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Smart Manufacturing and Information and Communication Technologies for Sustainable Supply-Chain - An Integrative Perspective

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Title: Smart Manufacturing and Information and Communication Technologies for Sustainable Supply-Chain - An Integrative Perspective

Abstract: The applications of information and communication technologies (ICT) for sustainable supply chain is being studied for more than one decade by operations management and information systems scholars. Much investment was made to apply new ICT technologies for western industrial parks to recover their competitiveness, in initiatives like Smart Manufacturing and Industrie 4.0, and improvements in the sustainability of operations are expected by these programs developers and researchers. How the sustainability can be impacted by these technologies, however, is not clear yet. This research uses the systematic review to map the previous research about ICT for sustainable supply chain and analyze it in the Smart Manufacturing perspective. The ICT literature presented some technology applications that are being included in Smart Manufacturing programs and has already some empirical applications that can guide and evaluate the real impact of them. As a result, the proposals of both types of research are very similar, and Smart Manufacturing can be seen as an evolution of previous concepts.

Keywords: Green Supply-Chain, Sustainable Manufacturing, Smart Manufacturing, Indutrie 4.0

1. INTRODUCTION

The sustainability is being incorporated in the corporations' strategy, not only by its importance for the future of the society, but as a competitive priority (Longoni & Cagliano, 2015). The adoption of information and communications technologies for sustainability objectives has been largely investigated by the scholar literature in recent years and its impact in the sustainability programs have been quite positive in many scenarios(Guide, Jayaraman, Srivastava, & Benton, 2000; C. K. M. Lee & Lam, 2012; Martínez-Sala, Egea-López, García-Sánchez, & García-Haro, 2009).

The possibility to use new ICT technologies for manufacturing companies to achieve competitive advantages has generated a lot of research interest. Technologies like cloud computing, internet of things, machine learning and new sensors are subjects of governmental and private programs to improve the regional industrial parks competitiveness. Some of these initiatives are Industrie 4.0, in Germany, Industrial Internet of Things and Smart Manufacturing, in United States and Factory of the Future in European Union (Buchholz, 2011; Kang et al., 2016; Sergi, 2015).

A more connected supply-chain, with available information about materials, products and energy enabling more refined decisions about productions and logistics is the common scenario among these initiatives. Improvements in the sustainability of the operations are expected by the program developers and researchers (Buchholz, 2011; Stock & Seliger, 2016).

Buchholz (2011), in the Factories of the Future roadmap, presents opportunities to impact the economic, social and environmental sustainability. (Stock & Seliger, 2016) propose a totally connected industrial system for the Industrie 4.0, with a better energy management scheduling renewable energy sources efficiently. Kang et al. (2016) defines Smart Manufacturing as a "future growth engine" that can improve manufacturing considering societies, human, and environment.

Information Systems and Supply Chain researchers have studied for more than one decade different models and applications of ICT for sustainable objectives. Information systems for reverse logistics (C. K. M. Lee & Lam, 2012), packaging reuse (Martínez-Sala et al., 2009) and green product development (Chung & Wee, 2010) are examples of subjects already explored.

Since the Smart Manufacturing research is still elaborating its operational model, and how the new proposed technologies can impact in more sustainable supply chain is not clear yet, a systematic literature review is required to evaluate how the ICT can be used to improve the sustainability and how the new technologies can change it.

This article aims to answer the following questions:

- What are the ICT applications for the sustainable supply chains already studied in the scientific literature?
- How these proposals can be incorporated or modified by the Smart Manufacturing technologies?

This document is organized by the sections: smart manufacturing, whit a bibliographic research about the smart manufacturing programs; research design, with the methodology followed; systematic review, with all steps of the review; discussion, integrating the review data with Smart Manufacturing, and conclusion.

2. SMART MANUFACTURING

The extensive offshoring of the industrial function of western companies during the 1990s resulted in twenty years of decline of manufacturing in Europe and USA (Prause, 2015). Due to the important role of this sector for job creation, drive research and innovation, and economical competitiveness, several public and private initiatives was created to recover the western regional industrial parks (Buchholz, 2011; Prause, 2015). Such programs has in common the extensive research in the applications of modern ICT to create a more connected and sustainable supply chain (Buchholz, 2011; Gorbach, Polsonetti, & Chatha, 2014; Henning, Wolfgang, & Johannes, 2013).

The most influential programs are the Industrie 4.0, from Germany, the Smart Manufacturing and Industrial Internet of Things, both from USA, and the Factory of the Future, from the European Union, all of them with collaboration agreements (Buda, Främling, Borgman, Madhikermi, & Kubler, 2015; Toro, Barandiaran, & Posada, 2015). Other important regional programs are Nouvelle France Indutrielle, from France, and the east initiatives Made in China 2025 and Manufacturing Innovation 3.0, from Korea (Kang et al., 2016; Toro et al., 2015).

Despite some regional particularities, all of them have as the central proposal a more integrated industrial system, with three integration axes: horizontal integration, vertical integration, and life-cycle integration. The horizontal integration in the inter-company network that coordinates the entire supply-chain, including materials and energy suppliers, factories and logistics. The vertical integration is in the factories, between the machines systems, also called Operation Technologies (OT), and business or IT systems. The life-cycle integration is the information flowing since the product engineering to this disposal, including its manufacturing and post-sales services(Agarwal & Brem, 2015; Henning et al., 2013; Schmidt, Lüder, Rosendahl, Foehr, & Vollmar, 2015).

This integration enable the digitization of the entire manufacturing system, working as a coordinated but decentralized linked physical and virtual elements. This cross-linked intelligence is called Cyber-Physical System (CPS) (Stock & Seliger, 2016). The main technologies present in the Smart Manufacturing are (Buda et al., 2015; Davis et al., 2015; Henning et al., 2013; Kang et al., 2016):

- Internet of Things: Internet of Things is the technology that enables a network of physical objects and its integration with software. It is one of the core technologies of Smart Manufacturing, responsible for communication with sensors and controllers.
- Big Data: Big Data is the data set with wide range, complex structure, and size, that cannot be processed by the traditional methods. Due to the large amount of data generated by the sensors and systems integrated in the Smart Manufacturing, the infrastructure has to be designed to deal with Big Data.
- Cloud Computing and Cloud Manufacturing: Cloud computing is a structure to outsource data processing and IT infrastructure. Cloud Manufacturing is the applications of this technology to communicate with distributed sensors and allocate manufacturing resources on demand.
- Additive Manufacturing: Additive Manufacturing is the technology that converts 3D models into physical objects. It is basically implemented in the 3D printers, that can be part of a highly flexible manufacturing plant, or a distributed manufacturing system.
- Sensors Technology: The Sensors are the most important hardware technology in Smart Manufacturing, responsible for the real time data collection and control. To make the

Smart Manufacturing viable, sensor have to be cost effective, resilient and offer open communication standards.

- Machine Learning and Data Mining: Machine Learning and Data Mining are technologies that can extract knowledge from the data and apply intelligence for optimized decisions. They are intelligent elements of Smart Manufacturing that can use all the data captured by the system to generate computational models and coordinate its elements.

Davis et al. (2015) suggests five operational categories impacted by the Smart Manufacturing technologies: smart machine line operations, in-production high-fidelity modeling, dynamic decisions, enterprise and supply chain decisions, design, planning and model development (Table 1).

Table 1 - Operational categories of smart manufacturing opportunities (Davis et al., 2015)

Smart machine line operations	In-production high-fidelity modeling	Dynamic decisions	Enterprise and supply chain decisions	Design, planning and model development
Integrated process machine and product management	Enhanced management complex behaviors	Performance management global integrated decisions	Smart grid interoperability	Design models in production
Benchmarking machine-product interactions	Rapid qualification components products materials	Untapped enterprise degrees of freedom in efficiency, performance, and time	In situ measurement and integrated value chains	Product/material in production quality
Machine-power management	Integrated computational material engineering	Enterprise analytics and business operational tradeoff decisions	Tracking, traceability, and genealogy	New product, material technology insertion
Adaptable machine configurations		Configurable data and analyses for rapid analytics and model development	External partner integration and interoperability	

A system that can capture real time data about production, logistics and products, and coordinate its resources, can improve the sustainability of the supply chain. An intelligent allocation of resources, like products, materials, energy and water, can cause a good impact in the environmental management (Stock & Seliger, 2016).

Buchholz (2011), for the Factory of the Future, suggests opportunities for environmental, economic and social sustainability. Best performance across the supply chain, reconfigurable factories capable of small-scale production, high-performance production and resource efficiency in manufacturing are opportunities for the economical sustainability. For the social, he lists increasing the human achievements, creating safe and attractive workplaces, and create sustainable care and responsibility for employees and citizens in global supply chains. For environmental, reducing the consumption of energy increasing the usage of renewable energy, reducing the consumption of water and other process resources, near-to-zero emissions in manufacturing processes, optimizing the exploitation of materials.

3. RESEARCH DESIGN

The literature review is an important tool to map an intellectual territory and, oriented by the research question, develop the existing body of knowledge (Tranfield, Denyer, & Smart, 2003). According to Tranfield et al. (2003), the adoption of a systematic review helps to counteracting bias, enhancing the legitimacy and authority of the resultant evidence.

According to Seuring & Müller (2008), the literature review model has four steps:

- Material collection: Definition of the unit of analysis such as single paper, and the limits for the material to be collected.
- Descriptive analysis: Summarization, usually quantitative, of the formal aspects of the material. For example, the number of publications per year.
- Category selection: Selection of structural dimensions to be applied to the selected material. This step can be reviewed after the material evaluation, adding new categories proposed by the literature.
- Material evaluation: Analysis of the collected material using the categories selected.

The result of the literature review is going to answer the first research question. The second research question is going to be dealt by the discussion of the results considering the Smart Manufacturing concepts, presented in chapter 2.

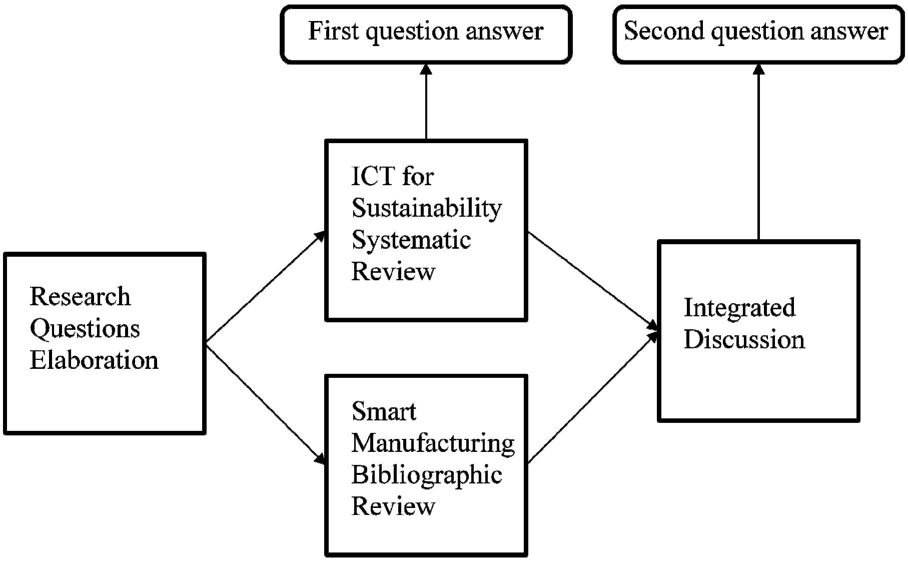

Figure 1 - Research process

4. SISTEMATIC REVIEW

The Web of Science, the Thompson Reuters scientific publications repository, was used to collect the material considered by this research. Web of Science and Scopus, from Reed Elsevier, are considered the most comprehensive scientific knowledge bases, and the best options to bibliographic and bibliometric studies (Archambault, Campbell, Gingras, & Larivière, 2009). According Archambault et al. (2009) both bases are highly correlated, so only one of them was selected for this study. It was only considered peer-review papers published in English.

The search terms was selected based on Fahimnia, Sarkis, & Davarzani (2015) review about green supply chain, with an additional expression about information systems. The query was composed for three groups of keywords. The first "Information Technology(ies)" and "Information System(s)", about ICT, the second "Manufacturing" and "Supply Chain", and the third "Green", "Ecological", "Environmental" and "Sustainable", and "Environmental" and "Sustainability". The logical expression used in search, using "*" as wildcard character, was:

> ("Information Technolog*" OR "Information Syste*") AND (Manufacturing OR "Supply Chain") AND [Green OR Ecological OR (Environmental AND Sustainable) OR (Environmental AND Sustainability)]

The search, applied to the title, abstract and keywords fields, and restricted by peer-reviewed papers and English language, returned 93 results. All of them had the abstracts read to eliminate the documents that didn`t have the ICT applications for sustainable supply chain as an important subject. Only 37 of them was kept in the final collection. It was not kept researches about sustainable supply chain for the IT industry, or that the application of sustainable IT in supply chain was only a minor example, for instance.

4.1 Descriptive Analysis

The 37 articles collected is distributed between 2000 and 2016, with a great concentration in recent years. Around 60% of them was published after 2013, as shown in Figure 2.

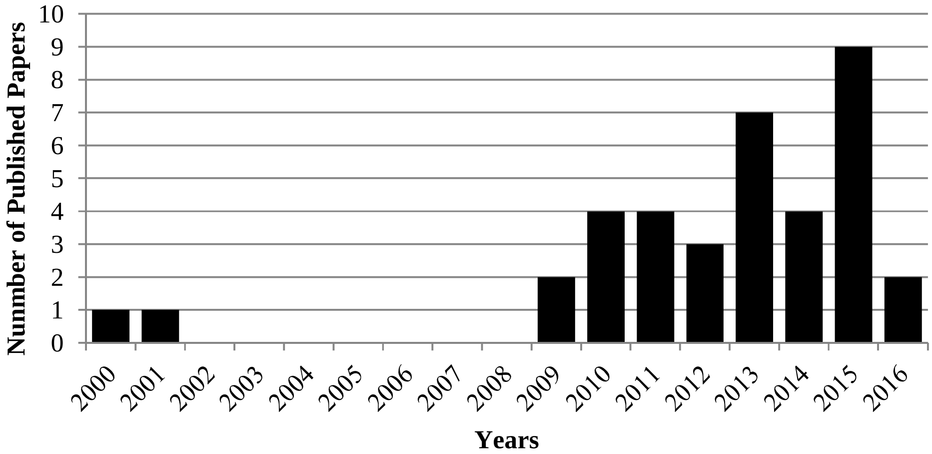

Figure 2 - Number of Published Articles per Year

The distribution of the papers in journals is very disperse, with only five journals with more than one publication. They are Journal of Cleaner Production and International Journal for Production Economics, both with 3 papers, MIS Quarterly, Supply Chain Management and Expert Systems with Applications, with two. Journals from different areas illustrates the multidisciplinary nature of the subject.

We have a diversity of research methodology adopted for this material. They are theoretical and conceptual (11), case study (9), survey (9), modeling and simulation (3), design science (3) and literature review (2). Besides the existence of new researches dedicated to theory development and case studies, that characterizes a body of knowledge still in development phase, the number of surveys shows that we already have some mature sub areas. The multidisciplinary nature of this research can be perceived too by the presence of modeling and simulation works, very common in operations management field, and design science, from the software development field.

We have two literature reviews, one about cleaner supply chain management practices (Subramanian & Gunasekaran, 2015) and another studying the corporate sustainability development in China. Both works have the technology as one of the resulting categories of the review.

4.2 Category Analysis

As initial category analysis was selected the three Smart Manufacturing integration axes, vertical, horizontal and life-cycle. The vertical integration category grouped all researches that proposes the integration with machines inside de manufacturing plants. The horizontal integration is the set of technologies that communicate between different companies of the supply chain. The life-cycle integration gathers papers that treats about the product technology, materials and engineering.

4.2.1 Vertical Integration

In the vertical integration category we have researches that collects real-time data from plant-floor equipments and to impact in the factory energy consumption. They are five works that presents technological alternatives for machines connection, and a framework to exploit this data. There are all non empirical works.

Tao, Zuo, Xu, Lv, & Zhang (2014) is the only one that includes the emission reduction in the objectives of the system. He presents the manufacturing as the most important polluting business, and its reduction, together with the energy consumption reduction, can have an important impact to the environment.

Park & Jeong (2013) addresses the energy problem in a indirect way, using the lean for green approach. The system is designed to reduce failures and non productive time in integrated circuits test lines, avoiding electrical energy waste.

The internet of things concept is used in two researches (Shrouf & Miragliotta, 2015; Tao et al., 2014) for sensor and automation systems communication. The cloud computing is proposed by Park & Jeong (2013) to facilitate the system adoption. H. Lee, Ryu, Son, & Cho (2014) proposes a modification on the Manufacturing Execution System, architecture for integration between plan-floor systems and Enterprise Resource Systems, with sustainable objectives.

4.2.2 Horizontal Integration

The horizontal Integration in the most studied subject in the selected papers, with 16 publications. The systems models and objectives are more diverse than the vertical integration, and there is some empirical researches, with three surveys, that characterizes a more mature field.

The problem of closed loop supply chain management is addressed by five researches, with more general management system for collaboration (Y. C. Chen et al., 2015) and flow optimization (Chung & Wee, 2010), reverse logistics management (García-Rodríguez, Castilla-Gutiérrez, & Bustos-Flores, 2013; Guide et al., 2000) and product recovery for recycling and repair (Guide et al., 2000; Toyasaki, Wakolbinger, & Kettinger, 2013). Two complexities of the closed loop supply chain are treated by most of the authors. The first is the planning uncertainty due to irregular return of after use products from the field, with a non predictable material availability for manufacturing. The second is the recovery of the discarded products from customers, that are very geographically disperse and with no predictable scheduler.

Three of the publications are about traceability in the food supply chain (Martínez-Sala et al., 2009; Opara & Mazaud, 2001; Wognum, Bremmers, Trienekens, Van Der Vorst, & Bloemhof, 2011). The agricultural practices and supply chain transparence for the end user is important in this market for safety and for the social and environmental sustainability reasons. The agriculture is showed as an important soil and water polluter, and uses more child and slave work than other industries, so the conscious consumers are becoming an important market. Appelhanz, Osburg, Toporowski, & Schumann (2016) presents a very similar traceability system, but for wood products, aiming to reach the premium market.

There are three works that uses quantitative methodologies to investigate the impact of ITC in the green supply chain. Dao, Langella, & Carbo (2011) finds the ITC as an important element to implement the sustainability culture in a supply chain, that is a necessary element of the collaboration to drive environmental impacts. Schniederjans & Hales (2016) concludes that the cloud computing adoption has a positive effect on the supply chain sustainability. Kenneth

W. Green Jr. et al. (2012) studies the green supply chain collaboration, and considers the ICT an necessary precursor of the green purchasing.

Wang, Sanchez Rodrigues, & Evans (2015) and Marett, Otondo, & Taylor (2013) research systems that can reduce the CO_2 emission monitoring and optimizing the road freight of a logistical system. Ahmad & Mehmood (2015) presents an integrated concept of Supply Chain Management System and Smart Cities, with a system that can coordinate big and small industries to reduce the impact in the city environment.

In this group of article, the adopted technology for each system is less studied than the last, but we have two papers about cloud computing (Ahmad & Mehmood, 2015; Schniederjans & Hales, 2016) and the use of Radio Frequency Identification (RFiD) (Martínez-Sala et al., 2009).

4.2.3 Life-cycle Integrations

This group of papers deals mostly with product design, with great emphasis in meeting regulatory standards and enable collaboration.

Taghaboni-Dutta, Trappey, & Trappey (2010) proposes a information system to record and exchange data about green products and parts to enable designers and manufacturers increase the use of green parts. Gong & Wang (2011), Y. C. Chen et al. (2015) and M.-K. Chen, Tai, & Hung (2012) design a system to deal with the complexity of design and manufacture products for customers in different regions, with different sustainability standards.

Guo, Zhou, Li, & Xie (2014) studies a model to use the Enterprise Information System to green design assessment of electromechanical products. Eun, Son, Moon, & Chung (2009) proposes an information system for on-line Life Cycle Assessment.

4.2.4 Other ICT Applications

The seven papers selected for this group treats about very general or very specific use of ICT that cannot be classified in previous sections.

Quantitative analysis about supply chain and manufacturing sustainability and the presence of more general or informative ICT are presented in four papers. Pondeville, Swaen, & De Rongé (2013) studies the adoption of environmental management control systems, and concludes that it is mainly motivated by regulatory stakeholders. Ryoo & Koo (2013) finds that the alignment of green practices and ICT have a positive effect in the coordination between green practices, manufacturing and marketing, with environmental performance improvement..

Benitez-Amado, Perez-Arostegui, & Tamayo-Torres (2010) concludes that the capability of innovativeness mediates the effect of ICT adoption in green manufacturing. Gimenez, Sierra, Rodon, & Andres Rodriguez (2015) propose the ICT as an ally to environmental practices to get better environmental performance.

Two papers studies about sustainability assessment. Muñoz, Capón-García, Laínez, Espuña, & Puigjaner (2013) proposes an ontology to develop systems for manufacturing and supply chain sustainability evaluation. Kusi-Sarpong, Bai, Sarkis, & Wang (2015) design an algorithm to evaluate green supply chain practices in the mining industry.

K. H. Lee (2011) is the only study about the adoption of environmental cost accounting systems in manufacturing, and finds a strong barrier to change existent accounting systems.

5. DISCUSSION

The ICT for supply chain sustainability literature shows a very diverse group of areas, fields and researchers, that proposes very similar applications than Smart Manufacturing programs. Considering the operational categories of opportunities (Table 1), proposed by Davis et al. (2015), we can clearly find parallels for the five items:

- Smart machine line operations: The vertical integration researches deals with plant-floor integration and the exploitation of this data to smarter manufacturing operations decisions.
- In-production high-fidelity modeling: Still in a preliminary phase, models of the manufacturing are used by horizontal, life-cycle integration and assessment works for planning and material management.
- Dynamic decisions, and Enterprise and supply chain decisions: The horizontal integration deals data from manufacturing and supply chain to planning and decisions.
- Design, planning and model development: The life-cycle works addressed some of this challenges.

The advantages of the modern ICT technology capabilities are the main promise of the Smart Manufacturing (Kang et al., 2016; Sergi, 2015). In the next sessions, these technologies are going to be discussed using the revised articles (excluding the additive manufacturing, since it is not an ICT technology).

5.1 Internet of Things and Sensors

The internet of things and sensors technology are connected in their application. The internet of things is the use of embedded sensors and communication technologies in the machinery, products and vehicles, allowing data collection and coordination between "things" (Kang et al., 2016; Yu, Xu, & Lu, 2015).

This technology can already be found in the ICT literature, mainly for vertical integration, collecting energy consumption and material from the plant-floor equipments (Shrouf & Miragliotta, 2015; Tao et al., 2014). Although the authors didn't identified as IoT, trucks real-time and autonomous monitoring are very similar applications (Marett et al., 2013; Wang et al., 2015). The possibility of measure and communicate physical quantities, from virtually any kind of equipment, can impact a lot of presented challenges.

The recovering in the closed-loop supply chain can take advantage of this technology collecting data from the product about its using profile and disposing, being user independent for the reverse logistics (Guide et al., 2000; Toyasaki et al., 2013). Sustainability reporting and assessment, highly dependent of the human process and adoption to obtain success (Kusi-Sarpong et al., 2015; K. H. Lee, 2011; Muñoz et al., 2013), can be automated with data grabbed from the manufacturing and logistics processes.

5.2 Cloud Computing

The cloud computing allows the development very scalable, modular and inclusive systems, adequate for the coverage of Smart Manufacturing (Davis et al., 2015; Kang et al., 2016). It can accelerate the adoption of inter-company systems, since the infrastructure and geographic location are not important barriers.

Some studied papers uses this technology, as Park & Jeong (2013), that implements a failure detection system using cloud computing, for easier adoption, Ahmad & Mehmood (2015) that adopts cloud to scale a system that can coordinate smart cities and the industrial supply chain.

5.3 Big Data, Machine Learning and Data Mining

With cloud computer infrastructures and sensor capturing all data from products and machines, it is needed algorithms that can deal with this big volume of data. The big data, machine learning and data mining are the technologies responsible for recording, recover, analyze and suggest actions based on data (Kang et al., 2016).

Machine learning and data mining are the core of the system intelligence, with prediction and adaptation capabilities (Qu, Jian, Chu, Wang, & Tan, 2015). They can support human decision makers with models based on process data, with better use of the human knowledge (Agarwal & Brem, 2015).

These technologies can address the problems studied in the literature review with an integrated manner. The same product data, gathered and communicated by an IoT system, can be analyzed for the supply chain optimization and new product development, just changing the context.

6. CONCLUSIONS

The Smart Manufacturing is a new research field, with few empirical examples and divergent models. The adherence of the ICT for sustainable supply chain literature with some of its proposals can generate new insights about the real potential of this model, a help to conduce future researches.

The application of ICT to improve the sustainability have shown a very positive effect in previous research. Dao et al. (2011) and Schniederjans & Hales (2016) are examples of papers that found the ICT as in important element do improve the collaboration in supply chain and keep the company engaged in achieve the sustainability goals.

This work intents to contribute to academic literature offering a map of previous works contextualized with the Smart Manufacturing concepts, that can be the basis of future empirical researches. For business readers, can be a guide to the principal concepts in Smart Manufacturing, and examples of real applications of ICT for sustainability.

This review has to be read considering its limitations. The papers selected to be studied are always a partial sample of the research in the field. Publications in non English language, not indexed and presented in scientific events wasn't considered.

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