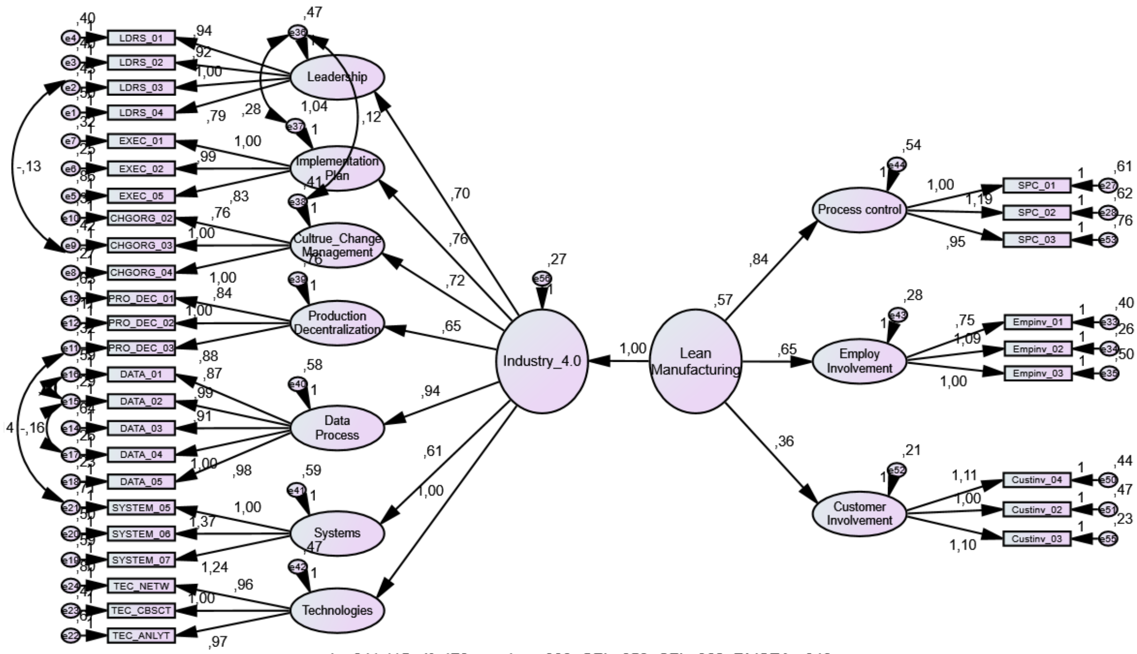


cmin=641,115; df=478; p-value=,000; GFI=,853; CFI=,962; RMSEA=,040

Influence of Industry 4.0 on Lean Manufacturing Maturity



cmin=55,150; df=24; p-value=,000; GFI=,948; CFI=,949; RMSEA=,078

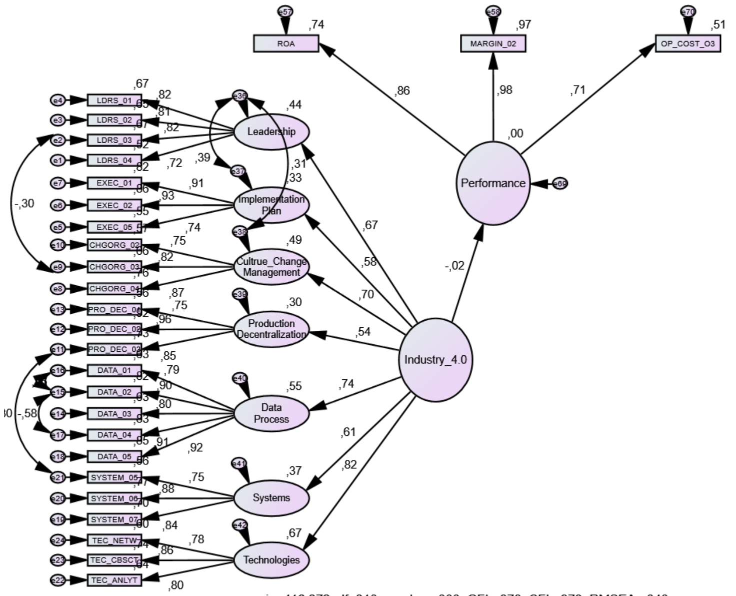


cmin=641,115; df=478; p-value=,000; GFI=,853; CFI=,962; RMSEA=,040

Appendix F – Supported Method to Test H2.

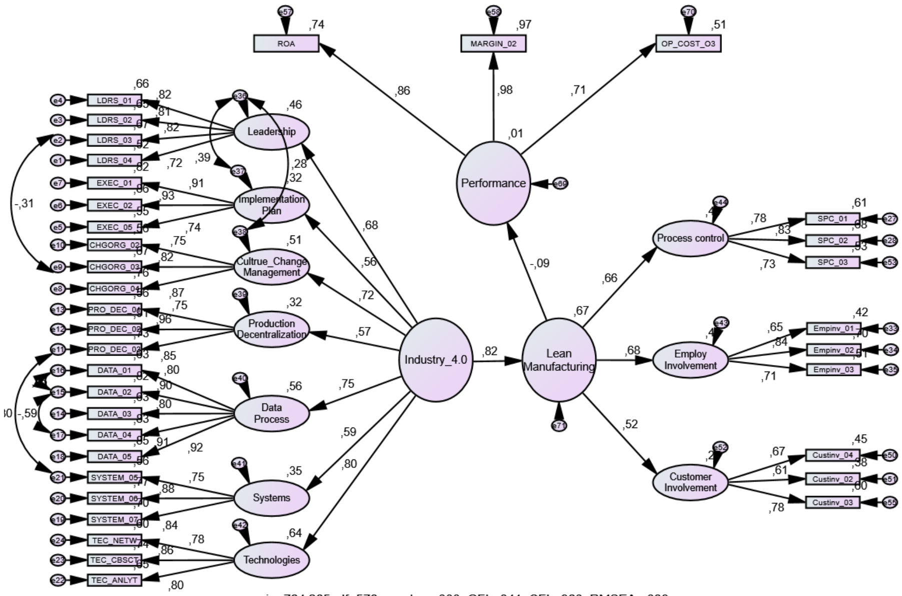
LM Mediation

Direct Effect



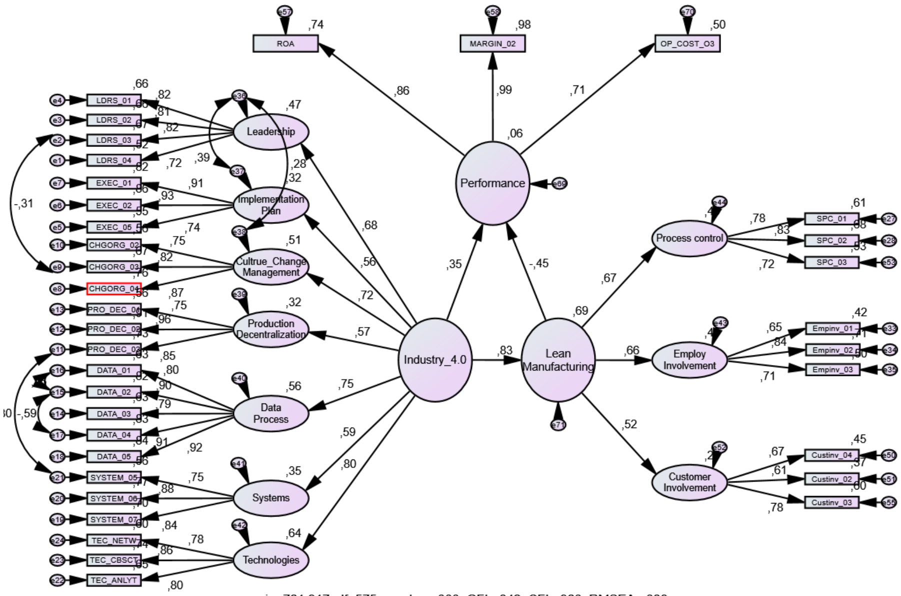
cmin=416,372; df=310; p-value=,000; GFI=,878; CFI=,973; RMSEA=,040

Indirect Effect



cmin=764,265; df=576; p-value=,000; GFI=,841; CFI=,960; RMSEA=,039

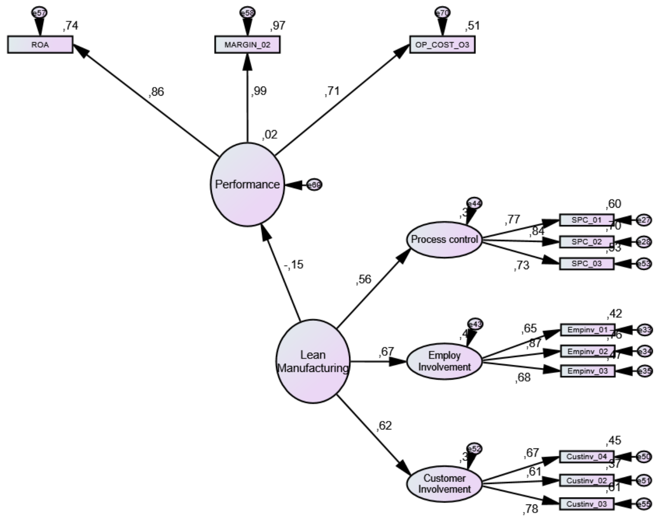
Direct and Indirect Effect



cmin=761,917; df=575; p-value=,000; GFI=,842; CFI=,960; RMSEA=,039

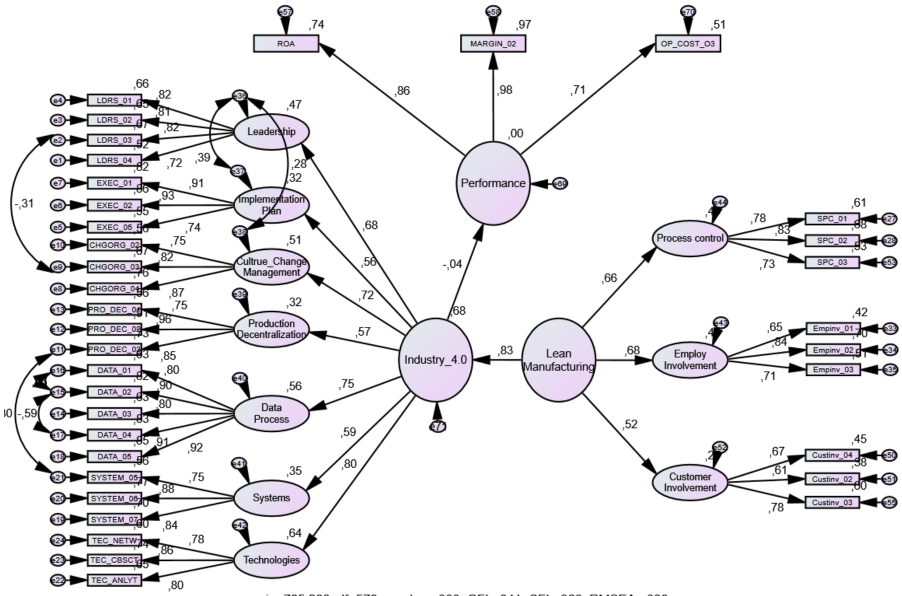
Industry 4.0 mediation

Direct Effect



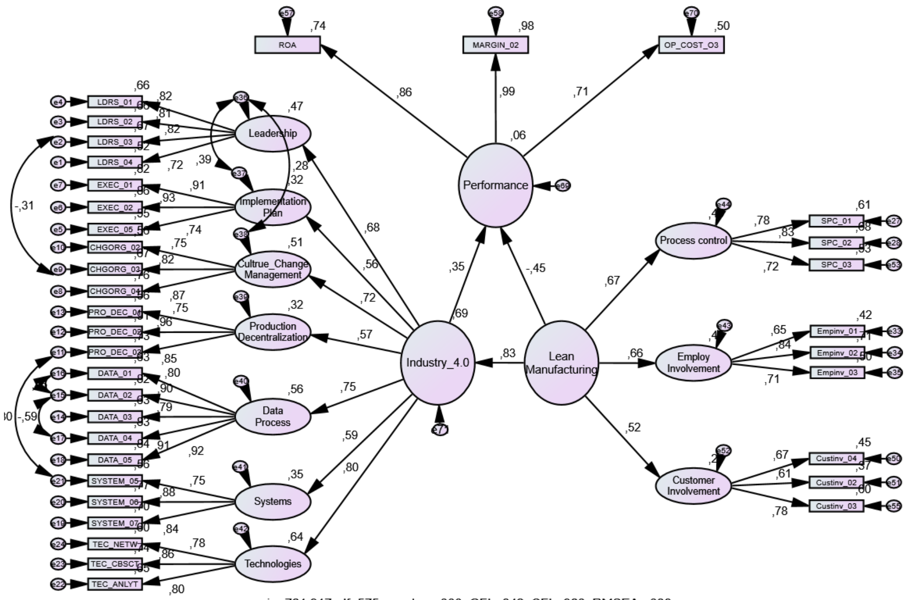
cmin=74,580; df=50; p-value=,014; GFI=,948; CFI=,976; RMSEA=,048

Indirect Effect



cmin=765,233; df=576; p-value=,000; GFI=,841; CFI=,960; RMSEA=,039

Direct and Indirect Effects



cmin=761,917; df=575; p-value=,000; GFI=,842; CFI=,960; RMSEA=,039

Appendix G

REGION	PROGRAM	YEAR	DESCRIPTION
North America	Industrial Internet	2014	Technical basis is very similar to Industry 4.0, but the application is broader than industrial production and also includes, e.g., smart electrical grids
European Commission	Public-Private Partnership (PPP) on 'Factories of the Future (FoF)	2014	It is under the Horizon 2020 programme that plans to provide nearly 80 billion euros of available funding over 7 years (from 2014 to 2020)
United States (US)	Advanced Manufacturing Partnership (AMP)	2011	To ensure the US to be prepared to lead the next generation of manufacturing
German	High-Tech Strategy 2020	2012	Plan to development of cutting-edge technologies. 'Industrie 4.0' represents the German ambitions in the manufacturing sector
France	La Nouvelle France Industrielle	2013	34 sector-based initiatives are defined as France's industrial policy priorities
United Kingdom (UK)	Future of Manufacturing	2013	Long-term picture for its manufacturing sector until the year of 2050. It aims to provide a refocused and rebalanced policy for supporting the growth and resilience of UK manufacturing over the coming decades
South Korea	Innovation in Manufacturing 3.0	2014	That emphasised four propulsion strategies and assignments for a new leap of Korean manufacturing
China	Made in China 2025 strategy alongside the 'Internet Plus'	2015	It prioritises ten fields in the manufacturing sector to accelerate the informatization and industrialisation in China
Japan	5th Science and Technology Basic Plan	2015	Particular attentions have been paid to the manufacturing sector for realising its world-leading 'Super Smart Society'
Singapore	RIE 2020 Plan (Research, Innovation and Enterprise)	2016	Eight key industry vertical have been identified within the advanced manufacturing and engineering domain

Governments and Industries worldwide development programs. (Drath & Horch, 2014; Liao et al., 2017; Stock & Seliger, 2016)

Appendix H

Dimensions of Lean Manufacturing	Challenges for lean implementation from integration perspective	Solutions provided by Industry 4.0
Supplier feedback	Limited expertise and resources	Collaborative manufacturing
	Difference in business models, operation and data maintenance practices	Better communication mechanisms
		Synchronisation of data
JIT delivery by suppliers	Incomplete goods' shipping status	Item tagging
	Mismatch in quantity of transported goods	Wireless tracking of goods
	Unexpected delays during transportation	Smart reallocation of order
Supplier development	Inadequate resources and expertise	Standardised interfaces
	Equipment compatibility between organisations	Virtual organisations - synergetic cooperation
Customer involvement	Little flexibility for product alteration	Elongated freeze period
	Relationship between needs and functions	Large volume QFD
	Acquiring exact customer needs	Usage analysis
Pull production	Improper track of supplied material quantity	Material replenishment monitoring
	Changes in production schedule	Schedule tracking and kanban updating
Continuous flow	Errors in inventory counting	Real-time inventory tracking
	Capacity shortages	Subcontracting
	Centralised control systems	Decentralised decision making
Setup time reduction	Human experience-based process adaptation	Self-optimisation & machine learning
		Workpiece-machine communication
Total productive/preventive maintenance	No control of machine breakdown	Machine-worker communication
	Unknown problem solving time	Self-maintenance assessment
		Predictive maintenance control system
Statistical process control	Ignorance of operators	Workpiece-machine communication
	Inability to track process variations	Improved man-machine interface
		Process tracking, integration & management
Employee involvement	Improper feedback mechanisms	Smart feedback devices
	Performance evaluation practices	Worker support systems
	Monotony in work	Improved man-machine interface

Summary of lean dimensions, challenges and solutions. (Sanders et al., 2016)