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LEAN MANUFACTURING, INDUSTRY 4.0 AND SUSTAINABILITY: ESTABLISHING A RESEARCH AGENDA

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Abstract: The current competitive environment of manufacturing is characterized by, among other things, increasing global competition, shorter product life cycles and increasing individualization of products. This puts pressure on the flexibility of manufacturing companies and on the efficiency of their resources to meet customer demand and stay competitive. To meet these challenges, companies are forced to continually innovate and improve their operations management strategies and processes. Lean manufacturing has been the most prominent methodology for improving the operational performance in manufacturing companies for several decades. Similarly, industry 4.0 is one of the most promising approaches to meet future challenges in the production environment. Different approaches are considered in the literature to analyze the link between these two domains. However, few studies investigate how these philosophies should be integrated to offer a streamlined and high quality transformation process, and their respective influence on the three main pillars of sustainability: economic, environmental, and social. The purpose of this paper is to present a review and analysis of the literature on the relationship between these three management systems. A conceptual framework for an integrative approach to LM, I4.0 and sustainability is also developed, pointing out the achievements and the gaps found in the literature.

Keywords: lean manufacturing, industry 4.0, sustainability, review, conceptual model

INTRODUCTION

Sustainability is the ability to meet current needs without compromising the ability of future generations to meet theirs, ensuring the balance between economic growth, environmental care and social well-being. This concept became widely used three decades ago after the consequences of human activities to the Earth's ecosystems had been realized. These were recorded from the first industrial revolution inevitably correlating those issues with industrial development [18]. Despite the multiple studies carried out, it is still difficult to choose the criteria and strategies that allow characterizing, evaluating and achieving an adequate degree of sustainability in the organization.

Based on current research, Lean Manufacturing (LM) and Industry 4.0 (I4.0) strategies are promising in this regard. In the literature, there are works on separate effects of LM and I4.0 on Sustainability, as well as high compatibility between both, where one strategy comprehends the use of another. However, only a few articles consider the integrated eff and mostly lack empirical validation [13].

LM has been defined as an integrated set of socio-technical practices designed to eliminate waste along the whole of the value chain within and across companies by focusing on the activities that create value for the customer. [12]. Since its introduction, the lean approach has increasingly expanded in the field of operations management until it has now become a fully holistic business strategy [5].Numerous tools, techniques and practices have been developed over time for this approach to be implemented, and many others that already existed have easily slotted into Lean's broader focus. its features are not restricted to the elimination of waste but cover the optimization of many manufacturing processes from product development to distribution.

According to a survey released in 2007, almost 70% of American manufacturing plants have implemented some form of lean manufacturing project [21]. While, a survey from Germany reports that over 90% of the surveyed manufacturing companies claim to have initiated a lean manufacturing initiative [9].

However, given the increasing complexity of operations, many companies have found that LM by itself is not sufficient to address their operational challenges.

Recently, a set of advanced digital technologies known as I4.0 has emerged to offer new approaches for dealing with complexity and improving productivity. By deploying the right combination of technologies, manufacturers can boost speed, efficiency, and coordination and even facilitate self-managing factory operations.

The I4.0 is the first industrial revolution to be announced in advance. Although a great opportunity to shape and optimize the solutions before they are fully released, the lack of empirical data makes the research highly theoretical or aimed at implementing solutions to very specific problems. All in all, I4.0 is seen as the future of manufacturing and is presented as a concept that manufacturers need to embrace to stay competitive.

The purpose of this study is, therefore, to explore the relationship of Lean and I4.0 with respect to sustainability from the review of the existing literature, analyze current proposals, identify gaps and define future lines of research.

Following this introduction, the study was divided into three parts. The following section "Materials and methods" exposes the main concepts about LM, I4.0 and sustainability, it also describes the methodological approach followed to

develop an adequate review of the literature. The third section is dedicated to outlining the main influences of LM and I4.0 on the three dimensions of sustainability. A conceptual framework for an integrative approach to LM, I4.0 and sustainability is also developed, pointing out the achievements and the gaps found in the literature. Finally, the conclusions focus on challenges that future research should address.

MATERIALS AND METHODS

This section aims to present a summary of the concepts which guided the selection and analysis of the papers in order to summarize a construct about the links between LM, I4.0 and sustainability.

— Lean Manufacturing

LM has been defined in many different ways. One reason for the lack of a coherent definition might be that the concept is still evolving [11]. However, the main goal of a lean system is to produce products or services of higher quality at the lowest cost and in the least time by eliminating wastes. In the lean context, waste (Muda) is any activity that consumes resources and time but does not create value.

A lean concept, in general, considers seven main losses: overproduction, defects, waiting, over-processing, unnecessary or ineffective inventory, motion or non-value-generating activities, and transportation, where each of these has sustainability impact. In theory, the likelihood of a philosophy like Lean that stands for the elimination of waste to support sustainability is high. Several works arrive at the same conclusion [15, 26]. However, eliminating what Lean perceives as waste does not always necessarily improve sustainability performance [7].

Apart from a holistic management focus based on a number of objectives and principles, lean also encompasses a set of practices, tools, techniques and methodologies. LM includes many tools, e.g., Muda, Jidoka, Just-in-Time (JIT), Value Stream Mapping (VSM), Kanban, Poka Yoke, Kaizen, 5S system, Root-case analysis, Zero defects. To understand how this affects sustainability, each principle and its impact should be considered.

LM may be viewed as a configuration of practices/tools because the relationships among the elements of LM are neither explicit nor precise in terms of linearity or causality. A configuration approach helps to explain how a lean system is designed from the interaction of its constituent elements taken as a whole, as opposed to designing the system one element at a time. From a theoretical standpoint, lean management is seen as a tightly coupled system where the constituent elements hold together in mutual dependence. It is the self-reinforcing effects of this kind of mutual dependence that contribute to the superior performance associated with lean management on the one hand and make it rare, valuable and difficult to imitate by competitors on the other hand [25].

— Industry 4.0

Several elements within the I4.0 concept have been handled: integration of complex machinery and devices, with software networks and sensors, used to predict, control, improve the business and its impact on society [19]; new level of organization and management of the value chain throughout the product life cycle [22]; holistic system of IT, people, machines and tools, which allows the flow of goods, services and data in a controlled way, through the value chain, with operations of a high degree of autonomy and capacity to transmit useful information in the decision making [23].

I4.0 concept is associated with the technical perspective of a Cyber Physical System (CPS) integrated into manufacturing operations and with Internet of Things (IoT) technologies into the industrial processes, which can be represented by smart factories, smart products, and extended value networks – vertical, horizontal and end-to-end integration.

This phenomenon will be the most powerful driver of innovation over the next few decades triggering the next wave of innovation [15].

Different authors state that the I4.0 can support value creation in all sustainability dimensions and, in this matter, they identify opportunities for industry development considering: development of business models driven by smart data, offering new product-services; closed-loop product life cycles and industry symbiosis creating value networks; equipment using CPS for retrofifitting SMEs (Small- and Medium-sized Enterprises) digitization; trainings and competence development supported by ICT technologies; motivation and creativity fomented by programs supported by CPS; sustainable-oriented decentralized organization focused on resource efficiency; sustainable process design using new technologies promoting closed-loop life cycles and cradle-to-cradle approaches [4].

To support effects of a solution on the sustainability dimensions, each sustainability dimension represents a specific system evolving around a digital value-creation solution, so one adopted solution can create direct impacts on one dimension system, but also have indirect effects on the other dimension systems of sustainability. The interactions between sustainability systems can occur in three different types: causal relations (effects between a solution and its direct and indirect impacts); magnitude and scale driver (direct and indirect impact is determined by the magnitude and scale of a solution's dissemination); and latency and timely duration dependencies (between effects and impacts) [10].

— Sustainable manufacturing

Sustainable Manufacturing can be defined as the integration of processes and systems capable to produce high quality products and services using less unsustainable resources and more sustainable resources, being safer for employees, customers and communities surrounding, and being able to

mitigate environmental and social impacts throughout its whole life cycle [3, 10].

This author defines the sustainable manufacturing scope in four areas with its respective objects and applied disciplines:

- Manufacturing technologies (how things are manufactured) with focus on process and equipment (machine-tool, facility);
- Product life cycles (what is to be produced) with focus on product and services' design;
- Value creation networks (organizational context) with focus on organizations of companies and manufacturing networks;
- Global manufacturing impacts (transition mechanisms towards sustainable manufacturing) with focus on studies about manufacturing impacts on the world, including society, environment, and economy.

Different aspects can contribute to a positive sustainable manufacturing strategy implementation, among others, the development of sustainability indicators, policies and procedures, company's cultures and internal conditions for sustainability, sustainable design strategies, and stakeholders' engagement for sustainability and technologies [2].

There are no criteria/KPI or universal models that can characterize and evaluate the degree of sustainability of an organization. Sustainability is therefore measured through indirect quantitative parameters using the triple bottom line (TBL) approach consisting of economic, environmental, and social pillars.

SYSTEMATIC LITERATURE REVIEW

The primary approach used in the study is a systematic literature review. This method has numerous advantages compared with traditional unstructured reviews. It adopts a replicable, scientific and transparent process that allows: minimization of bias and errors; improvement in the quality of the review process and outcomes; confirmation of their validity through the replication of clear steps during the review process; and synthesizing and organizing the literature accumulated in a specific field, often providing academics and practitioners with frameworks of the existing knowledge.

A structured process was adopted according to the sequence o outlined below:

Scopus was used as the index from which to identify documents for this review. Scopus offers a wide coverage of disciplines that were deemed relevant to the interaction LM, I4.0 and sustainability as well as access to bibliographic data used by bibliometric software.

The 'source' of documents was left open-ended during the search as opposed to predefining a specific set of journals. In terms of 'types of documents', the review included articles, conferences, and book chapters. The search is framed in the period of time between the years 2010-2022.

This approach assumed that authors writing on this topic 'self-organized' the literature through the use of terms used to describe their research in the title, abstract, and keywords of their papers.

The following string of keywords is used to generate the initial database of documents in Scopus. Several existing terminologies to refer to both LM and I4.0 are considered to perform the search. As well as the terminology referring to sustainability, sustainable development and the three axes of the TBL.

TITLE-ABS-KEY ('industry 4.0' OR 'cyber physical production system' OR 'digitalization' OR 'smart manufacturing' OR 'smart production' OR 'smart factory') AND TITLE-ABS-KEY ('lean' OR 'lean manufacturing' OR 'lean management' OR 'lean production') AND TITLE-ABS-KEY ('sustainability' OR 'sustainability development' OR 'operational sustainability' OR 'environmental sustainability' OR 'social sustainability')

This search returned 88 documents. Scopus filters were used to filter documents based on broad categories (language: English, publication stage: final), reducing the database to 72 articles, 18 subject area, 46 publication sources, 231 authors, 2 345 references.

The convergence of LM, I4.0 and sustainability is a topic which has evolved in recent years, and papers' distribution indicates an evolutionary trend compatible with a new research field (figure 1).

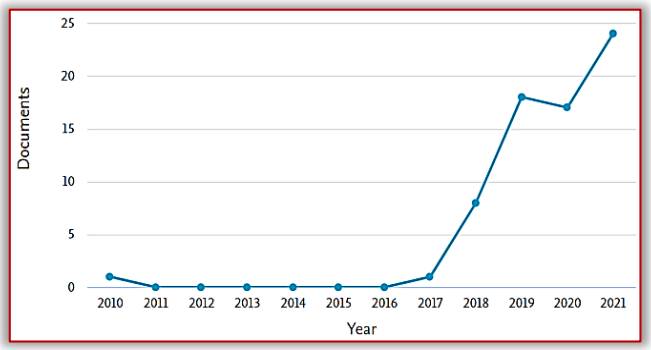

Figure 1. Distribution of articles by year

As identified several authors [6,8], the scope and disciplines concerned with sustainable manufacturing are multidisciplinary, and the same trend is being applied in the context of the I4.0. Figure 2 shows the documents organized by subject area. The most representative areas are those referred to: engineering (25.4%), business, management and accounting (16.2%) and computer science (14.5%).

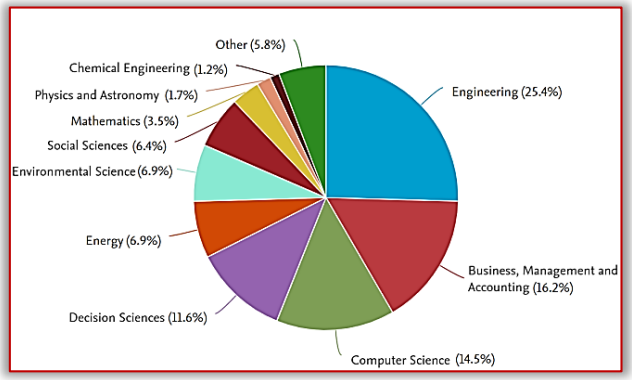

Figure 2. Distribution by subject area

The list of journals and conferences more representative in the sample is available on Figure 3, allowing to identify allowing to identify the most relevant journals in the last 5 years.

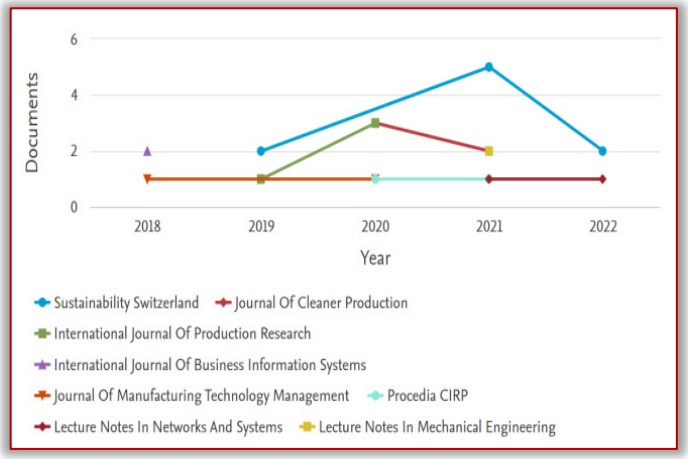

Figure 3. Documents per years by source

Analysis of keywords co-occurrence was the bibliometric method used to map the research field. The process of creating keywords networks and clustering keywords was supported with the use of the VOS viewer application, developed by the Centre for Science and Technology Studies of the University of Leiden, the Netherlands.

The papers comprising the research sample provide 189 keywords. The most often cited expressions are: industry 4.0 (54), sustainability (48) and manufacturing (26). The minimum number of occurrence of keyword is 2, in consequence, the number of high-frequency keywords in the co-occurrence network is 172, for building a network with 6 cluster, 1442 links and 1481 total link strength. In the map the size of nodes manifests the frequency of keyword's occurrence, while lines show relationships among keywords (see Figure 4).

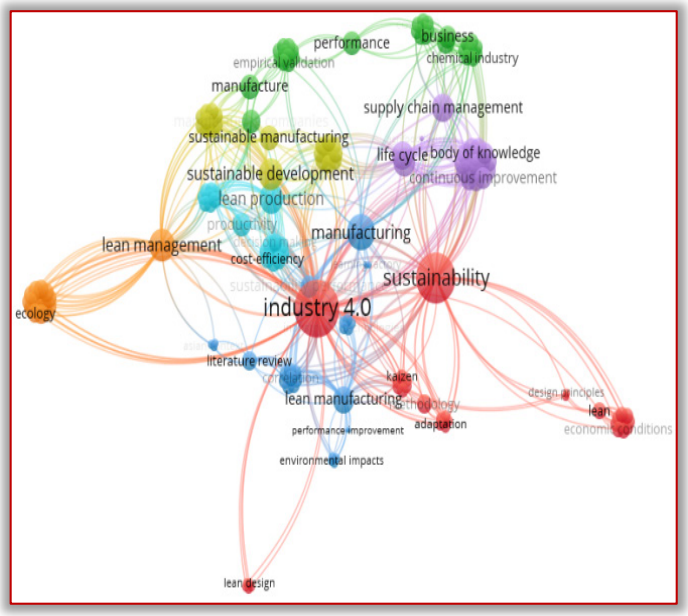

Figure 4. Keywords' Network visualization

- red cluster: I4.0 enablers and some LM tools increase sustainability
- orange: sustainable smart production. lean production practices and waste elimination at all stages of the life cycle, ecological impact
- green cluster: management system and impact on business performance.
- purple cluster: sustainable design and life cycle assessment. supply chain management
- yellow cluster: sustainable value creation for smart factories
- blue cluster: lean manufacturing practices and impact on the different edges of sustainability.

An analysis of the visualization overlay network shows that this is a recent research area, where the most current themes focus on designing new business models and measuring the impact on operational performance, social and environmental impact (Figure 5). It is not until 2020 that a greater interaction between LM, I4.0 and business sustainability can be seen in the reviewed literature.

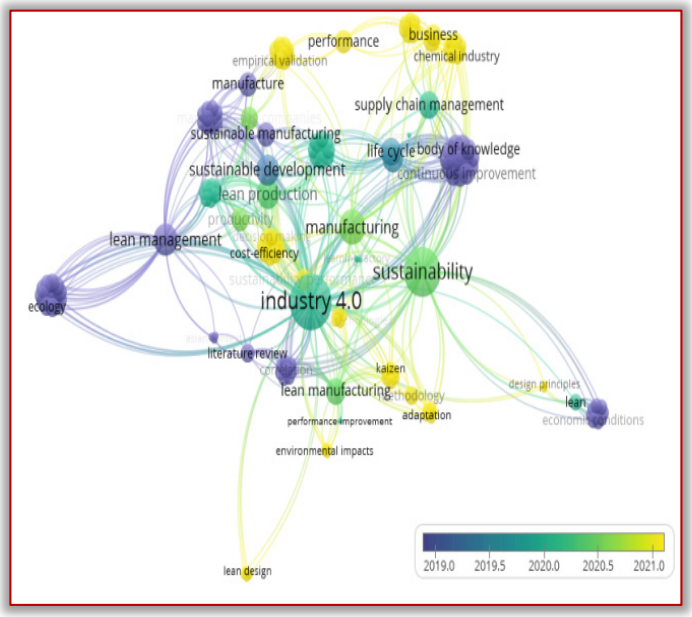

Figure 5: Keywords' Network overlay visualization

RESULTS AND ANALYSIS

Based on the reviewed literature on LM and I4.0 interconnection, the perspectives could be grouped into three categories: LM as a basis to I4.0, I4.0 enhances LM and positive correlation between the two. The third perspective stating that current demand for digitalization needs an extension of the lean production system to integrate new technologies on the shop floor. The combination of lean and I4.0 is argued to not only bring short-term operational excellence but also to contribute to long-term sustainability.

— Lean Manufacturing and Sustainability

This sections discusses the relations between LM and the three dimension of sustainability. Companies that have adopted LM to improve their results also want to be seen as socially responsible. Sustainability is considered the new LM frontier [3]. Productivity and cost-saving are necessary for

the economic survival of organizations. However, these tasks should be achieved in a sustainable way, by mitigating negative environmental and social impacts and contributing to a sustainable society [20].

In Table 1, a resume about some main contributions regarding the relation or influence of LM in the three dimensions of sustainability are presented.

Table 1. Influence of Lean Manufacturing in the dimension of sustainability

Dimension	Influence
Economic	Increase profits
	Increase turnover
	Increase market share of the products
	Decrease operational costs and production cost
	Increase process performance
Environmental	Decrease industrial waste
	Increase the practice of circular economy
	Increase the collaboration with partners that follow good environmental practices
Social	Increase the participation of its employees in decision-making and liability
	Increase the quality of work conditions
	Increase in workplace safety

The author [1] indicates that when considered as a whole, lean positively impacts business performance on an aggregate level, as well as market performance individually. However, these effects are highly variable. This high variability therefore offers great opportunities for further research into the potential moderating variables that may affect these relationships.

The authors [16] establish a link between lean and green showing that adopters of lean manufacturing principles are more likely to also adopt ISO 14000 environmental standards. Results show, as expected, that the main impact of lean is related to an increase in the productivity and efficiency of manufacturing processes. It also identifies a very positive relationship between lean implementation and employee satisfaction and it positive impact on the company financial strength. These two aspects together indicate that implementation of lean methodologies can lead to an increased sustainability of the company.

— Industry 4.0 and Sustainability

I4.0 has changed the way businesses and production are conducted in their entirety, in terms of procedures, methods, and practicability. The cost of I4.0 infrastructure seems to be reasonable when budgeted environmentally, but it is still difficult to predict its direct impact on sustainability.

The Table 2 show main recent contributions that have emerged for researchers on I4.0 and sustainability, underlying main dimensions considered are summarized.

According to the reference [6], environmental sustainability is positively impacted by I4.0 through comprehensive digitization that provides more accurate, high-quality management and real-time event management for the external environment.

Table 2. Influence of Industry 4.0 in the dimension of sustainability

Dimension	Influence
Economic	Increase: profits, value creation, efficiency, flexibility
	Increase turnover, and create new business models
	Increase in market share
	Decrease operational and production costs
	Improve processes performance, increase renewable resources, and improve circular economy
	High revenue through vertical and horizontal integration
Environmental	Decrease industrial waste
	Decrease energy intake of non-renewal energy sources
	Increase production of renewal energy
	Practice of circular economy
	Increase in development of new green technologies
	Increase collaboration with partners that follow good environmental practices
Social	Corporate social responsibility is undertaken by companies towards consumers
	Customization and digitization
	Improve conditions of the surrounding society
	Decrease working accidents
	Increase participation of employees in decision-making and liability

It should be noted that sustainability is a broad concept; therefore, flows chosen to address environmental sustainability have already been used elsewhere. When an event is implemented, calculations of flow patterns will become simpler. Nonetheless, the positive effect of activities on the flows is highly dependent on the production quantity. When production increases, flows will also increase and there will be a transformation of negative impacts into positive trends by adopting an e-commerce environmental sustainability dimension.

Therefore, a gap still exists on how to integrate the efficient use of scarce resources, raw materials, information, responsible consumption, and energy with sustainable development goals in long-term solutions. To reduce pollution in the environment and achieve sustainability, the 4Rs—reduce, reuse, recycle, and replace—can be used. Hence, efficiency and eco-innovation will be realized in I4.0 and the sustainability.

The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency'. – Bill Gates (cited in [17]).

This quote illustrates why lean thinking is still important in an increasingly automated and digitalized world. It highlights the inevitable fact that an inefficient process that is automated is still inefficient and is basically automating some type of waste. The cost of automating an inefficient process also tends to be higher [14, 24].

However, several of these studies only discuss and hypothesize on a conceptual level, while some of the empirical studies collect their data from secondary sources. To motivate an I4.0 and lean manufacturing integration, it is necessary to further investigate the potential performance implications through empirical studies. Although the current sample of studies gives some indications on the potential performance impacts, the studies are clearly insufficient in both width and depth. Central research issues in the future will be to measure what a successful I4.0 and lean manufacturing integration entails, as well as comparing the sustainability impacts with those of a 'pure' I4.0 or lean manufacturing system.

Some topics are more developed and are moving towards a normative approach, such as energy efficiency, life cycle management, use and analysis of big data, and systems integration models; while others present opportunities to be more explored, such as human factors, sustainable products and service development, and global manufacturing impacts of Industry 4.0.

— Conceptual model

The main point of interest for this article is to analyze the link between I4.0 and LM, as well as examine its implications on sustainability and the external factors influencing these relationships. Therefore, the last step is to develop a conceptual model that explains the main constructs and the relationships between them.

The proposed model (Figure 6) illustrates the different theoretical lenses regarding these relationships and establishes a structure for summarizing the findings from the literature presented in the previous section.

The conceptual model, in its graphic presentation, considers the environment as a moderating entity in the potential to integrate LM and I4.0, as well as the impact resulting from such integration on sustainability. The success of the execution of any management practice is closely related to the socio-economic context where it is developed (country, business sector, supply chain) that can influence to a greater or lesser degree, in a differentiated way, on each company analyzed.

The central segment of the model shows one of the currently unsolved problems in the literature, how to apply LM and I4.0 in an integrated way. This integration should allow technology enablers to further support and develop LM practices and in turn these exert facilitating effects on the implementation of I4.0. This integration starts from instituting in the organization the pillars of both work philosophies, generating new business models on their bases.

As the central core of the conceptual model, five strategic points are represented to analyze to evaluate, implement and maintain a transformation project: strategy and business model, processes, organization and human resources, infrastructures, products and services. The two influencing circles on the central core represent lean practices (left) and I4.0 technology enablers (right). Both have been represented in an interrelated way because the implementation of an LM practice or a technological enabler (I4.0) is not simply the sum of the results of each of them. Rather, they complement and work synergistically to create a streamlined, high-quality system that increases business profits. This helps explain how a lean system is designed from the interaction of its constituent elements taken as a whole, rather than designing the system one element at a time. The self-reinforcing effects of this type of mutual dependence are those that contribute to a higher associated sustainability.

At the center of the model and inscribed in the central nucleus, the dynamo of future research, composed in this case by the permanent interrelation between lean production models and IT. Its internal logic of execution, this interaction must occur in an environment of continuous improvement, supported by the four stages of the so-called Deming cycle (Plan-Do-Check-Act).

The model also represents an existing GAP in the preceding studies: how to measure the impact of the changes imposed on the production system by the integration of LM and I4.0 on operational performance and on the different dimensions of sustainability (economic, social and environmental)?

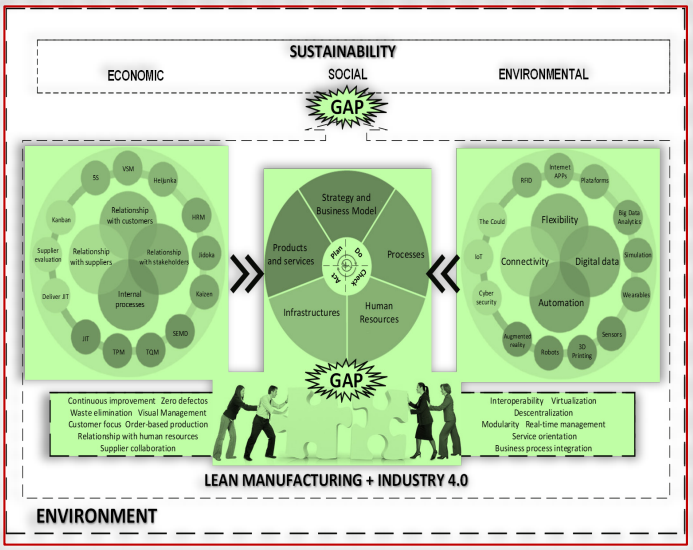

Figure 6. Conceptual model illustrating the relationships between I4.0, LM and sustainability

CONCLUSIONS

In conclusion, after reviewing all these studies, the challenges and opportunities associated with the implementation of I4.0 are still uncertain, and the technologies associated with this industry in terms of sustainability have not been adequately explored because these are still new technologies.

The literature findings are classified into four research streams: (1) I4.0 supports LM, (2) LM supports I4.0, (3) implications of an I4.0 and LM integration in the sustainability, and (4) the effect of environmental factors on an I4.0 and LM integration. It is clear from the findings that

this area is still immature, with seemingly no common platform of knowledge to build the research on.

The conceptual model, in its graphic presentation, considers the environment as a moderating entity in the potential to integrate LM and I4.0, as well as the impact resulting from such integration on sustainability. This proposal illustrates the different theoretical lenses regarding these relationships and establishes a structure for summarizing the findings from the literature.

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ISSN: 2067–3809