Sustainable Smart Manufacturing applications in the Industry 4.0 context

Popolo V.*, Grassi A.*, Gebennini E., Gargiulo F.***

**Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università degli Studi di Napoli Federico II, Piazzale Tecchio, 80 80125 – Napoli – Italy, (valentina.popolo@unina.it, andrea.grassi@unina.it, francesco.gargiulo3@unina.it)*

*** Dipartimento di Economia, University of Mercatorum, Piazza Mattei 10, 00186– Roma – Italy (elisa.gebennini@unimercatorum.it)*

Abstract: With the strong development of industry 4.0, manufacturing companies are increasingly approaching advanced technologies such as Internet of Things (IoT), Cyber-Physical System (CPS), Cloud Computing (CC), Artificial Intelligence (AI), Big Data Analytics (BDA). These are key elements of Smart Manufacturing (SM) which, based on the application of advanced technologies, aims to create links between the real and virtual worlds. On the wave of this technological evolution, the opportunity for companies to develop more efficient and environmentally sustainable production processes rises. Indeed, there is much debate about the possibilities and future developments that these new industrial paradigms may have an impact on the environmental sustainability of companies. This document, through an analysis of the literature, aims to point out the links and trends that have emerged so far on the sustainability of Smart Manufacturing. After defining a methodology for the analysis of the literature, a bibliographic search has been conducted on the main scientific search engines identifying the most frequent keywords. Based on this analysis, the tools used by the SM were then delineated. The environmental sustainability of Product Life-cycle Management (PLM) was then developed in an SM context. Finally, gaps and future development in this research area will be identified.

Keywords Smart Manufacturing; Sustainable; Industry 4.0; Environmental sustainability;

1.Introduction

We are in the heart of the Industrial Revolution for manufacturing industries and from this new strand have developed in different geographical areas around the world. (Kang et al., 2016) highlighted how these paradigms have evolved in Korea, Germany and the USA. In fact, Manufacturing Innovation 3.0 is developed in Korea, Industrie 4.0 in Germany and Smart Manufacturing (SM) in the USA.

These philosophies are in full evolution and are studied and expanded every day. In these times of strong change, one aspect becomes fundamental for manufacturing companies: sustainability.

Three different dimensions of sustainability are considered in the literature: social, environmental and economic. (Mauerhofer, 2008) introduced a new concept for sustainability, "3-D Sustainability" where he showed that the three dimensions of sustainability can be represented in a broader way, compared to the classic triangular or spherical representations; thus linking the three aspects of sustainability with the social. economic and environmental capacity and the limits of the environmental system.

(Garetti & Taisch, 2012) have defined the Sustainable Manufacturing as "the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economical, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life".

Also have identified research cluster: business models and processes, asset and **product life cycle management**, resources and energy management, enabling technologies.

Moreover, (Jayal et al., 2010) had already identified the problem of sustainable manufacturing and identified that sustainability must not only look at the product or process but must involve the whole Product Life cycle Management (PLM).

PLM become relevant aspects if sustainable production is to be made. In fact, it is necessary to implement different functioning policies to make the industry green.

The aim of this work is to bring to light recent developments of the SM, with the main focus on environmental sustainability. The focus of this work is summarized in these questions:

- Can Smart Manufacturing help factories to be more sustainable in environmental terms?

- Can PLM be used to strengthen environmental sustainability in a SM context?

The review of literature is an important part of any scientific research work. Using literature review, relevant to the field of study, new ideas and new points of view on a given issue emerge and are evaluated and analysed. Another fundamental aspect of a review is to investigate the literature with the aim of finding possible gaps in research.

Section 2 describes the methodology that has been conducted for the research of this review. Section 3 provides an analysis of the literature on Smart Manufacturing System (SMS) and tools it uses. Environmental sustainability and PLM are proposed in section 4 and discussed in section 5. Finally, section 6 draws conclusions and future research.

2.Research methodology

As mentioned in the previous section, literature research has been an important part of this study and here is the methodology used.

Such gaps in research make it to identify new areas of study and address new points of view and serve to reinforce a given field of research (Tranfield et al., 2003). Following the approach given by (Ren et al., 2019) and (Thürer et al., 2018), a bibliographic research of scientific articles has been developed with the focus on Smart Manufacturing and sustainability.

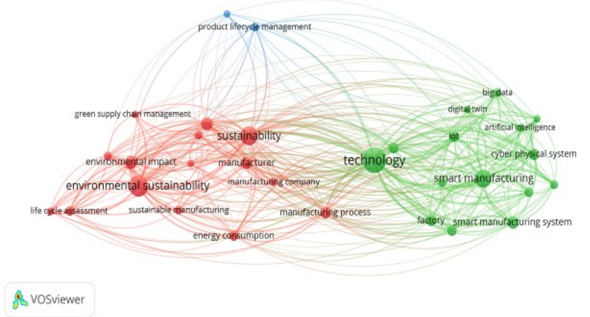

Figure 1- Keywords found through the VOSviewier program

The literature has been studied and the key words to consider have been extracted from it. For the identification of these words a program, called VOSviewer, of which an image is reported, has been used. In Fig.1 we can see how the program groups the words in clusters and shows them with different colors; in fact we can see that the area identified by the red color we can define it as the area of **environmental sustainability**, in green the **technologies** and the **SM**, finally in blue we see the area defined by the **PLM**.

Table 1 shows the searches made, where keywords have been entered in the middle of the searches made on the Scopus search engine.

The search methodology has been developed as follows: using the Scopus website, keywords placed between quotation marks have been inserted in order to perform a precise search for important words. The website carries out the search respecting precise fields, in this case the search is carried out only for "Article title, Abstract, Keywords". Once launched the search it was decided to limit the articles according to "Article, Engineering, English" in order to narrow the field in the best way.

It is interesting to see an example: as can be seen from the first element of Table 1, was identified by the keywords *"Smart manufacturing"* and *sustainab** have been started them on Scopus in the section "Article title, Abstract, Keywords" obtaining 115 results. Restricting the search to the fields "Article, Engineering, English" 26 results were obtained.

The keyword *"sustainab*"* has been searched for all declensions of the same word.

This have been done for all the keywords found, part of which can be found in the above Table 1.

Fig. 2 shows the articles published for years and the related citations that have been found on Scopus by entering *"smart manufacturing"* and *sustainab** as keywords.

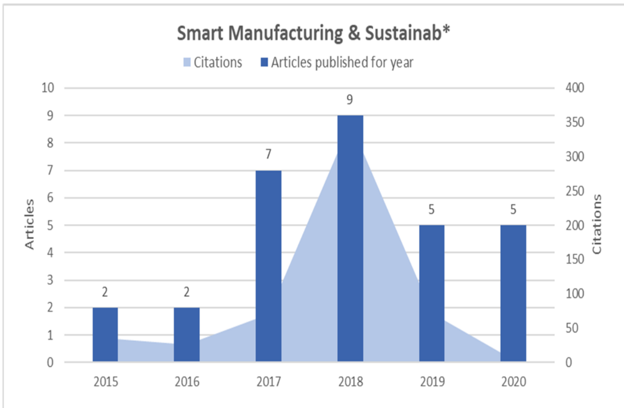

Figure 2- Articles and citation found by *"Smart Manufacturing"* and *Sustainab**

Articles with a high relevance, with respect to tools, aspects and perspectives, have been considered to obtain a specific focus on SM, sustainability and PLM. Instead, all articles applying the research to case studies were excluded, as they were not relevant in this first article.

Table 1: Summary of searching methodologies used for this literature review paper.

Literature search strings	Search field	Number of document results	Limit to	Number of refined document results
("Smart manufacturing" AND sustainab*)	Article title, Abstract, Keywords	115	Article, Engineering, English	26
("Smart manufacturing system")	Article title, Abstract, Keywords	194	Article, Engineering, English	59
("Smart manufacturing" AND definition)	Article title, Abstract, Keywords	48	Article, Engineering, English	15
("Smart manufacturing" AND environmental)	Article title, Abstract, Keywords	48	Article, Engineering, English	14
("smart manufacturing" AND environmental AND sustainability)	Article title, Abstract, Keywords	8	Article, Engineering, English	2
(environmental AND sustainability AND "industry 4.0")	Article title, Abstract, Keywords	61	Article, Engineering, English	12
("industr* 4.0" AND "environmental sustainab*")	Article title, Abstract, Keywords	19	Article, Engineering, English	7
("Smart manufacturing system" AND sustainab*)	Article title, Abstract, Keywords	21	Article, Engineering, English	5
("Smart manufacturing" AND "industr* 4.0")	Article title, Abstract, Keywords	477	Article, Engineering, English	140
("industr* 4.0" AND sustainab*)	Article title, Abstract, Keywords	609	Article, Engineering, English	111
("environment* sustainab*" AND manufacturing)	Article title, Abstract, Keywords	1036	Article, Engineering, English	236
("Sustainab*" AND "Product Lifecycle Management")	Article title, Abstract, Keywords	139	Article, Engineering, English	29
("industr* 4.0" AND "Product Lifecycle Management")	Article title, Abstract, Keywords	42	Article, Engineering, English	10

3.Smart Manufacturing System and Tools

A clearer definition of SMS has been investigated in the literature. Various proposals for definitions have been identified. Later in the section, the typical implementation tools for SMS have been defined.

As a first element of the literature analysis the different definitions that have been found of SM has been compared. The National Institute of Standards and Technology (NIST) defined the Smart Manufacturing System (SMS) as "fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs" (NIST, 2017). The Smart Manufacturing Leadership Coalition (SMLC, 2011) defined SM as "the ability to solve existing and future problems via an open infrastructure that allows solutions to be implemented at the speed of business while creating advantaged value". Three other possible definitions are proposed by (Qu et al., 2019) according to three points of view: from an engineering point of view, from the point of view of interconnection and communication and from the point of view of predictive analysis and decision making. In the research carried out on scopus have been identified (Schaffer, 1986) as the first author to talk about Smart Manufacturing.

Some articles discussing the link between SM and I4.0 and proposing objectives and technologies to clarify the possible difference between the two paradigms are reported.

(Thoben et al., 2017) have presented two definitions of the two initiatives and assigns 8 key areas to I4.0 and 3 main objectives to SM (Plantwide optimization, Sustainable production and Agile supply chains).

According to (Frank et al., 2019), SM is a front-end technology of I4.0 together with Smart Working, Smart Supply Chain and Smart Products; their article also have identified 4 basic technologies (internet of things, cloud services, big data and analytics) at the service of I4.0.

(Kang et al., 2016) after locating the three paradigms discussed in the introduction, identify the key elements of the three countries and compare them to obtain 8 tools that are representative of the three paradigms: CPS, IoT, cloud computing (cloud production), big data, additive production (3D printing), sensors, energy saving and holograms.

In the literature there is no clear distinction between the two paradigms, the fact is that they can be considered as two sides of the same coin and that they drive both industries to be more technologically advanced. As for SMS tools, there is a lot of fragmentation in the literature. The most common tools to this paradigm are reported.

(Mittal et al., 2019), through a review of the literature, have identified and divided the features and tools typically used by SMS. The result of this study are 5 features (modularity, heterogeneity, interoperability and compositionality) and 10 technologies (including intelligent control, cyber security, CPS, IoT, cloud computing/cloud manufacturing, 3-D printing, data analytics).

Other authors have spoken more broadly and specifically about the tools that are applied to SMS. (Tao et al., 2018) have introduced us to the problem of data-driven SMS, in which they identify 5 characteristics of data and possible applications such as Smart Design, Manufacturing Process Monitoring and Smart Planning And Process Optimization.

(Tran et al., 2019) have identified the SMS built upon CPS as the heart of the industrial revolution and in function of this they develop a Smart Cyber-Physical Manufacturing System (Smart-CPMS) that adapts to the different changes in manufacturing.

(J. Wang et al., 2018), after comparing different Deep Learning (DL) models, have proposed DL applications to SMS and identifies data matters, model selection, model visualization, generic model, and incremental learning as elements of discussion for future developments.

(Yang et al., 2019) proposes a review on the application of IoT in smart manufacturing, in particular they have discussed the potential of networks of the new SM specific methodology, Internet of Manufacturing Things (IoMT).

Therefore, the most used and therefore to be considered fundamental tools for the SMS are: data-driver, Smart-CPMS, DL, IoMT.

Another author who talks about SM is (Kusiak, 2018) who identified 6 main pillars on which this methodology is based. In particular, he identified sustainability as one of the pillars and described it as not what is produced but how it is produced. He also identifies possible scenarios for this pillar, ranging from sustainable product design to production processes. Based on this work, as the sustainability pillar has been identified, this aspect will be developed in the next section.

4.Enviromental sustainability and PLM

The purpose of environmental sustainability is to protect and support the world around us by trying to reduce man-made damage. This includes reducing emissions and pollution, reducing scrap and waste, protecting the soil and oceans and much more. Nowadays, manufacturing industries are among the main sources of contamination; in fact, they have large levels of emissions and waste. For these reasons, environmental sustainability must become the focus of companies that want to be more competitive and eco-friendlier. To this end, industries must start from product design to regeneration, i.e. product life cycle management.

The Product Life-cycle Management concept is a strategic business approach for the management of all phases of the product and aims to simplify product development and promote innovation in production. (Sudarsan et al., 2005) has defined PLM as the integration of all information produced in all phases of product life to all users of the organization (suppliers and customers).

PLM consists of three phases: Beginning Of Life (BOL), where design and production is carried out; Middle Of Life (MOL), which includes product use, service and maintenance; and End Of Life (EOL) including reclamation, recycling, reuse and disposal (Zhang et al., 2017).

In reference to the sustainability of PLM many authors have discussed what the developments in era 4.0 could be. From this point of view, (Ren et al., 2019), first of all, wrote a complete review on big data in SM, also identifying knowledge gaps; then they have coined the term Sustainable Smart Manufacturing (SSM) defining it as "a new manufacturing paradigm that integrates and applies the latest information and data analytics technologies in operations and decision-making processes of PLM" and to achieve an intelligent and sustainable production. Finally, they have proposed a conceptual framework of big data for SSM in PLM.

(Zhao et al., 2015) have analysed the sustainability of production by introducing a new information model for product life cycle management that integrates an energy simulation framework. In addition, they have defined indicators for the sustainable development of a PLM in a Green Manufacturing context. The indicators have related to environmental sustainability are: materials used, energy, emission, biodiversity, compliance.

However, the PLM manages information on the various phases of the product's life cycle, starting from design, production, maintenance and disposal. Another vision of this cycle is the Closed Loop Lifecycle Management (CL2M) (Kiritsis, 2011) which collects and uses information on the various products thanks to new emerging technologies; this allows to continuously improve the product life phases, from design to disposal. (Främling et al., 2013), instead, have created a new concept defined as Sustainable PLM which, unlike CL2M, focuses on improving product life but from the point of view of environmental sustainability. In particular, the basis of Sustainable PLM is the communication among Intelligent Products, through messaging interfaces and other information systems, to obtain information on the product life cycle and to reduce CO_2 emissions.

(Brundage et al., 2018) have outlined and assessed the methods and tools for the assessment of environmental sustainability that can be applied at individual stages of the product life cycle. They also identify whether a tool is not explicitly used for sustainability assessment or can be adapted to do so.

In the EOL phase of PLM the recycling and reuse phases of the product are analysed, but little importance is given to the regeneration of the parts. (Y. Wang et al., 2020), after examining various applications of digital technologies (CPS/digital-twin, big data, IOT/cloud) in remanufacturing, proposes a new paradigm "big data driven hierarchical digital-twin predictive remanufacturing" (BDHDTPREMfg) which focuses on the multi-life-cycle remanufacturing.

(Beier et al., 2018) have discussed the use of the Industrial Internet of Things (IIoT) from the point of view of the environmental dimension of sustainable development. They try to assess the potential benefits of IIoT in relation to three environmental issues: resource efficiency, sustainable energy and transparency.

One of the gaps that were identified was that in the development of PLM little importance was given to the aspect of product regeneration, as there were insurmountable problems that can be overcome today with new technologies. Therefore, the regeneration of products under environmentally sustainable conditions becomes of current interest. Machines are starting to communicate with each other, products are getting smarter and smarter, factories are getting smarter and more interactive, all this allows us to keep the product under continuous monitoring and to receive data not only during the production progress of a given product.

Monitoring products outside the factories could be an advantage from a remanufacturing point of view. Therefore, future research could focus on the possibility to continuously monitor the product, in this way we could know the maintenance status of the parts and during the regeneration phase we could know in advance the entire life cycle of the product.

A further gap identified is the lack of articles discussing environmental sustainability aspects of the product life cycle in Smart Manufacturing. In particular as technologies advance, regeneration should be reconsidered from an SM and environmental sustainability perspective.

5.Discussion

From this study, it emerges that nowadays many authors have questioned the aspects presented here.

In particular, it shows how SM is presented as an area where the most advanced technologies are developed and integrated. SM is globally integrated into an advanced industry that applies the 4.0 logic for production and resource management. In fact, in industrial production we can see how machines become collaborative and products become more and more intelligent. Object to object communication is no longer seen as a strange thing but rather is increasingly used in the company. All this can only be done by the integration of innovative tools with the structural elements of the company. In addition to the structural elements, innovation is also applied to the managerial elements of the company. In fact, you can see how the management of the product life cycle must take into account the whole process, starting from design to regeneration. Therefore, PLM becomes the first place where the advanced tools of SM are highlighted.

From the point of view of production, sustainability must become a fundamental point for companies that want to be increasingly competitive. For this reason, since PLM considers the entire production process, the sustainability of the company must be the focal point for the development of all phases of PLM.

In particular, environmental sustainability can be further developed in the EOL phase of the product, where waste can be recovered. Regeneration is one of the objectives of environmental sustainability, as materials can be recovered and recycled down to the smallest detail. With the support of SM tools, product information can be used to find out the useful life of a given component and based on this data it can be evaluated whether to reuse, recycle, discard the component.

To use the SM tools, we need to get into the heart of another phase of PLM, the BOL. In fact, in this phase we evaluate the design of the product that becomes fundamental if we want to insert an innovative tool inside the product. The insertion of a sensor could be of help for the reception of data for recovery.

Continuous receipt of product usage data can be reused to automate certain manufacturing and remanufacturing processes. This aspect must be thoroughly investigated, as it will become of interest to make the environment cleaner and with less waste.

6.Conclusion

This document, through an analysis of the literature, aims to point out the links and trends that have emerged so far on the sustainability of Smart Manufacturing. In particular, linking this aspect at all stages of the product's life and through the supply chain.

As a first aspect, a literature review was carried out involving 50 articles, which were selected with appropriate keywords, with which this study was carried out.

Through this research we have identified two clear definitions on the SMS. Subsequently, through the classification of the typical tools of the two paradigms, a possible link between SM and I4.0 was discussed. Compared to I4.0, strong similarities were found, especially with regard to the instruments involved. In particular, the tools considered fundamental for SM were described.

Environmental sustainability was the focus of the study, as it was assessed not only as an extension of the SM paradigm, but also from the perspective of PLM. In fact, they were fundamental elements for the research of smart manufacturing sustainability because without PLM it would not be possible to make a green company.

Many authors have wondered about this aspect, finding different solutions to apply either on the whole PLM or in some phases of it. Looking on the final phase of PLM, regeneration has been identified as a research gap, as little attention is paid. In particular, the analysis of product data has been evaluated as a future research element.

Until now, the use of data has only been applied to aspects of product maintenance. In the future, however, as products become more and more intelligent, the product itself could keep track of its use and how its parts have been used. In this way, by knowing the conditions of use of all the parts of the product, during remanufacturing it is possible to understand if some parts have to be tested or discarded or reused without being tested.

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