On analysing sustainability assessment in manufacturing organizations: A survey

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Abstract: Manufacturing organizations are now facing unexpected challenges due to scarcity of the natural resources and consequent governmental rules that urge to adopt new organisational or even manufacturing strategies. Adopting the sustainability paradigm at the present seems to be the only viable strategy to respond appropriately to this changed market conditions and customer's demand. As the pressure for changing the traditional manufacturing approach to reach a sustainable operating condition increases, the urge for assessing their sustainability performance has been reinforced accordingly. Various methods have been accomplished so far, trying to find a way to assess the sustainability state of companies, to select among sustainable solutions, to define and to solve practical problems and to identify potential sustainable solutions. Due to this abundance, the present study is cantered by a systematic literature review based on sustainable manufacturing and sustainability assessment to explore questions on sustainable manufacturing: 'How can sustainable manufacturing be achieved?' and 'How can sustainable manufacturing be assessed?' The study led to stipulation of the true essence of sustainable manufacturing and sustainability assessment. It also brought new hints on the sustainability assessment of manufacturing recognising true gaps needed to be filled. Furthermore, to investigate the regularity of the methods and tools of sustainability assessment, a Formal Concept Analysis (FCA) was adopted. At the end, a new holistic framework for sustainability assessment in a manufacturing organization is proposed.

Keywords: sustainability assessment; sustainable manufacturing; manufacturing organization; sustainable development

Introduction

Manufacturing organizations are facing the urge to adopt new strategies to reach an adequate level of sustainability to challenge the evolving market and customer's demand of sustainable products, related to the scarcity of the natural resources or related governmental rules. They also need to offer a higher return of investment while they reduce the environmental impacts simultaneously. On the other hand, they are asked to constitute an attractive workplace for people focusing on collaboration, learning, and development of competencies (Machado, Winroth, and Ribeiro da Silva 2019). Among several strategies, the sustainable manufacturing paradigm has garnished a great deal of attention, since it also represents an opportunity for the organizations to survive the harsh competitive market of today and also connect to the other competitors. 'Sustainable manufacturing' is believed to be a formal name for an exciting new way of doing business and creating value by addressing contemporarily the economical, the environmental and the social issue of any step of the manufacturing activities. This new paradigm, to a certain extent, is implicitly changing the "goal function" of any company to encompass the raising of their competitive power, the increase of their profit, the reduction of ecological and social risks, gaining more social trust and satisfying customers while creating a much affordable environment for its stakeholders. Apart from the urgent need for environmental actions, all companies around the world are facing elevated social expectations of customers on one hand and increasing prices for raw materials, energy and compliance on the other. Therefore, the sustainability issue seems to be vital and has changed face from a show-off achievement to a competitive imperative and a must have in today's market. In addition, the bottom-up demand of customers for more sustainable products and the top-down requirement to comply with the governmental rules and regulation, made the manufacturing organizations think about ways, tools and methodologies to evaluate and assess the level of sustainability in the whole manufacturing system.

Various methods have been accomplished trying to find a way for companies to assess their sustainability state, choose between sustainable solutions, define and solve problems on the way to sustainability and identify potential solutions. Therefore, sustainability assessment becomes a principle focus for sustainable development and a common practice in product, policy and in institutional appraisals (Sala, Ciuffo, & Nijkamp, 2015). In other words, the concept of sustainability assessment is introduced to offer new perspectives to impact assessment geared toward planning and decision making on sustainable development (Hacking & Guthrie, 2008). Devuyst (2001) defined sustainability assessment as '*a methodology "that can help decision makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable'*.

An intensive study was done by the authors (Eslami et al. 2018) in which sustainability and sustainable manufacturing was stipulated, and the insights of the concepts were explored. The study is then extended here to the present work by moving to the concept of sustainability assessment and trying to scrutinize its essence by searching for an answer for the following question: 'How can sustainable manufacturing be achieved?' and 'How can sustainable manufacturing be assessed?' To this purpose a thorough analysis has been conducted to delineate sustainability assessment in manufacturing and explore its feature. The paper is structured as the following: the methodology for the literature review will be described in section 2. As in the third section, previous surveys will be investigated. Afterwards, the samples will be introduced in section 4 and the applied criteria for the content analysis comes after in section 5. Section 6 makes a discussion on the essence of the sustainable manufacturing and a short discussion on the concept "6R" at the end. Consequently, section 7 does the same for sustainability assessment, the used tool and an

FCA analysis on the applied tools. Considering all the results, a framework will be proposed in section 8. Finally, conclusions and future work are raised.

Method of the literature review

The present study forms a systematic literature review on the basis of assessment of the sustainable manufacturing in manufacturing organizations. To do so, a sequence of questions have been answered through the work: ‘how can sustainable manufacturing be achieved?’ and ‘how can it be assessed?’ To that aim, papers were identified by means of a structured keyword search on major databases and publisher websites (Scopus©, Elsevier ScienceDirect©, and Web of Science©). Keywords such as “manufacturing”, “assessment”, “supply chain”, “manufacturing system”, “Product” and “process” were combined (using AND) with sustainability related ones, such as “sustainable/sustainability”, “sustainable development”, “sustainability assessment”, “sustainable manufacturing system”. All the searches were applied in “Title, Keyword, Abstract” field. There were two issues excluded from further analysis, as they seemed bias from the scope of the research, due to the dissimilarity of interests and distant from the authors’ aptness zone: (1) chemical product manufacturing process and (2) manufacturing by renewable energy. However, it is highly important to note that the focus of the study was on statistical data, therefore, business-oriented papers and the papers which investigate sustainability in a global level were also decided to be considered out of scope and be excluded from the search.

A content analysis was conducted to systematically assess the papers: material collection has been already described, which is by means of the literature search and the reduction mode mentioned above. For the analysis itself, a set of criteria was used at first for describing the sample. Then, the discussion is taken into the content analysis itself, whether the paper is in the design for sustainability mode or an assessment one. Respective content analysis is outlined as the following sectors.

Previous surveys

Due to (Chun and Bidanda 2013), *sustainability* (including sustainable development, green manufacturing and green supply chain), *operations research* (which utilizes methodologies such as linear /integer programming, Markov decision process and multi-objective) and *product life cycle analysis* (cost analysis, environmental effect and intelligence) are the three main categories of research in the field of sustainable manufacturing and are used to quantify sustainability performance in industrial practices. Authors in (Seuring 2013) did a literature review on sustainability in manufacturing through supply chain management. They first explored the works done due to the three sustainability dimensions, and then analysed the works that were on the modelling approaches. Regarding to their search, the modelling approaches can be divided into 4 main groups as life cycle assessment models, equilibrium models, multi-criteria decision making and analytical hierarchy process. They also illustrated the empirical research presented in the models and concluded that theoretical content is the most popular while such data is not linked to the formal assessment offered by quantitative models. Two parallel works have been done in (Mahesh Mani, Haapala, Smullin, & Morris, 2016) to find the gaps and barriers in process modelling and its assessment: a traditional literature review and an industry focus group investigation. The results and findings of the literature review were then compared to the findings of the 3 roundtable meetings with representatives of different companies. Based on the comparisons made in this paper and the results, the urge to introduce standards for representing manufacturing processes and collecting data required for sustainability assessment is felt. In the paper (Chan, Li, Chung, & Saadat, 2017) the manufacturing systems are categorized into three main groups, according to the main elements of the system: production planning and control, inventory management and control and finally manufacturing network design. Furthermore, they focused on the mathematical models and optimization methods corresponding to each category of the manufacturing system. Among all methodologies, algebraic methods and simulation-based methods following the dynamic programming were the most used ones for the first category. As concerns the second category, more than half of the reviewed papers were dedicated to algebraic methods, while Mixed Integer Linear Programming (MILP), Non-Linear Programming (NLP) and meta-heuristics dominate in the third and last category. Authors in (Karl R. Haapala et al. ,2013) divide sustainable manufacturing into two parts: sustainability of manufacturing processes and sustainability of manufacturing systems. In the first part, the paper proposes two main manufacturing processes: metal manufacturing process development, process chemical and lubricants founding out that energy and resource efficient utilization need to be enabled through developing new manufacturing equipment and processes, that have reduced eco-footprint guided by environmental LCA evaluations. The second part, on the other hand, investigates manufacturing systems and concludes that environmental impact reduction, waste production and resource consumptions through continuous improvement methods are the areas with the most focus on. In (Arena et al. 2009) industrial sustainability, its tools and metrics are analysed. The main part of the work is dedicated to sustainability dimensions and their sub dimensions throughout the literature. However, the paper investigates the possibility of adding “technological dimension” as the fourth pillar to the traditional three pillars of sustainability. In (Mitra and Datta 2014) a survey on Green (sustainable) Supply Chain Management (GSCM) is performed to assess the extent of GSCM practices and their impact on the performance of firms. Throughout the survey, the authors came up with the two most significant Key Success Factors (KSF) impacting the performance of the firms: supplier collaboration, product design and logistics for environmental sustainability. Thereupon, they proposed the hypothesis whether environmentally sustainable purchasing practice and environmentally sustainable manufacturing and logistics practices are positively related to competitiveness and economic performance. Consequently, the existence of a positive relationship between competitiveness and economic performance was also tested. Getting the surveys filled by the firms and running the factor analysis, the hypotheses were tested and it was stated that supplier collaboration is positively related to environmentally sustainable product design and logistics which in turn has a positive impact on competitiveness and economic performance. By doing a research on the elements of sustainability, its tools and software during the design stage, the authors in (Mohd Fahrul Hassan, Saman, Mahmood, Nor, & Rahman, 2016) concluded that a sustainability assessment can create critical challenges for product-based assessments in manufacturing if it takes place during the product phase. In (Moldavska & Welo, 2015), the authors discussed the applicability of sustainability assessment tools in manufacturing and claimed that a tool can be counted as applicable if it is capable of: providing reliable information, addressing a manufacturing company’s context, pointing out problem areas and being conducted within limited time and resources. A framework that allows assessment from the customer’s perspective accompanied by product development assessment was then proposed, having a holistic view toward sustainability since it covers economic, environmental and social dimensions alongside assessment of value chain activities, material/information flow and customer relationship.

Samples and descriptive analysis

The overall sample considered in this study is 185 papers (published up to December 2019 as in the Reference section); built according to the criteria above stated. The time distribution of the papers published is shown in figure 1. As it can be seen from the figure, only 2 papers belong to the years prior to 2000 (Costanza and Patten 1995; Loucks 1997), (Costanza and Patten 1995) discusses the definition of sustainability and tries to disclose the characteristics of a (sub) system claimed to be sustainable. Hereof, three main questions are raised and discussed: (1) which (sub) systems are to be sustained? (2) for how long they are to be sustained? (3) when we can assess whether the system has actually been sustained? On the other hand, efforts are made in (Loucks 1997) to quantify sustainability for the purpose of decision-making. In this regard, sustainability index as a weighted combination of (Reliability × Resilience ×Vulnerability) is defined. However, it is also stated that no plan and development path is possible to have all the three factors involved in the index and a trade-off among them is needed based on the decision-maker's opinion.

A small peak appeared on 2004-2005 with 4 papers. However, between 2007 and 2013 the raise in the number of papers comparing to previous years is clear. A sharp growth appeared on 2013-2014 with gradual changes to the current years which shows the rise of concerns on the topic recently.

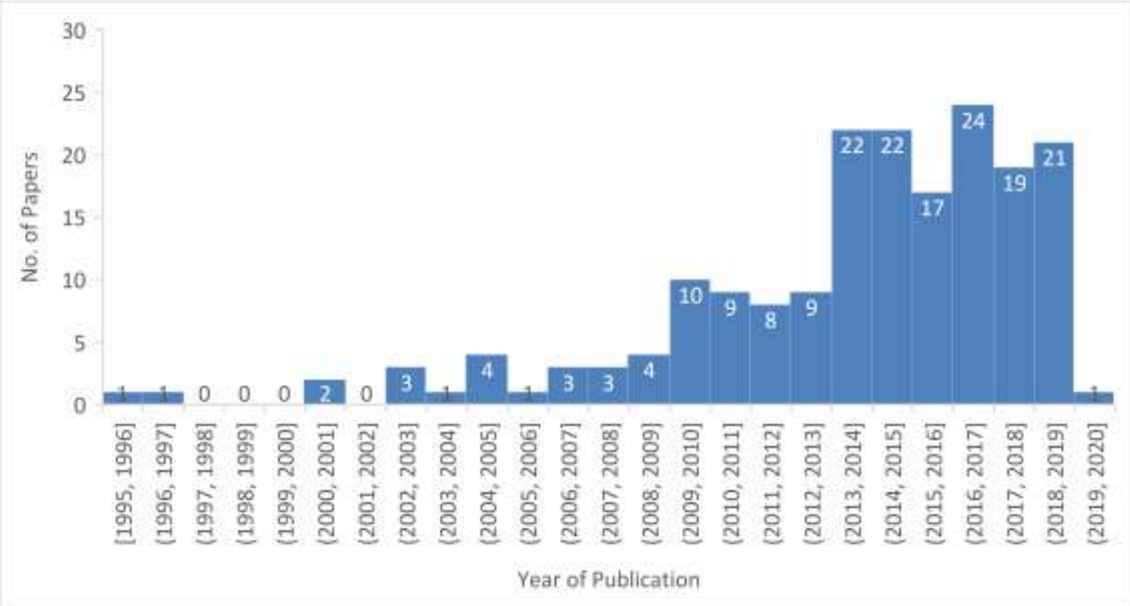

Figure 1. Time distribution of the papers in the sample

Criteria applied in the context analysis in terms of sustainable manufacturing

The criteria for the content analysis can be established based on whether the analysis performed in the paper is deductive or inductive (Seuring 2013). In the present study, as mentioned above, the aim is to generalize research findings in sustainable manufacturing and sustainability assessment issues to a certain extent as well as to get the essence of sustainability assessment in a manufacturing organization: the choice of the content-analysis criteria was mostly deductive, however, in some cases the criteria could only be established during the process of the review and after digging into the concept. Thus, the following criteria were decided to be discussed and stipulated: sustainability dimensions and sustainable manufacturing grouping (systems). In the former criterion, the papers were assessed based on the authors' choice about which dimension of sustainability (economic, environmental and social or any other dimension) they concerned the discussion. The analysis related to this criterion was completed in a previous work

(Eslami et al. 2018a): these results will be used for the purpose of the present work. The latter criterion (systems) is mainly based on the division of sustainable manufacturing provided by the National Council for Advanced Manufacturing (NACFAM, 2009) according to two main categories: (a) manufacturing of 'sustainable' products and (b) sustainable manufacturing of all products. Hereof, the same grouping was considered as the initial point, but they were broken into further subcategories afterwards. The following will show the work done regarding to the division.

Sustainable Manufacturing Grouping (Systems)

Haapala et al. (2013), stated that the term 'sustainable manufacturing' can be carelessly used to describe the actions relating to characterizing and reducing the environmental impacts of manufacturing while it implies a much greater deal than that. To dig a little deeper, sustainable manufacturing was studied in two main categories as mentioned above: (a) manufacturing of 'sustainable' products and (b) sustainable manufacturing of all products.

Based on the definition by (NACFAM,2009), sustainable manufacturing of products (the first group) includes manufacturing of renewable energy, energy efficiency, green building, and other 'green' & social equity-related products. However, to reach sustainable manufacturing of products, it is needed to consider two key issues: which manufacturing processes are performed and where they are performed. The former issue is important from the economic dimension of sustainability, as Nations have a strategic interest in manufacturing activities as a key to raising standards of living and sustaining quality of life. Examples of these processes can be named as: metals manufacturing processes (like casting, forming, machining, grinding …), electronics manufacturing processes (like semiconductor manufacturing) and process chemicals and lubricants (considering solvents, lubricants, etchants and …). The latter on the other hand, is crucial from the environmental dimension since rules and regulations, values and workplace practices differ in different countries (K.R. Haapala et al. 2013). Conclusively, the group of *sustainable manufacturing product*, mostly focuses on the renewable energy and manufacturing processes and the technologies which are outside the defined scope for the present study; therefore, it was excluded from the search, the importance is not negligible though.

The second group on the other hand, mainly focuses on two main criteria: 1) the design of a sustainable production system and 2) design of a closed loop supply chain that considers the complete life cycle of the product from cradle to cradle/grave (Karl R. Haapala et al. 2013). Different key elements have been considered for these two criteria based on the scope of the work. In (Jayal, Badurdeen, Dillon, & Jawahir, 2010), three elements of facility issues, production control and supply chain were studied while (Karl R. Haapala et al. 2013) considered energy auditing, process planning, production scheduling and supply chain. Acknowledging them and the scope previously defined for the present study, the group sustainability of manufacturing system was divided into three main groups: i) facility design and operations, ii) production planning and control and iii) supply chain network design. The final grouping of sustainable manufacturing is shown in figure 2.

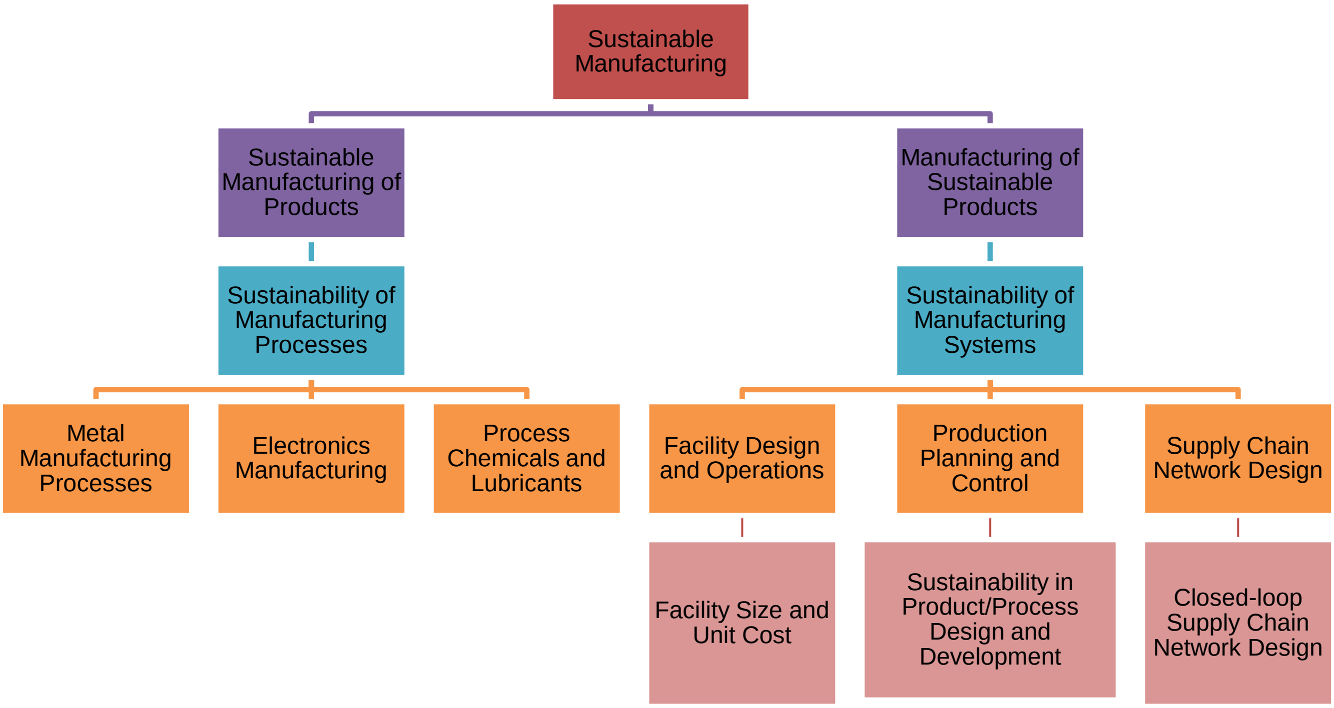

Figure 2. Sustainable manufacturing categorization adopted in this study.

Papers were analysed and categorized based on the element of manufacturing system they cover: the ones covered planning, design, construction, operation, maintenance and decommissioning of facilities were put in facility design and operations; the ones that studied direct manufacturing were categorized as production planning and control and finally if they considered planning and management of sourcing procurement, conversion and logistics activities during the life cycle of the product, laid under supply chain network design. A brief description of each category is brought in the following as well as the statistics of the papers covering the three category is shown in table 1 and figure 3.

Table 1. Paper concerning Sustainable Manufacturing grouped based on sustainability criteria

Sustainable Manufacturing Systems	Sustainable Manufacturing Sub-systems	References
Sustainable Manufacturing of Products	Sustainability of manufacturing Processes	**Omitted From the study**
Manufacturing of Sustainable Products	**Facility Design and Operations**	**(Cochran, Jafri, Chu, & Bi, 2016); (Cochran, Kinard, & Bi, 2016); (Cochran, Hendricks, Barnes, & Bi, 2016); (Heilala et al., 2008); (Ramírez, Packianather, & Pham, 2011); (Smirnova et al., 2015); (Mauricio-Moreno, Miranda, Chavarría, Ramírez-Cadena, & Molina, 2015); (Jung, Morris, Lyons, Leong, & Cho, 2015); (McDermott, Folds, Ender, & Bollweg, 2015); (Loucks, D. P. 1997); (Clarke, Zhang, Gershenson, & Sutherland, 2008); (Sutherland, Jenkins, & Haapala, 2010); (Bentaha, Battaiä, & Dolgui, 2015); (Calvo, Domingo, & Sebastin, 2008); (Anvari & Turkay, 2017); (Yoon and Chae 2019); (Ibrahim, Hami, and Othman 2019); (Yazdi, Azizi, and Hashemipour 2018); (He, Pan, and Deng 2018)**
	Sustainability through Production Planning and Control	(Lillehagen & Petersen, 2015); (Caruso, Dumbacher, & Grieves, 2010); (Tagliaferri et al., 2016); (Atwater & Uzdzinski, 2014); (Garcia-Herrero et al., 2017); (Haanstra, Toxopeus, & van Gerrevink, 2017); (Jayal, Badurdeen, Dillon, & Jawahir, 2010); (Jawahir et al., 2006); (Gutowski et al., 2005); (Güçdemir & Selim, 2017); (Ruiz-Mercado, Gonzalez, & Smith, 2014); (Santucci & Esterman, 2015); (Rezvan, Azadnia, Noordin, & Seyedi, 2014); (Shin & Colwill, 2017); (Mani, Larborn, Johansson, Lyons, & Morris, 2016); (Haapala et al., 2013); (AlKhazraji, Saldana, Donghuan, & Kumara, 2013); (Hassan, Saman, Mahmood, Nor, & Rahman, 2016); (Huang & Badurdeen, 2017); (Lu et al., 2011); (Ranky, 2010); (Li, Mirlekar, Ruiz-Mercado, & Lima, 2016); (Bakshi, 2014); (Grünwaldt, Hofstetter, & Palm, 2011); (Shi & Yang, 2003); (Petnga & Austin, 2014); (Faezipour & Ferreira, 2011); (Salama, Galal, & Elsayed, 2015);

Sustainable Manufacturing Systems	Sustainable Manufacturing Sub-systems	References
		(Bradley, Jawahir, Badurdeen, & Rouch, 2016); (Roy et al., 2014); (Maginnis, Hapuwatte, & Jawahir, 2017); (Hapuwatte, Badurdeen, & Jawahir, 2017); (Hapuwatte, Badurdeen, & Jawahir, 2017); (Badurdeen & Jawahir, 2017); (Yan & Feng, 2014); (Koren, Gu, Badurdeen, & Jawahir, 2018); (Jawahir & Bradley, 2016); (Gao & Wang, 2017); (Chakravorty & Hales, 2017); (Masmoudi, Yalaoui, Ouazene, & Chehade, 2017); (May, Stahl, Taisch, & Prabhu, 2015); (Romli, Prickett, Setchi, & Soe, 2015); (Mouzon, Yildirim, & Twomey, 2007); (Bevilacqua, Ciarapica, & Giacchetta, 2007); (Lye, Lee, & Khoo, 2001); (Giovannini, Aubry, Panetto, Dassisti, & El, 2012); (M.-L. Bentaha, Voisin, and Marangé 2020); (Shivajee, Singh, and Rastogi 2019); (Jiang and Zhang 2019; Liu et al. 2019); (Diaferio et al. 2019; Ramezanian, Vali-Siar, and Jalalian 2019); (Goyal et al. 2019; Rubaiee and Yildirim 2019); (Vimal, Vinodh, and Jayakrishna 2019); (L'Abbate et al. 2018; Paprocka 2018); (Zhang et al. 2018; Bajpai, Fernandes, and Tiwari 2018); (Nujoom, Mohammed, and Wang 2018); (Marshall and Archibald 2018)
	Sustainable Supply Chain Network Design	(Nakano, 2010); (Martin-Rubio, Tarquis, & Andina, 2016); (Varsei, Soosay, Fahimnia, & Sarkis, 2014); (Ramos, Gomes, & Barbosa-Póvoa, 2014); (Choi & Shen, 2016); (Brandenburg, Govindan, Sarkis, & Seuring, 2014); (Smith & Ball, 2012); (Gunasekaran & Spalanzani, 2012); (Urata, Yamada, Itsubo, & Inoue, 2017); (Miranda-Ackerman, Azzaro-Pantel, & Aguilar-Lasserre, 2017); (Umpfenbach, Dalkiran, Chinnam, & Murat, 2017); (Martí, Tancrez, & Seifert, 2015); (Boonsothonsatit, Kara, Ibbotson, & Kayis, 2015); (Jindal & Sangwan, 2014); (Nagurney & Nagurney, 2010); (Badurdeen et al., 2009); (Shuaib & Badurdeen, 2013); (Rosenthal, Fatimah, & Biswas, 2016); (Kuik, Nagalingam, & Amer, 2011); (Badurdeen et al., 2009); (Inman & Green, 2018); (Kaur, Sidhu, Awasthi, Chauhan, & Goyal, 2018); (Das, 2017); (Keivanpour, Ait-Kadi, & Mascle, 2017); (Golini, Moretto, Caniato, Caridi, & Kalchschmidt, 2017); (Quariguasi, Walther, Bloemhof, Van, & Spengler, 2010); (Nugroho and Zhu 2019; Papetti et al. 2019); (Shraddha Mishra and Singh 2019); (Z. Chen and Bidanda 2019); (Jiang and Zhang 2019; S. Mishra and Singh 2019); (J. Gao et al. 2018; Banguera et al. 2018); (Bradley et al. 2018); (Kusi-Sarpong, Gupta, and Sarkis 2019)

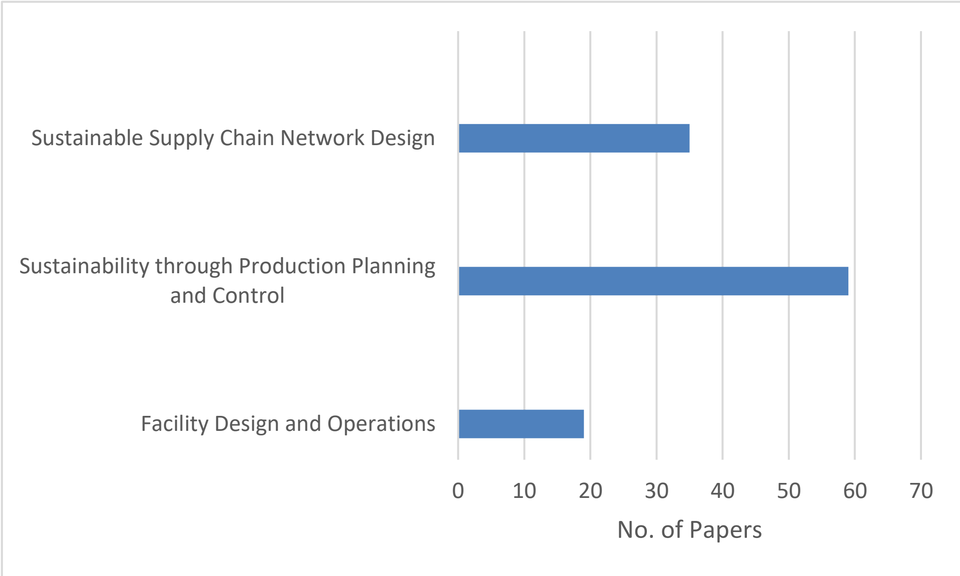

Figure 3. Statistics of papers concerning Sustainable Manufacturing

Facility Design and Operations

The urge to incorporate sustainability principles into decisions regarding planning, design, construction, operation, maintenance and decommissioning of facilities, has imposed increasing pressure to engineers and decision makers. Thus, allocating resources to facilities and infrastructures targeting sustainability is critical, especially within the constrained budget. The authors in (Sutherland, Jenkins, and Haapala 2010) challenged a size-selection problem for a remanufacturing facility, where various aspects were considered, namely: production, transportation and inventory-related costs and explained economy of scale effects. The model resulted in optimal unit cost and facility size as a function of remanufacturing efficiency, product yield, and transportation cost rate. Clarke et al. (2008) discussed the problem of the identification of suitable sites for remanufacturing facilities with a shoe manufacturing case study, they derived a solution by introducing a p-median formulation and a set of economic and environmental factors.

As another approach, authors in (Cochran, Jafri, et al. 2016) employed a manufacturing system design decomposition (MSDD) to uncouple the elements of the manufacturing design and reflect the interaction and priorities of the system elements to reach a sustainable system. As the same approach, (Cochran, Kinard, and Bi 2016) adopted MSDD alongside big data analytics to identify bottlenecks for system improvement and cost-justify/resource-allocation decisions for the continuous improvement and sustainability of the manufacturing enterprise.

Production planning and control

As in (Karl R. Haapala et al., 2013; Hosseini, Nosratabadi, Nehzati, & Ismail, 2012), the total energy required for direct manufacturing processes such as metal working operations, deformation or removal of materials may be not as high as the functions needed at the background for manufacturing equipment operations. In (Gutowski et al., 2005) Gutowski stated that more than 85% of the energy in a production plant is utilized for functions related indirectly to the actual production of parts. Thus, it results that based only on the machines and technologies to save energy is not sufficient and more efforts at the system level of the production is required to gain desirable results to assure sustainability of manufacturing operations (Karl R. Haapala et al., 2013). Employment of Life Cycle Assessment (LCA) has been one of the most common assessment effort in production planning. In (Srinivasan and Sheng, 1999) a process modelling approach connected with LCA is introduced to make modification on product and process design to assist production planning (as in (Atwater & Uzdzinski, 2014; Garcia-Herrero et al., 2017; Pouyan Rezvan et al., 2014; Gerardo J. Ruiz-Mercado, Gonzalez, & Smith, 2014; Salama, Galal, & Elsayed, 2015; Santucci & Esterman, 2015; Tagliaferri et al., 2016) as examples). Authors in (Caruso, Dumbacher, and Grieves, 2010) employed Product Life-cycle Management (PLM) to optimize the phases of the life cycle to reach sustainability.

The model considers the total life-cycle costs as critical decision-making variables and it has been implemented by the Engineering Directorate at the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Centre. The goal of the model is to deliver quality products that meet or exceed requirements on time and within budget. Author in (Utne 2009) discussed the usefulness of Life Cycle Cost (LCC) as a method to enhance sustainable designs of fishing vessels for ship owners, and to improve the decision-bases for fisheries management. Other authors (Güçdemir and Selim, 2017) integrates customer relationship management (CRM) and Production Planning Control (PPC) techniques to use manufacturing resources of job shops more effectively aiming at gaining more sustainable competitive advantage by focusing on customer satisfaction.

Supply chain network design

Sustainable supply chain management was defined as "*the planning and management of sourcing, procurement, conversion and logistics activities involved during premanufacturing, manufacturing, use, and post-use stages in the life cycle in closed-loop through multiple life cycles with seamless information sharing about all product life cycle stages between companies by explicitly considering the social and environmental implications to achieve a shared vision"* (Fazleena Badurdeen et al. 2009). Based on this definition and as observed through the analysis of the papers, sustainable supply chain network design can be categorized as designing of a green enterprise or making a closed loop production by adding the 3R paradigm (Reduce, Reuse and Recycle) or in more innovative cases the 6R paradigm (Reduce, Reuse, Recover, Redesign, Remanufacture and Recycle) (Jawahir et al., 2006; Jayal, Badurdeen, Dillon, et al., 2010) to the conventional production loop. Authors in (Urata, Yamada, Itsubo, & Inoue, 2017) propose a design for a global supply chain networks in Asian countries, by which they could balance the cost of procurement and transportation alongside the material-based

CO_2 emissions to determine the suppliers and factory locations that should be selected to achieve reduced CO_2 emissions. In (Umpfenbach, Dalkiran, Chinnam, & Murat, 2017) a mixed-integer linear programming formulation is presented for integrated assortment and supply chain network design models for automotive products to provide effective decision support and directional guidance to strategic product planners. (Martí, Tancrez, & Seifert, 2015) takes demand uncertainty into account in a supply chain network design model and includes decisions on supply chain responsiveness under carbon policies, such as supply chain carbon footprints, market carbon footprints, and carbon taxes. The suggested model supports the analysis of the effect of different policies on costs and optimal network configuration. In (Jindal & Sangwan, 2014) a multi-product, multi-facility capacitated closed-loop supply chain framework is proposed in an uncertain environment including reuse, refurbish, recycle and disposal of parts. The uncertainty related to demand, fraction of parts recovered for different product recovery processes, product acquisition cost, purchasing cost, transportation cost, processing, and set-up cost is handled with fuzzy numbers. They also propose a fuzzy mixed integer linear programming model for the decisions regarding to the location and allocation of parts at each facility and number of parts to be purchased from external suppliers, all aiming at maximizing the profit of organization. A mathematical model proposed in (Nagurney & Nagurney, 2010) simultaneous determines the supply chain network link capacities, through capital investments, and the product flows on various links simultaneously. However, the optimization model claims that the demands for the product are satisfied at minimal total cost, while the objective function also includes the total cost associated with environmental emissions.

The "6R" paradigm

During the analysis of the papers in terms of sustainable manufacturing, it was observed that attempts to close the material loop and to transform the life cycle have been made to support product and material reutilization and product end-of-life management. Many works like (Lu et al., 2011) accomplished the task by using 3R paradigm (Reduce, Reuse and Recycle) or the 6R paradigm (Reduce, Reuse, Recover, Redesign, Remanufacture and Recycle) throughout the manufacturing cycle and the product life cycle. On the other hand, based on the analysis (Gupta, Dangayach, and Singh 2015) and (Madan, Kannan, and Udhaya , 2017) made, the concept "6R" was announced as the one factor that plays the most important role in reaching environmental sustainability, and the one with the highest influential level in sustainable manufacturing respectively. In this regard, a short survey was run to first dig a little bit deeper in the concept of "6R" and to see to what group of sustainable manufacturing belong to it. Therefore, 19 papers were selected with the keywords "6R", "Sustainable Manufacturing" and/or "sustainability" and were studied whether they lie in "Facility Design and Operation", "Production Planning and Control" or "Sustainable Supply Chain Network Design" categories of sustainable manufacturing. In addition, the sustainability dimension they took into account was also checked. Table 2 shows the result.

Table 2. Analysing the concept "6R"

		Sustainable Manufacturing			Sustainability Dimension		
Reference	**Year**	**Facility Design and Operations**	**Production Planning and Control**	**Supply Chain Network Design**	**Environmental**	**Social**	**Economic**
(Badurdeen et al., 2009)	2009			●	●	●	●
(Jayal, Badurdeen, Dillon, & Jawahir, 2010)	2010		●		●	●	●
(Lu et al., 2011)	2011		●		●	●	●
(Kuik, Nagalingam, & Amer, 2011)	2011			●	●	●	●
(Shuaib & Badurdeen, 2013)	2013			●			
(Roy et al., 2014)	2014		●		●	●	●
(Yan & Feng, 2014)	2014		●		●	●	●
(Bradley, Jawahir, Badurdeen, & Rouch, 2016)	2016		●		●	●	●
(Rosenthal, Fatimah, & Biswas, 2016)	2016			●	●		
(Jawahir & Bradley, 2016)	2016		●		●	●	●
(Maginnis, Hapuwatte, & Jawahir, 2017)	2017		●		●	●	●
(Hapuwatte, Badurdeen, & Jawahir, 2017)	2017		●		●	●	●
(Badurdeen & Jawahir, 2017)	2017		●		●	●	●
(Huang & Badurdeen, 2017)	2017		●		●	●	●
(Gao & Wang, 2017)	2017		●		●	●	●
(Koren, Gu, Badurdeen, & Jawahir, 2018)	2018		●		●	●	●
(Dassisti et. alii, 2018)	2018		●	●	●	●	●
)(Bradley et al. 2018)	2018			●	●	●	●
(J.-K. Choi, Thangamani, and Kissock 2019)	2019			●	●		●

As it can be seen from table 2, the very recent concept of “6R”, is more used in the group “Production Planning and Control” and was never considered in “Facility Design and Operation”. On the other hand, 16 out of 19 analysed papers covered all three traditional dimensions of sustainability.

Discussion on the Essence of Sustainable Manufacturing

Sustainability Dimensions

It was observed in (Eslami et al., 2018) that among sustainability dimensions like social, technological, economic, environmental, technology, efficiency and performance management, the traditional three - namely: economic, environmental and social, also known as the Triple Bottom Line (TBL) - were the ones with the most concentration on publications. However, social dimension seems to be the one which was hardly discussed comparing to the other two, regarding to its qualitative nature. On the other hand, as the majority of the papers analysed insisted on considering all the three dimensions simultaneously, it endorses the urge to have a holistic view through sustainability by considering all the three traditional pillars.

Criteria for pursuing Sustainable Manufacturing

The grouping of the papers analysed shows that sustainable manufacturing is addressed throughout the whole life cycle of the product, from design to manufacturing processes, including production planning and the supply chain of the product. Areas like resource consumption (including energy, water, material and external resources), waste management, managing emissions, optimizing cost of operations, supply chain costs, customer satisfaction and increasing health and safety of the personnel were the most studied ones.

The '6R' paradigm (Redesign, Remanufacture, Reuse, Recover, Recycle and Reduce) and its usage in sustainable manufacturing was also studied. It is proved that 6R can be a very effective assessment factor in terms of pursuing sustainable manufacturing, especially in the category of production planning and control, and it can cover all the three traditional dimensions of sustainability.

Concluding the points above bolds the urge for companies to leave the traditional approach behind and go beyond, to reach the sustainability paradigm in manufacturing. Traditionally, the whole focus for sustainability was on the two stages of manufacturing and logistics, while now it is needed to be concentrated on all the stages. On the other hand, the elements of the 6R, which are claimed as the innovative elements by (Jayal, Badurdeen, Dillon Jr., et al., 2010) must be integrated in the Life cycle of the product, to pave the path to sustainable manufacturing.

Sustainability Assessment

The need for assessment of sustainability in manufacturing tasks was recognized more than forty years ago. As the pressure of the demand for sustainability increases on the manufacturing companies, the urge for assessing their performance has been reinforced. However, at the time the concept appeared, the most focus was on environmental impacts only, which was gradually expanded to the other pillar of sustainability (social) (Pope, Annandale, & Morrison-Saunders, 2004) while economic dimension was the preeminent approach followed. In (Devuyst, 2001) sustainability assessment is defined as a methodology "*that can help decision makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable"*. On the other hand, the goal of Sustainability Assessment (SA) is defined by (Verheem, 2002) to pursue *'plans and activities that make an optimal contribution to sustainable development'*. Sustainability Assessment (SA) is known to be a complex appraisal method and conducted for supporting decision making and policy in a broad environmental, economic and social context (Sala, Ciuffo, & Nijkamp, 2015). Various methods and assessment have been accomplished through the scientific literature so far, trying to find a way for companies to assess their sustainability state, help the companies choose between sustainable solutions, define and solve problems on the way to implement sustainable solutions.

Methodologies and Tools

Tools and methodologies for sustainability assessment have been studied and categorized throughout the scientific literature. The review authored by (Moldavska & Welo, 2015) on the tools employed for sustainability assessment and about their categorization (as shown in table 3), claimed that the tools addressed to all three aspects of sustainability. Those tools are of the greatest interest among all and can be applied at the company level. With a different view, (Hacking & Guthrie, 2008) categorized the assessment features to the three categories of *context features* (features that characterize the planning and decision-making context and describe the relationship between the assessment and its context), *process features* (including when and by whom, the assessment is undertaken) and *features within the assessment* (the type and level of analysis used, and what the output of the assessment process contains). In (Konys, 2018) the authors categorized the several groups of sustainable measurements to 3 main ones as frameworks, indicators and measures. However, they state that - although these groups and methods differentiate from each other, as the application for these approaches are vast and the result of impact assessment can vary considerably based on the sustainability dimension - they still share some features with each other. For example, frameworks provide the guidelines for a given domain of interest or considered problem about the sustainability dimensions, while metrics and indicators are used to assess the sustainability performance of a process or a system, to evaluate the process toward enhancing sustainability and to assist decision-makers in evaluating alternatives. Other categorizations observed through the literature are shown in Table 3.

Considering the tools used to assess sustainability, the one that has been used the most was the assessment through sets of indicators and metrics which can be confirmed by (KEI, 2005): “Indicators and composite indicators are increasingly recognized as a useful tool for policy making public communication in conveying performance information on countries’ in fields such as environment, technological economy, society, or development”. Indicators can summarize, quantify, condense and analyse enormous and complicated concepts and transform them to manageable and applicable information for the corporate (Godfrey and Todd, 2001; Warhurst, 2002). On the other hand, they should be used carefully, provided the related decision may strongly impact the true effect on manufacturing. Sustainable development indicators in general, can assess and evaluate the performance, provide trends on improvements plus warnings in case the corporate is facing a drop off in dimensions of sustainability and provide information to decision makers (Lundin, 1999; Spohn, 2004). Authors in (M.F. Hassan, Saman, Mahmood, Nor, & Rahman, 2017) did an environmental and technical sustainability assessment on an existing water distribution system, when reclaimed water is used for non-potable water demand and fire flow. The authors provided scenario-based solutions for decision makers to illustrate the trade-off between the environmental and technical sustainability. Considering reliability, resiliency, and vulnerability performance criteria a sustainability Index has been defined to measure the sustainability performance of the water system. In (Krajnc & Glavič, 2005) difficulties existing on the way of comparing companies in terms of sustainability due to a large number of performance measurements was apprised. Therefore, they proposed model for designing a composite sustainable development index (ICSD) that depicts performance of companies along all the three dimensions of sustainability: economic, environmental, and societal. They represented how sustainability indicators can be associated into sustainability sub-indices and finally into an overall indicator of a company performance. In (Huang & Badurdeen, 2017) the authors propose a framework to enable the manufacturing sustainability assessment at the system level. A five-stage metrics hierarchy to assess the sustainable performance is then introduced covering the TBL, product life cycle and also the 6R paradigm. In (Lu et al., 2011) the work done in (Jayal, Badurdeen, Dillon, et al., 2010) was extended with a framework for evaluating the sustainability content of a product through Product Sustainability Index (PSI) in terms of all three components of sustainability (economy, environment and society) throughout all four stages of the product life cycle (pre-manufacturing, manufacturing, use, post-use) comparing various competitive products of the same family.

Table 3. Assessment Tools Categories done through literature

Citation	Tools
(Pope, Annandale, & Morrison-Saunders, 2004)	EIA-driven integrated assessment
	Objectives-led integrated assessment
	Assessment for sustainability
(Dewan,2006)	Monetary Aggregation Method
	Physical Indicators
(Ness, Urbel-Piirsalu, Anderberg, & Olsson, 2007)	Indicators
	Product-Related assessment
	Integrated Assessment
(Videira, Antunes, Santos, & Lopes, 2010)	EIA-driven integrated assessment
	Objectives-led integrated assessment
	Integrated Sustainability Assessment
(Singh, Murty, Gupta, & Dikshit, 2012)	Indicators
	Product-Related assessment
	Integrated Assessment
(Moldavska & Welo, 2015)	fuzzy based sustainable manufacturing assessment model (Singh, Olugu, & Fallahpour, 2014);
	sustainable manufacturing mapping (Paju et al., 2010);

	sustainable manufacturing indicators Moneim, Galal, & Shakwy, (2013);
	indicators for sustainable production (Veleva & Ellenbecker, 2001);
	Integrated assessment of sustainable development (Krajnc & Glavič, 2005);
	integrated sustainability based on Gibson's approach (Winfield, Gibson, Markvart, Gaudreau, & Taylor, 2010);
	an AHP-based model for sustainable manufacturing performance evaluation;
	a holistic and rapid sustainability assessment tool (Chen, Thiede, Schudeleit, & Herrmann, 2014);
	sustainable value stream mapping (Faulkner & Badurdeen, 2014);
	combining sustainable value stream mapping and simulation (Sparks & Badurdeen, 2014);
	sustainable domain value stream (sdvsm) framework (yusof, Saman, & Kasava, 2015)
(Morrison-Saunders, Pope, & Bond, 2015)	EIA-driven integrated assessment
	Objectives-led integrated assessment
	Contribution to sustainability

Among many disciplines and methods to assess sustainability, Life Cycle Assessment (LCA) was used the most after indicators. However, as (Onat et al., 2017) stated, LCA is an interdisciplinary framework for integration of models rather than a method itself. Authors in (Garcia-Herrero et al., 2017) only focused on the environmental dimension of sustainability and combined LCA and Linear Programming to reach higher level of sustainability in production. By employing LCA and using the environmental sustainability assessment (ESA), the authors meant to obtain two main indices of natural resources (NR) and environmental burdens (EB). Normalized indices were optimized to determine the optimal joint of weighting factors that led to an optimized global Environmental Sustainability Index to determine the environmental improvement actions which resulted in sustainable production. In (Santucci and Esterman, 2015) system engineering tools and a functional analysis-based approach was adopted to establish a standardized LCA method to develop a framework by which environmental impacts of a product system can be assessed and addressed during product development. The framework helps designers develop, classify, and explore different product designs based on predictive environmental impact. Lee et al. (2014) introduces MAS2, by which sustainable manufacturing can be assessed through an integrated modelling and simulation-based life cycle evaluation approach. This work provided a way to assess the sustainability performance by combining sustainability concepts with engineering technologies using mathematical modelling. Authors in (P. Rezvan et al., 2014) proposed a hybrid approach of fuzzy inference system and analytical hierarchy process (AHP) to evaluate the sustainability level of concrete manufacturing processes based on Life Cycle Assessment (LCA) principals.

Improving Unit Manufacturing Processes (UMP) throughout industry can be noted as another methodology to elevate the sustainability performance. As an example, (Mani, Larborn, et al., 2016) discussed the effectiveness of the E3012-16 standard regarding to assessment and improvement of the sustainability of production processes through three different case studies. The paper defines a generic representation to support structured processes and tried to link multiple unit manufacturing processes (UMPs) to support system-level analysis, such as simulation and evaluation of a series of manufacturing processes used in the manufacture and assembly of parts. Garretson et al. (2014) used unit manufacturing process models to chain together a sequential manufacturing process flow to generate a product sustainability assessment: the method brings together upstream inventory analysis and in-house unit process modelling. In this way, cradle-to-gate assessments can support decisions made during product, process, and supply chain design. They also came up with a software is also using Visual Basic to create a graphical user interface for an MS Excel calculation engine. (Eastwood and Haapala, 2015) addresses sustainability factors and tries to quantify these through understanding unit manufacturing processes and the collection of process-specific data. It combines unit process modelling and life cycle inventory techniques to aggregate and quantify sustainability performance metrics for the process level through the three traditional dimensions of sustainability. The assessment that the authors propose makes it possible for the product designers to consider sustainability performance of similar processes and designs by exploring the design alternatives, while our approach in the present work mixes up the features of the different objects belonging to the three levels, process, product and system.

Value Stream Mapping (VSM)-based tools were also tested to assess sustainability mostly based on applying indicators to manufacturing processes. In (Paju et al., 2010) the authors did an assessment as they combined value stream mapping alongside a new methodology called sustainable manufacturing mapping (SMM), discrete event simulation (DES) and life-cycle analysis (LCA). In the proposed methodology, DES works as an add-on element and VSM is considered as a visualization technique used to implement environmental indicators. SMM carries out VSM and takes a goal-oriented approach, as defined in LCA (ISO 14040 2006) and chooses sustainability indicators according to that goal. However, they also mention that since the assessment does not use the same indicators, the cross comparison between system can be challenging. (Faulkner and Badurdeen, 2014) on the other hand, presents a methodology to develop Sustainable Value Stream Mapping (Sus-VSM) by identifying suitable metrics and methods to visually present them. The metrics are related to evaluation of environmental and societal sustainability performance of a manufacturing line. The authors then created visual symbols for each proposed metric to ensure visual clarity and the usefulness of the proposed method.

Nevertheless, other tools and models were developed to assess sustainability. To name a few, in (Chen et al., 2014) a tool for assessing sustainability for small manufacturing enterprises is presented. Based on the authors, the tool is holistic and rapid and since it is industry-independent, it can be used as a generic cross industry assessment tool. In (Ciceri et al., 2010) a product bill-of-material-based approach is proposed to estimate the material and manufacturing energy, in which the estimation is through compiling available data from sources like material embodied figures, empirical data and bill of material. Authors in (Morrison-Saunders and Therivel, 2006) stated that lack of a practical definition of sustainable manufacturing, shortcomings of existing sustainability assessments to analyse sufficiently current conditions of the organization, and the uncertainty of the effect of actions proposed by decision makers based on the result of a sustainability assessment are the barriers on the way of transitioning of manufacturing organizations to sustainable ones. To overcome the mentioned constraints, they used complexity theory and developed a model which represents the complexity-based definition of a sustainable manufacturing which can help reduce the complexity of sustainability and manufacturing issues; thus, it can serve sustainability assessments. In (Hegab, Darras, and Kishawy, 2018) a manufacturing ecosystem model was developed based on industrial ecology and it aims at building quantitative modelling tools to seek integrated solutions for lower resource input, higher resource productivity, fewer wastes and emissions, and lower operating cost within the boundary of a factory. The focus of the model is on overall performance of manufacturing systems using a build cross-disciplinary model of the Material, Energy and Waste (MEW) flows to link all three components of the system: the manufacturing operations, the supporting facilities and the surrounding buildings.

Considering all abovementioned approaches, a categorization of the methodologies for sustainability assessment in manufacturing was done as presented in table 4. The base for the categorization is on the primary tool used for the process of assessment. On the other hand, the secondary tools and other tools in case of existence are mentioned.

Table 4. Sustainability assessment categorization based on the primary tool used

Methodologies	**Reference**	Primary Tool	Secondary Tool	Other Tools I	Other Tools II
Indicators	(Lanz et al., 2014)	Indicators	A Network Analysis Tool		
	(Aydin, Mays, & Schmitt, 2014)	Sustainability Index (SI)	Linear Programming	Multi Criteria Decision Analysis (MCDA)	
	(Loucks, D. P. 1997)	Indicators			
	(Ruiz-Mercado, Gonzalez, & Smith, 2014)	Indicators	LCA		
	(Krajnc & Glavič, 2005)	Indicators	Mathematical Modeling		
	(Labuschagne, Brent, & van Erck, 2005)	Indicators			
	(Eastlick & Haapala, 2012)	Indicators	Process Modeling		
	(Mani, Madan, Lee, Lyons, & Gupta, 2014)	Indicators	Process Modeling		
	(Huang & Badurdeen, 2017)	Indicators			
	(Lu et al., 2011)	Indicators			
	(Jawahir et al., 2006)	Indicators			
	(Justin J. Keeble et al., 2003)	Indicators			
	(Veleva & Ellenbecker, 2001)	Indicators			
	(de Silva, 2009)	Indicators			
	(Li, Mirlekar, Ruiz-Mercado, & Lima, 2016)	Indicators	LCA		
	(Garbie, 2015)	Indicators			
	(Hapuwatte, Badurdeen, & Jawahir, 2017)	Indicators			
	(Kluczek, 2016)	Indicators	AHP		

Methodologies	**Reference**	Primary Tool	Secondary Tool	Other Tools I	Other Tools II
	(Chaim, Muschard, Cazarini, & Rozenfeld, 2018)	Indicators			
	(Hegab, Darras, & Kishawy, 2018)	Indicators			
	(Garbie, 2014)	Indicators	AHP		
	(Harik, El, Medini, & Bernard, 2015)	Indicators	AHP	System Dynamics	
	(Ahmad, Wong, and Rajoo 2019)	Indicators			
	(J.-K. Choi, Thangamani, and Kissock 2019)	Indicators			
	(Zarte, Pechmann, and Nunes 2019)	Indicators			
	(Krajnc & Glavič, 2005)	Indicators			
Manufacturing Process	(Smith & Ball, 2012)	Process Flow Modeling			
	(Garretson, Eastwood, Eastwood, & Haapala, 2014)	Unit Manufacturing Process (UMP)	LCA		
	(Wang, Zhang, Liang, & Zhang, 2014)	UMP	Indicators		
	(Mani, Larborn, Johansson, Lyons, & Morris, 2016)	UMP	LCA	Discrete Event Analysis (DES)	
	(Eastwood & Haapala, 2015)	UMP	LCI	Mathmatical Modeling	Indica tors
LCA-Based	(Santucci & Esterman, 2015)	LCA	Systems Engineering		
	(Kellens, Dewulf, Overcash, Hauschild, & Duflou, 2012)	LCA	UMP		
	(Zhao, Perry, & Andriankaja, 2013)	LCA	Product Life-cycle Management (PLM)		
	(Joglekar, Kharkar, Mandavgane, & Kulkarni, 2018)	LCA	MCDA		
	(Heidrich & Tiwary, 2013)	LCA			
	(Lake, Acquaye, Genovese, Kumar, & Koh, 2015)	Hybrid LCA			

Methodologies	Reference	Primary Tool	Secondary Tool	Other Tools I	Other Tools II
	(Intini, Kühtz, Milano, & Dassisti, 2015)	LCA			
	(Onat, Kucukvar, Tatari, & Egilmez, 2016)	LCSA	System Dynamics		
	(Dassisti, Cozzolino, et al. 2016)	LCA			
	(Dassisti, Intini, et al. 2016)	LCA			
	(A. Moldavska and Welo 2018)	LCA	Indicators		
Fuzzy	(Rezvan, Azadnia, Noordin, & Seyedi, 2014)	Fuzzy	AHP	LCA	Indicators
	(Jayawickrama, Kulatunga, & Mathavan, 2017)	Fuzzy	AHP	Indicators	
	(Singh, Olugu, & Fallahpour, 2014)	Fuzzy	Indicators		
Value Stream Mapping (VSM)	(Faulkner & Badurdeen, 2014)	VSM	Indicators		
	Yusof, N. M., Saman, M. Z. M., & Kasava, N. K. (2015	VSM	Indicators		
	(Xing, Wang, & Qian, 2013)	Value Assessment Model	LCA	NPV	
	(Sunk, Kuhlang, Edtmayr, & Sihn, 2017)	VSM	MTM(Method-Time Measurement)		
	(Paju et al., 2010)	VSM	Indicators	LCA	DES
System Thinking	(Moldavska & Welo, 2016)	System Thinking	MBSE		
	(Uphoff, 2014)	System Thinking			
	(Ries, Grosse, & Fichtinger, 2017)	Systematic Assessment	Indicators	Factorial Analysis	
	(Thirupathi, Vinodh, and Dhanasekaran 2019)	System Dynamics	Indicators		
	(Long, Pan, Farooq, & Boer, 2016)	System Thinking	Indicators		
Mathematical Modeling	(Ramos, Gomes, & Barbosa-Póvoa, 2014)	Vehicle Routing Problem (VRP)			

Methodologies	**Reference**	Primary Tool	Secondary Tool	Other Tools I	Other Tools II
	(Balkema, Preisig, Otterpohl, & Lambert, 2003)	Mathematical Modeling	Indicators		
	(Tsai et al., 2015)	Mathematical Modeling	LCA	ABC	
	(Garcia-Herrero et al., 2017)	Linear Programming (LP)	LCA	Indicators	
	(Shin & Colwill, 2017)	SLCA	AHP		
Integrated Sustainability Assessment	(Dewulf et al., 2015)		LCA (Social LCA)	Resource Criticality	
	(Videira, Antunes, Santos, & Lopes, 2010)		System Dynamics		
	(Lee, Kang, & Noh, 2014)		LCA	Simulation	Indicators
	(Ramos, Ferreira, Kumar, Garza-Reyes, & Cherrafi, 2018)	Lean Cleaner Production Benchmarking	Lean Manufacturing (LM)	Cleaner Production (CP)	Indicators
	(Rondini, Tornese, Gnoni, Pezzotta, & Pinto, 2017)	Hybrid Simulation Modeling	DES	Agent-Based Modeling	
	(Dai & Blackhurst, 2012)		AHP	QFD	
	(Halog & Manik, 2011)		System Thinking (System Dynamics)	Agent-Based Modeling	Network Theory
Other Methodologies	(Moldavska, 2016)	Complexity Theory			
	(Despeisse, Ball, Evans, & Levers, 2012)	Resource Flow			
	(Chen, Thiede, Schudeleit, & Herrmann, 2014)	Connection Matrices			
	(Garbie, 2013)	Design For Sustainable Manufacturing Enterprise (DFSME)	Sustainability Index		
	(Lee & Lee, 2014)	SAiM Model			
	(Ciceri, Gutowski, & Garetti, 2010)	Proposed Tool to estimate materials and manufacturing energy for a product			

Methodologies	Reference	Primary Tool	Secondary Tool	Other Tools I	Other Tools II
	(Keivanpour & Ait, 2017)	Visualization (Design for Environment)	LCA		
	(K. E. K, Vinodh, and Gurumurthy 2018)	graph-theory based Modeling	Indicators		

Looking through the tools used for sustainability assessment, the regularity of the application of assessment tools was scrutinized as primary, secondary and the combination of both.

Clustering Assessment Methodologies and Tools for manufacturing sustainability

To serve the purpose of the present paper, Formal Concept Analysis (FCA) as a clustering technique was chosen to help discover the hidden relations between the assessment tools. FCA is a branch of lattice theory (Wille, 1982) and it is best used for knowledge representation, data analysis, and information management. It detects conceptual structures in data and consequently extraction of dependencies within the data by forming a collection of objects and their properties (Mezni and Sellami, 2017; Wajnberg et al. 2017).

FCA method starts with the input data in a form of a matrix, in which each row represents an object from the domain of interest, and each column represents one of the defined attributes. If an object has an attribute, a mark (e.g. symbol "●") is placed on the intersection of that object's row and that attribute's column. Otherwise, the intersection is left blank. The matrix is called the “formal context” on which the analysis will be performed. For the present study, the rows with at least one assessment tool in table 4 are used as the “formal context”. The FCA method results in two sets of output data: The first set gives a hierarchical relationship of all the established concepts in the form of line diagram called a concept lattice, while the second one gives a list of all found interdependencies among attributes in the formal context (Škopljanac-Mačina and Blašković 2014). The second set is used for the analysis and the results will be represented consecutively in table 5. In the table the suffixes I, II, III and IV are referring to primary tool, Secondary tool, other tools I and other tools II respectively as shown in table 4.

Table 5. FCA results for sustainability assessment tools

Intent	No. of Papers
{Indicators IV}	4
{Indicators III}	2
{LCA III}	2
{System Dynamics II}	2
{Indicators II}	9
{AHP II}	6
{LCA II}	9
{LCA II; Indicators IV}	2
{Integrated Sustainability Assessment I}	7
{Integrated Sustainability Assessment I; Indicators IV}	2
{Integrated Sustainability Assessment I; Agent-Based Modelling III}	2
{Integrated Sustainability Assessment I; system Thinking II; Agent-Based Modelling III; Network Theory IV}	1
{Integrated Sustainability Assessment I; DES II; Agent-Based Modelling III}	1
{Integrated Sustainability Assessment I; Lean Manufacturing (LM) II; Cleaner Production (CP) III; Indicators IV}	1
{Integrated Sustainability Assessment I; System Dynamics II}	1
{Integrated Sustainability Assessment I; AHP II; QFD III}	1

Intent	No. of Papers
{Integrated Sustainability Assessment I; LCA II}	2
{Integrated Sustainability Assessment I; LCA II; Simulation III; Indicators IV}	1
{Integrated Sustainability Assessment I; LCA II; Resource Criticality III}	1
{Mathematical Modelling I}	5
{Mathematical Modelling I; Indicators II}	1
{Mathematical Modelling I; LCA II}	2
{Mathematical Modelling I; LCA II; Indicators III}	1
{Mathematical Modelling I; LCA II; ABC III}	1
{System Thinking I}	5
{System Thinking I; MBSE II}	1
{System Thinking I; Indicators II}	3
{System Thinking I; Indicators II; Factorial Analysis III}	1
{Value Stream Mapping (VSM) I}	5
{Value Stream Mapping (VSM) I; MTM (Method-Time Measurement) II}	1
{Value Stream Mapping (VSM) I; Indicators II}	3
{Value Stream Mapping (VSM) I; Indicators II; LCA III; DES IV}	1
{Value Stream Mapping (VSM) I; LCA II; NPV III}	1
{Fuzzy I}	3
{Fuzzy I; Indicators II}	1
{Fuzzy I; AHP II}	2
{Fuzzy I; AHP II; Indicators III}	1
{Fuzzy I; AHP II; LCA III; Indicators IV}	1
{LCA-Based I}	10

Intent	No. of Papers
{LCA-Based I; System Dynamics II}	1
{LCA-Based I; MCDA II}	1
{LCA-Based I; Product Life-cycle Management (PLM) II}	1
{LCA-Based I; UMP II}	1
{LCA-Based I; Systems Engineering II}	1
{UMP I}	4
{UMP I; Indicators II}	1
{UMP I; LCA II}	3
{UMP I; LCA II; Mathematical Modelling III; Indicators IV}	1
{UMP I; LCA II; Discrete Event Analysis (DES) III}	1
{Manufacturing Process I}	1
{Indicator I}	26
{Indicator I; AHP II}	3
{Indicator I; AHP II; System Dynamics III}	1
{Indicator I; Process Modelling II}	2
{Indicator I; Mathematical Modelling II}	1
{Indicator I; LCA II}	1
{Indicator I; Linear Programming II; Multi Criteria Decision Analysis (MCDA) III}	1
{Indicator I; A Network Analysis Tool II}	1

As mentioned above, FCA helped find the link between the tools used for the purpose of sustainability assessment. However, since considering all levels of assessment tools will widen the area of research more than desired, the focus of the present study will be only on the primary and the secondary tools, and how often they have been used.

Consequently, as observed in table 5 and shown in figure 4, indicators as a primary tool has the highest rate of application among the others with a notable difference; which itself offers the tendency toward quantifying sustainability and measuring it through the literature. The next ones are LCA-based methods and integrated sustainability assessment methodologies which both are used as paradigms to assess sustainability. Tools like system thinking and fuzzy methodology were used the least, which doesn't refer to the lack of importance of the tools but the need for more attention to them. Manufacturing processes were also used the minimum; however, it is believed the result is due to the domain of research and excluding manufacturing processes from the research. On the other hand, both indicators and LCA-based methods ranked the highest as the secondary tools but with ignorable differences as presented in figure 5. When it comes to the combination of primary and secondary tools (figure 6), less fluctuation between methodologies is observed, the aforementioned tools (indicators and LCA-based) were the ones repeated the most both as primary and as secondary tool as it was expected since there were the ones ranked the highest as a solo tool to assess sustainability.

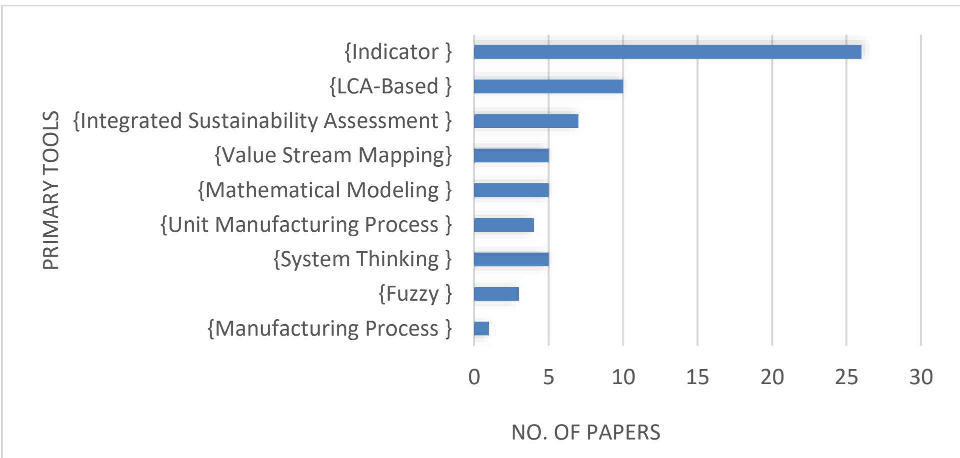

Figure 4. Primary tools for sustainability assessment after FCA analysis

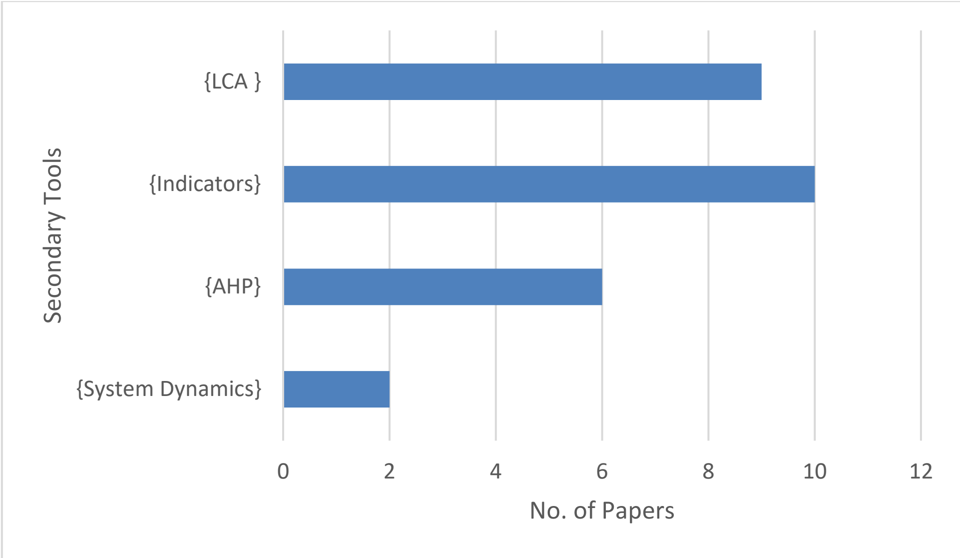

Figure 5. Secondary Tools for sustainability assessment after FCA analysis

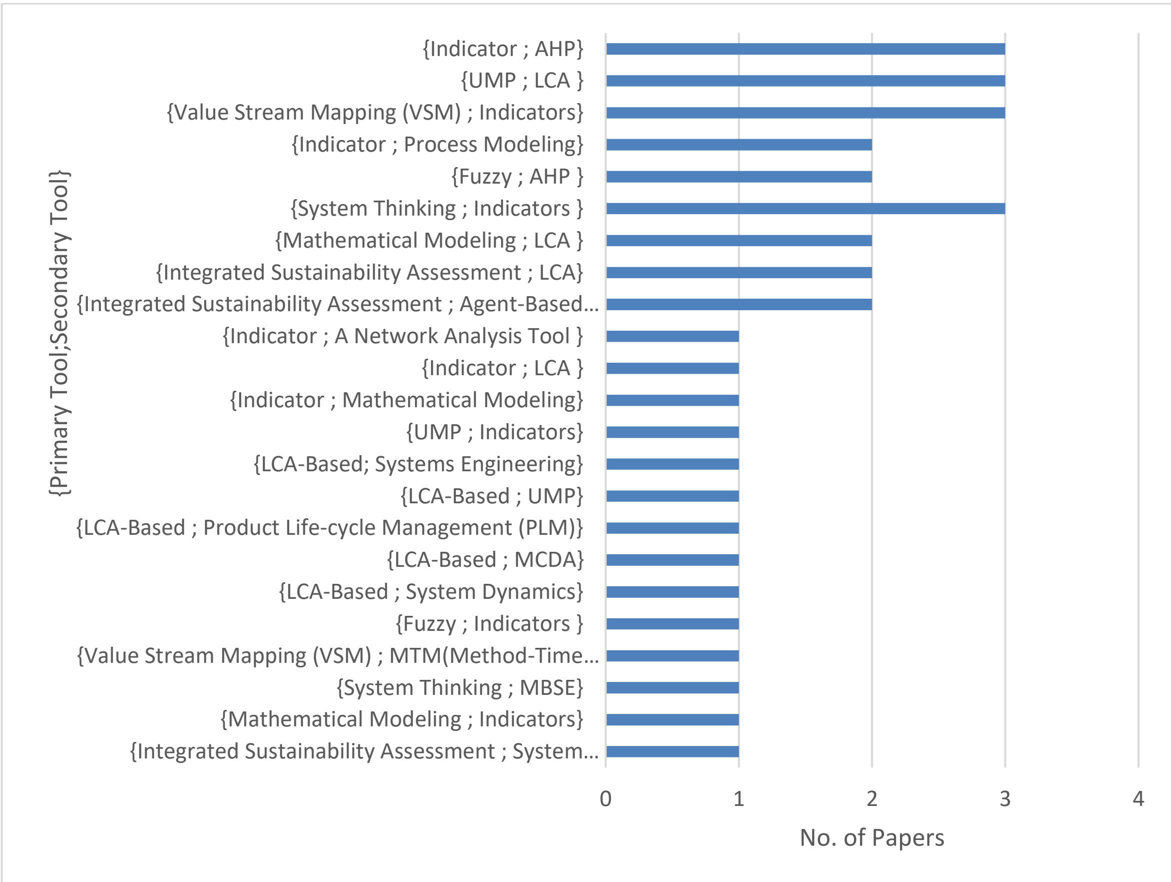

Figure 6. Combination of {Primary Tools; Secondary Tools} for sustainability assessment

Discussions

Out the 185 papers analysed, 81 papers laid in the category “Sustainability assessment and its tools” and were studied to assess if they meet our main three needs: covering all three dimensions of sustainability (which was the result of the previous study on the dimensions of sustainability), investigating all levels of the organization and whether the assessment procedure encompasses the life cycle of the product or not. The investigation also allowed identifying a set of different approaches for sustainability assessment, as mentioned before, and also to draw several conclusions as here summarised.

The result of the filtering of the studied paper in the field of sustainability assessment is shown in figure 7 and table 6 both. It has been observed that the most common feature among all, is that studied assessment tools are trying to cover all three traditional dimensions of sustainability: environmental, economic and social. About 58% of the papers analysed in the assessment category (47 out of 81 papers) covered these dimensions, which reconfirms one of the conclusions drawn from the sustainable manufacturing sector and proves that all the three pillars are of the same importance when it comes to sustainability.

Many papers, like (Jawahir et al., 2014), (Huang & Badurdeen, 2017) and (Lu et al., 2011), stressed that sustainable manufacturing can be looked for in three different levels and it does not occur only at the manufacturing floor. They focused on the three general levels of product, process and system level. Product sustainability metrics are mostly covering the sustainability dimensions throughout its life cycle, with or without considering products’ end-of-life management. Process metrics, on the other hand, consider manufacturing costs, environmental impacts, waste management, energy consumption, operational safety and personnel health. The system level in this paper was divided into four groups, indeed: line, plant, enterprise and supply chain; the relative metrics were discussed accordingly. However, each division was assessed separately and (see (Huang & Badurdeen, 2017) as an example) and not altogether. Therefore, a more detailed classification and a holistic view of the organization can be a good contribution to the reader. In addition, as the study on sustainable manufacturing clarified, the life cycle of the product is also effective in assessing the sustainability of manufacturing. However, as shown in figure 8, assessment tools seem to miss covering the whole organizational levels as a whole in the evaluation process.

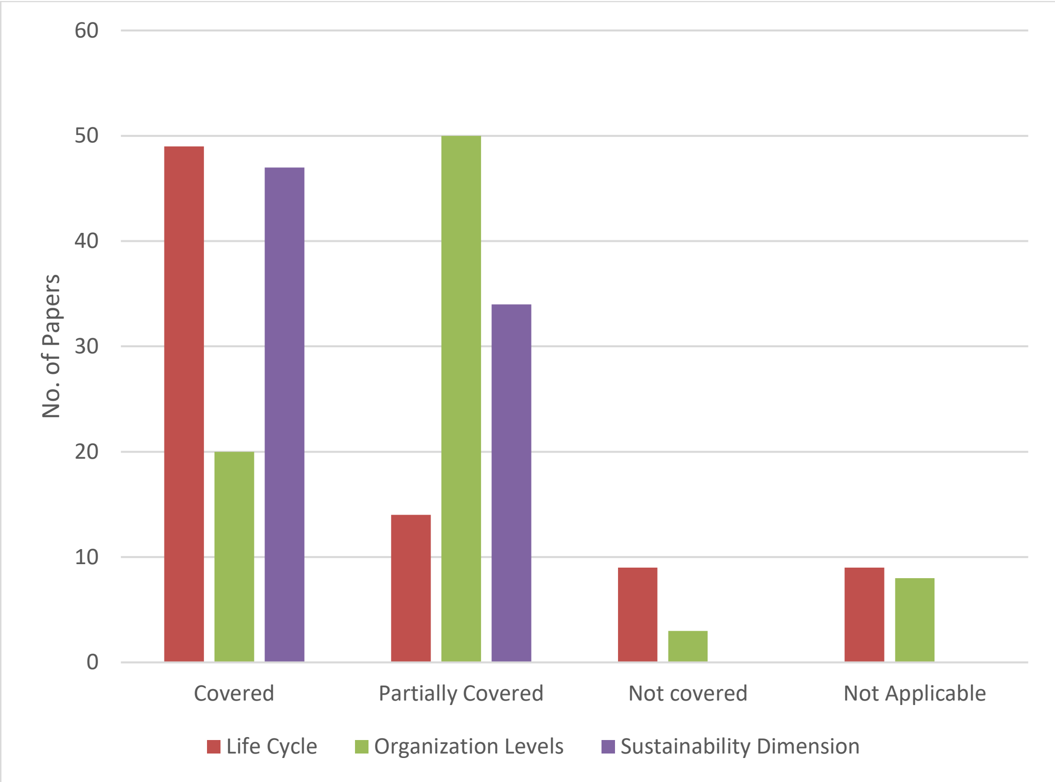

Figure 7. Coverage of sustainability dimensions, Life Cycle and Organizational Hierarchy by Analysed Assessment Tools

Table 6. Sustainability dimensions, Life Cycle and Organizational Hierarchy in assessed papers

Reference	Year of Publication	Life Cycle	Organization Levels	TBL
(Moldavska, 2016)	2016	○	●	●
(Smith & Ball, 2012)	2012	●	▲	▲

Reference	Year of Publication	Life Cycle	Organization Levels	TBL
(Moldavska & Welo, 2016)	2015	○	●	●
(Despeisse, Ball, Evans, & Levers, 2012)	2012	○	▲	▲
(Lanz et al., 2014)	2014	○	●	▲
(Halog & Manik, 2011)	2011	●	●	●
(Uphoff, 2014)	2014	○	▲	●
(Ramos, Gomes, & Barbosa-Póvoa, 2014)	2014	▲	▲	▲
(Rezvan, Azadnia, Noordin, & Seyedi, 2014)	2014	●	▲	●
(Garcia-Herrero et al., 2017)	2017	●	▲	▲
(Aydin, Mays, & Schmitt, 2014)	2014	▲	NA	▲
(Loucks, D. P. 1997)	1997	▲	NA	▲
(Ruiz-Mercado, Gonzalez, & Smith, 2014)	2014	▲	▲	▲
(Mani, Larborn, Johansson, Lyons, & Morris, 2016)	2016	●	▲	▲
(Krajnc & Glavič, 2005)	2005	NA	●	●
(Chen, Thiede, Schudeleit, & Herrmann, 2014)	2014	○	●	●
(Labuschagne, Brent, & van Erck, 2005)	2005	●	▲	●
(Eastlick & Haapala, 2012)	2012	▲	▲	●
(Mani, Madan, Lee, Lyons, & Gupta, 2014)	2014	●	▲	▲
(Balkema, Preisig, Otterpohl, & Lambert, 2003)	2003	●	NA	●
(Huang & Badurdeen, 2017)	2017	●	▲	●
(Lu et al., 2011)	2011	●	▲	●
(Jawahir et al., 2006)	2006	●	▲	●
(Justin J. Keeble et al., 2003)	2003	NA	●	●
(Veleva & Ellenbecker, 2001)	2001	●	●	●
(de Silva, 2009)	2009	●	▲	●
(Li, Mirlekar, Ruiz-Mercado, & Lima, 2016)	2016	●	▲	●
(Santucci & Esterman, 2015)	2015	●	▲	▲
(Faulkner & Badurdeen, 2014)	2014	●	●	▲

Reference	Year of Publication	Life Cycle	Organization Levels	TBL
(Videira, Antunes, Santos, & Lopes, 2010)	2010	○	▲	▲
(Lee & Lee, 2014)	2014	▲	▲	●
(Lee, Kang, & Noh, 2014)	2014	●	▲	●
(Paju et al., 2010)	2010	●	●	●
(Singh, Olugu, & Fallahpour, 2014)	2014	▲	▲	●
(Shin & Colwill, 2017)	2017	●	▲	▲
(Rachuri, Sarkar, Narayanan, Lee, & Witherell, 2011)	2011	●	▲	●
(Ciceri, Gutowski, & Garetti, 2010)	2010	●	▲	▲
(Kellens, Dewulf, Overcash, Hauschild, & Duflou, 2012)	2012	●	▲	▲
(Krajnc & Glavič, 2005)	2005	▲	▲	●
Yusof, N. M., Saman, M. Z. M., & Kasava, N. K. (2015	2015	●	▲	●
(Bertoni, Hallstedt, & Isaksson, 2015)	2015	●	▲	▲
(Garretson, Eastwood, Eastwood, & Haapala, 2014)	2104	●	▲	●
(Long, Pan, Farooq, & Boer, 2016)	2016	●	▲	●
(Eastwood & Haapala, 2015)	2015	●	▲	●
(Wang, Zhang, Liang, & Zhang, 2014)	2014	●	▲	●
(Garbie, 2015)	2015	NA	●	▲
(Jayawickrama, Kulatunga, & Mathavan, 2017)	2017	●	▲	●
(Hapuwatte, Badurdeen, & Jawahir, 2017)	2017	●	▲	●
(Zhao, Perry, & Andriankaja, 2013)	2013	●	▲	▲
(Rondini, Tornese, Gnoni, Pezzotta, & Pinto, 2017)	2017	○	▲	▲
(Onat, Kucukvar, Tatari, & Egilmez, 2016)	2016	●	▲	●
(Kluczek, 2016)	2016	NA	▲	●
(Dewulf et al., 2015)	2015	●	NA	●
(Ramos, Ferreira, Kumar, Garza-Reyes, & Cherrafi, 2018)	2018	●	●	▲
(Joglekar, Kharkar, Mandavgane, & Kulkarni, 2018)	2018	●	NA	●
(Hegab, Darras, & Kishawy, 2018)	2018	NA	▲	●

Reference	Year of Publication	Life Cycle	Organization Levels	TBL
(Chaim, Muschard, Cazarini, & Rozenfeld, 2018)	2018	NA	▲	▲
(Sunk, Kuhlang, Edtmayr, & Sihn, 2017)	2017	●	▲	▲
(Harik, El, Medini, & Bernard, 2015)	2015	●	●	●
(Garbie, 2014)	2014	●	●	●
(Garbie, 2013)	2013	NA	●	▲
(Ries, Grosse, & Fichtinger, 2017)	2017	NA	▲	▲
(Keivanpour & Ait, 2017)	2017	●	NA	▲
(Lake, Acquaye, Genovese, Kumar, & Koh, 2015)	2017	●	●	▲
(Tsai et al., 2015)	2015	●	▲	▲
(Xing, Wang, & Qian, 2013)	2013	●	▲	▲
(Heidrich & Tiwary, 2013)	2014	●	●	▲
(Dai & Blackhurst, 2012)	2012	▲	▲	●
(Intini, Kühtz, Milano, & Dassisti, 2015)	2015	●	NA	▲
(Ahmad e Wong 2019)	2019	▲	○	•
(Choi, Thangamani, e Kissock 2019)	2019	•	•	▲
(Thirupathi, Vinodh, e Dhanasekaran 2019)	2019	•	•	•
(Zarte, Pechmann, e Nunes 2019)	2019	•	▲	•
(Dassisti et al. 2016)	2016	▲	○	▲
(Dassisti et al. 2016)	2016	▲	○	▲
(Moldavska e Welo 2018)	2018	•	•	•
(K. E. K, Vinodh, e Gurumurthy 2018)	2018	○	▲	•
(Hendiani and Bagherpour 2019)	2019	NA	NA	▲
(Madanchi et al. 2019)	2019	▲	▲	●
(Moldavska and Welo 2019)	2019	●	▲	●
(Saad, Nazzal, and Darras 2019)	2019	▲	▲	●

Proposed Framework

Taking into account the challenges identified in the analysis of the papers presented above, the authors here propose a framework for sustainability assessment in a generic manufacturing organization. The framework tries to address manufacturing needs, as discussed above, and cope with the challenges manufacturing organizations are imposed to face in terms of sustainability assessment.

The special characteristics of the framework are: it looks at the big picture while it maintains the awareness of the interconnectedness of the components of the picture: its combination of hierarchical level inside a manufacturing organization (defined as System, Product and Process) with the life cycle of the product (pre-manufacturing, manufacturing, use and post-use) for the three main dimensions of sustainability (Economic, social and environmental). In addition, and due to the derived essence of sustainability manufacturing, the 6R concept (Redesign, Remanufacture, Reuse, Recover, Recycle and Reduce) is considered inside the life cycle of the product at the "post-use" stage. By means of the present framework, the conditions have been created for description, implementation and assessment of the sustainability concept in different dimensions interconnected. It prepares a detailed definition for sustainability for each intersection of the three domains. The framework enables the manufacturers, respectively: to detect a sustainability prevention cause; to define to what hierarchical level it belongs; to discover in what stage of the product life cycle it occurs and to know if the specific problem comes from environmental, social or economic issues.

Based on the above mentioned, three pillars of sustainability can thus be assessed in all levels of a manufacturing organization throughout the whole life cycle of the product. To make that assessment possible, the three-dimensional framework is proposed as shown in figure 8.

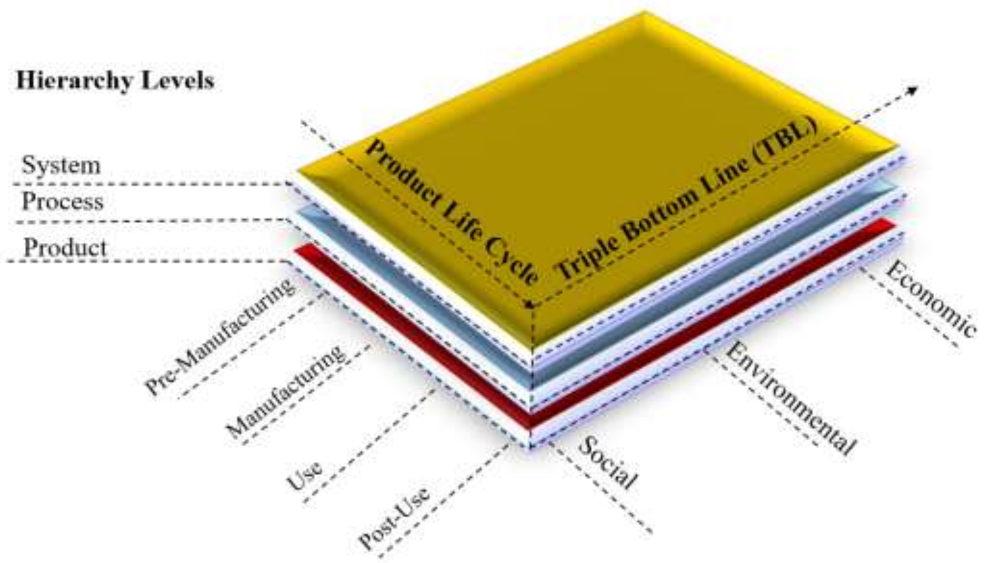

Fig 8. Three-Dimensional framework for Sustainability Assessment

To sum up the objectives, the reference framework:

- Complies with standards;
- is simple and manageable so it can be used by the manufacturers;
- Identifies the gaps and loopholes lead to low sustainable performance;
- Identifies the overlaps and stipulation of preferred solutions;
- Prepares a holistic assessment for the manufacturing organization.

Conclusion, contributions and future work

The present study, alongside the previous work done by the authors(Eslami et al. 2018), formes a systematic literature review that led to a new framework aiming at assessing sustainability in manufacturing organizations with an holistic interconnected approach (the approach is summarized in figure 9).

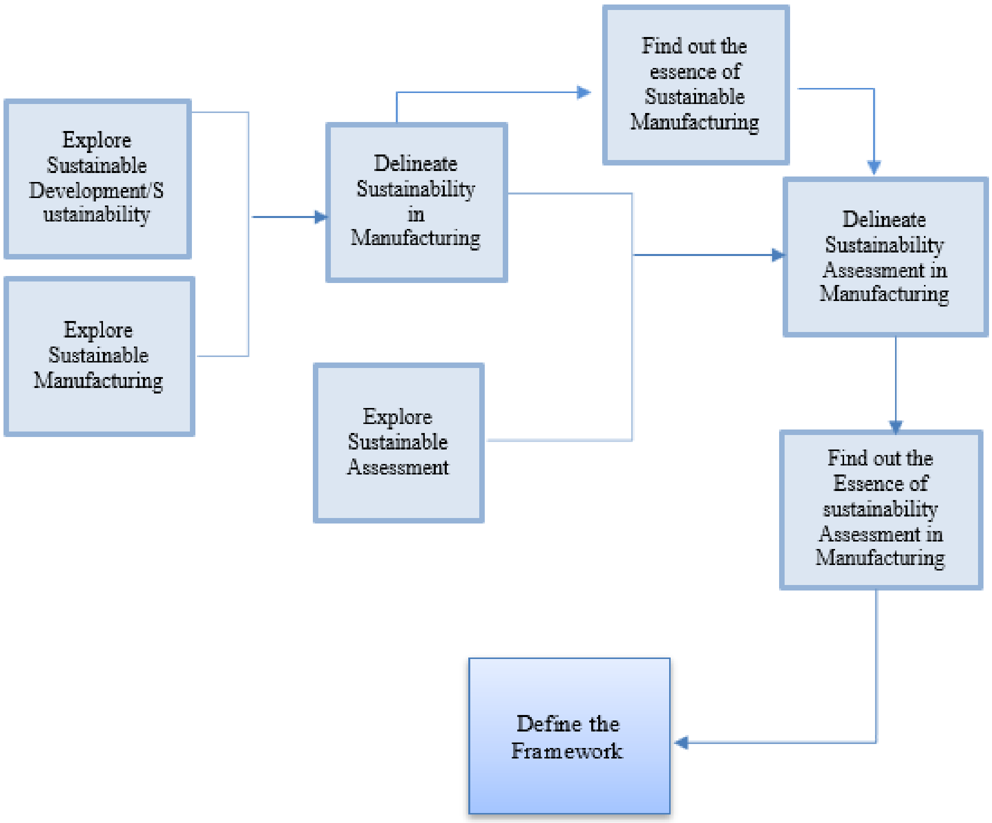

Figure 9. summary of the literature review

This literature review tries to answer different research questions at different level of abstraction, namely: structural problem and behavioural problem. The structural level focuses on establishing the baseline of the model by trying to reply to the research question "How can sustainable manufacturing be achieved?" while having in mind that all three traditional dimensions of sustainability (environmental, economic and social) must be covered. The behavioural level on the other hand, focuses on the methodology and the tool needed for sustainability assessment inside manufacturing organizations. To that point, the fourth research question investigated in the present study ("How can sustainable manufacturing be assessed?") tries to analyse the utilized assessment tools in the literature. The proposed framework, has thus the following objectives:

- It looks at the big picture while it maintains the awareness of the interconnectedness of the components of the picture
- It combines the hierarchical level inside a manufacturing organization (product, process and system) with the life cycle of the product (pre-

manufacturing, manufacturing, use and post-use) for the three main dimensions of sustainability (economic, social and environmental).

- Due to the derived essence of sustainability manufacturing, the 6R concept (Redesign, Remanufacture, Reuse, Recover, Recycle and Reduce) is considered within the life cycle of the product at the "post-use" stage.
- The conditions have been created for description, implementation and assessment of the sustainability concept in different dimensions. It prepares a definition for sustainability for each intersection of the three domains with stipulation and requirements.
- The model enables the manufacturers, respectively: to detect a sustainability prevention cause; to know to what hierarchical level it belongs; to discover in which stage of the product life cycle it occurs and to know if the specific problem comes from environmental, social or economic issues.

In addition to all novelties supposed by the framework, the present paper contributes in the following way:

The analysis of the sustainability assessment tools and methodologies was done based on the Formal Concept Analysis (FCA), the clustering algorithm which detects conceptual structures in data and consequently extracts the hidden relationship between the assessment tools. However, the novel use of FCA can enlighten the idea of exploring the relationship between data and their properties in also in the concept of sustainability to better understand strategies behind use of methodologies.

The proposed framework suggests a holistic sustainability assessment, which can both assess sustainability inside a manufacturing organization and also detects the loopholes that lead to a lower sustainability performance. The bright idea the framework can offer of the sustainability performance of the organization, can help manufacturers and decision makers diagnose better the sustainability related problems and come up with clearer solutions while saving efforts and time.

The proposed framework thus gives to the decision maker a new opportunity to assess sustainability inside manufacturing organizations for the grace of the holistic view toward both the organization and sustainability. To that point, development of a model that measures sustainability performance in manufacturing organizations following the proposed framework will be the next future work of the authors and a possible track for others to face from the above the sustainability assessment in an organization.

Acknowledgements

This work was supported by the Italian Ministry of Education, University and Research under the Programme "Department of Excellence" Legge 232/2016 (Grant No. CUP - D94I18000260001). The paper was developed under the moral patronage of the SOSTENERE working group of AITEM (www.aitem.org).

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