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Benchmarking the sustainable manufacturing paradigm via automatic analysis and clustering of scientific literature: A perspective from Italian technologists

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Abstract

The number of scientific papers in the field of Sustainable Manufacturing (SM) shows a strong growth of interest in this topic in the last 20 years. Despite this huge number of publications, a clear statement of the profound meaning of Sustainable Manufacturing, or at least a strong theoretical support, is still missing. The 6R framework seems to be a first attempt to rationalize this issue, as it is an axiomatic identification of its true nature. Recognizing the pursuing of one or more of the Reduce-Recycle-Reuse-Recover-Redesign-Remanufacture principles allows users to identify if any manufacturing action is in the right direction of sustainability. In the paper, the authors speculate on the use of this framework and its possible extension by referring to all the existing scientific contributions on Sustainable Manufacturing in the SCOPUS® databases as a source of data. Starting from the measurement of the distribution of the scientific papers allocated onto the 6Rs dimensions, by using both author keywords and automatically extracted multiword from texts, the distribution of the scientific papers among the 6R was derived. A new framework is proposed based on analytical text tools to compare the affinity of the applied research activities of the Italian Technologist network SOSTENERE to sustainable manufacturing and provide also a benchmarking view to describe the Italian way to SM with respect to the rest of existing applications.

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Keywords: Sustainable manufacturing, 6R, Document clustering

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1. Sustainable Manufacturing: Introduction

One of the most important objectives of Sustainable Manufacturing (SM) is the development of innovative and viable engineered materials, manufacturing processes and systems to provide multiple life-cycle of products. In SM the old concept ‘from cradle to grave’ is now transforming into ‘from cradle to cradle’ [1], tending toward multiple product life-cycles or even a ‘near-perpetual’ product/material life. Scientific contributions in the sustainable manufacturing field mostly deal with energy and resource consumption. In this respect, two different main fields of causes can be identified: the process level and the material efficiency one. As a matter of fact, manufacturing processes have a significant role also in putting in place material efficiency strategies [2]. As far as the processes are concerned, a first classification of research contributions was discussed in the CIRP General Assembly [3]. There the authors state that research in manufacturing field, oriented to environmental impact reduction, can be clustered in five main sub-classes: (*1*) unit process level (individual device or machine tool in the manufacturing system), (*2*) manufacturing system level, (*3*) facility, (*4*) multi-factory system up to considering the whole (*5*) supply chain level. Another review paper was presented at the ASME international manufacturing science and engineering conference [4]. In that paper, the authors scrutinize the research contributions focusing more on the differentiation between manufacturing processes and manufacturing systems.

The role of manufacturing processes in putting in place material efficiency/reuse strategy was also outlined by Ingarao [3]. In fact, manufacturing processes deserve to be considered as means for enabling material efficiency strategies. SM may be pursued by several strategies, such as re-designing and/or even changing manufacturing practices to conceive new-generation products, as well as by creating closed-loop environmentally-friendly material flows. SM paradigm seems to embrace principles encompassed into the 6R framework, namely: Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture. To a certain extent, it appears that the best definition available so far of sustainability, for a given manufacturing operation, is based on the degree of correspondence to one (or more) of these principles. The existence of these principles may thus become a rationale to allow the decision maker to search for new sustainable solutions or to a certain extent measure the ‘degree of sustainability’ of any manufacturing operation. The true question nowadays is if the 6R framework may capture the essence of SM, provided that it is really challenging to clearly define the SM paradigm rationale to the scientific community. To a certain extent, one can speculate, that the higher the number of principles satisfied, the higher the potential positive impact on sustainability can be for a given adopted solution. This paper aims to stimulate the reflection on this point, based on the benchmark of a sample of research outcomes produced by the Italian Technologists research-network SOSTENERE on production technologies, referring to the revision of the 6R classification scheme made by an automatic classification of papers.

1.1. A possible general comprehensive definition of Sustainable Manufacturing

Sustainability (from *sustain* and *ability*) refers to the set of properties of a given system (either natural or artificial), which allows the same system to maintain itself for an almost indefinite period of time, according to WCED [7]. From this general definition, further conceptualizations have been provided for manufacturing activities and/or processes. According to the Organization for Economic Co-operation and Development, Sustainable Manufacturing (SM) is a formal name for a new way of doing business and creating value. Different statements of sustainability in literature are available [8-12]; these share the same focus on the following three main aspects: economy, environment and society. The authors performed a huge literature review based on an automatic searching algorithm [13] on the SCOPUS® database from which it was possible to summarize a possible definition for sustainable manufactured processes/products, according to the following set of prescriptions:

- (-) minimize business risk;
- (-) minimize negative environmental impacts;
- (-) conserve energy and natural resources;
- (-) are safe for employees, communities and consumers;
- (-) are economically sound;
- (+) a new way of creating value;

• (+) are socially and creatively rewarding for all working people;
• (+) providing access to basic services, green and decent jobs and a better quality of life for all;
• (+) adopt sustainable infrastructures,

where the (-) sign stands for those prescriptions oriented to preservation of resources without any significant change of the present condition, while the (+) sign indicates those prescriptions aiming at ameliorating/modification of the trends with respect to traditionally manufactured processes/products. To summarize by simplifying, sustainable manufacturing is about minimizing business risks of any manufacturing operation while maximizing the new opportunities that arise from improving processes and products. Fascinating in principle, these general statements are really difficult to deploy, or even to recognize, into real operations and production settings. The focus of the present paper is to derive a clear definition of the concept of manufacturing sustainability based on clear evidences derived from literature analysis, rather than referring to general ethical or social principles, which appear to be a 'top-down' definition. Conversely, as the thesis of the present paper, information extracted from all the scientific papers available on SM on SCOPUS® database can provide a sort of 'bottom-up' statement. Evidences are here defined as the relevant words and short concepts contained in papers can be related to sustainability. To do so, in [13] the authors adopted a text mining process to analyze the 6R framework as tool for defining sustainability of a manufacturing operation. The process started from a manual classification of 339 papers on Sustainable Manufacturing. The manually classified documents were thus clustered using a Spherical K-Means Clustering algorithm. The results (the assignments of each paper to a cluster) were then compared with the manual classification. The number of resulted clusters was 6, having this number of clusters no specific relation with the number of 6R classes. The output of the clustering process is thus a 6x6 Matrix (Class(row)/Cluster (column)) as it is shown in Figure 1. This provides a first evidence of the limit of the 6R scheme: in order to define SM, one need to recognize the existence of more than one 6R's single class.

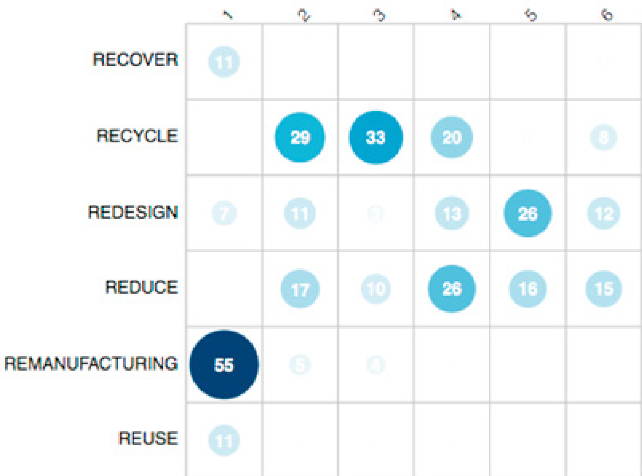

Fig. 1. Matrix comparing the manual classification and the clustering output.

To go then further beyond the 6R scheme and a clearer representation of the sustainability issue, scientific papers analyzed were manually labelled by 6 independent experts in the field of manufacturing and sustainability. Then a seventh expert took in input the results of the manual naming and synthetized the label. The final results are the names of the following 12 topics: (*1*) Smartness for Sustainability; (*2*) Sustainable Machining; (*3*) Manufacturing Environmental Efficiency; (*4*) Modelling Manufacturing Sustainability; (*5*) Welding Sustainability; (*6*) AM Sustainability; (*7*) Life-cycle Product Management; (*8*) Advanced Material Sustainability; (*9*) Production Management for Sustainability; (*10*) Sustainable Energies; (*11*) Innovation for Sustainability; (*12*) Sustainable Logistic. This list represents to a certain extent a 'topic model' of the sustainable manufacturing issue.

Relating the topics above to 6R classes may better allow to recognize the rationale of any SM approach. This statement is partially proved by the analysis of the set of research outcomes produced by the Italian Technologists research-network SOSTENERE in production technologies as below described. The thesis sustained here is that by following these two schemes, to a certain extent, a clear benchmark of the existing Italian approaches to SM was possible.

2. The Italian technologist view to sustainable manufacturing

The Italian technologist perspective to sustainable manufacturing here presented is defined by attempting to classify the scientific contribution according to the joint 6R's framework dimensions with the topic model above defined. The set of research activities here classified descends from a partially coordinated activity of applied researches on the field of sustainable manufacturing made by a network of Italian Technologists belonging to Public Universities (the AITeM - SOSTENERE network). The network is made of seven poles, mostly related to production technologies, reflecting the variety of Italian industrial scenario as the activities selected were generally related to industrial applications. This network is strongly committed with applied research activities for national and international companies: the resulting picture in some sense may represent a possible picture of the Italian solution to SM. Accordingly, the different SM proposals here synthesized belongs surely to the SM domain: the multi-faceted picture emerging represents the real perspective of SM the field. This will allow to recognize if the proposed scheme allows a better definition of SM.

The Polytechnic University of Bari's pole (BA) of the network has experienced the exergetic manufacturing optimization by focusing on the Small and Medium size Enterprises (SME) needs, which belong to a mix of Reduce and/or Redesign approach to topic 1 and 9. This is typically the Italian dimension of most of the enterprises, and it has specific needs and requirements which may differ from other existing approaches worldwide. Despite this approach has been experienced to companies of larger dimensions, in SMEs it may also act as a criterion to implement the smartness paradigm [14]. Another approach (Recycle dimension to topic 7 and 10) derived from a patented recycling process, proposed in [15], is to a certain extent less tied to Italian reality, but in any case, strongly related to the growing interest of several Italian companies to enter the new business of recycling with a different and innovative perspective provided by sustainability with respect to the existing market solutions.

Research outcomes from Politecnico di Torino's pole (TO) pertain to the modelling and optimization of economic and environmental sustainability of additive, subtractive, and mass conserving manufacturing processes, which have been assessed with reference to the entire life cycle of manufactured products as in [16-19]. The approaches mostly belong to Reduce and Reuse in a perfect mix, while topics of concern are 2,3,4 and 8.

The research outcomes of the Polytechnic University of Marche's pole (UM) concerned both the machining operations and the development of innovative processes in welding and recycling of light and ultralight alloys with the reuse and reduce goals. As far as the machining operations are concerned, researches have aimed at improving the environmental sustainability (reduce and topic 3) of the entire system used to carry out the machining operations, without neglecting the need to improve the quality of the machined surfaces, the cost-effectiveness of the process and the tool life [20, 21]. The study of innovative welding processes has been based on the Friction Stir Welding (FSW) technology, which is considered an environmental-friendly and versatile 'green' technique for the obtaining of solid state joints in metal sheets, this addressing the Reduce class of 6R and the topic 5. By concerning the environmental aspects, the quantification of the environmental impact of the FSW process has been performed using the Life Cycle Assessment methodology [22, 23], addressing again topic 3 and the Reduce class.

The University of Palermo's pole (PA) has been working on energy and resource flow analysis at unit process level. Specifically, thorough analyses were developed to analyze the role of both process and material parameters as well as of machine tool size/architecture on the process. Electrical energy demand was analyzed, by addressing the Reduce class and topic 3. This research approach was applied to single point incremental forming [24], punching [25] and Friction Stir Welding processes [26], thus addressing also topic 2. Researchers from University of Palermo have also developed researches with a broader perspective considering the environmental impact of the whole product/component life cycle, thus enlarging to topic 4 the same research stream. This approach was applied also on industrial case studies such us an aluminum high speed train panel [27] and food packaging [28].

The research activity carried out at the CAIMan (Artificial Intelligence in Manufacturing research group) of the

University of Bologna's pole (BO) has been basically based on two topics (namely 1 and 2) related to Redesign class. A more recent one deals with the use of intelligent tools in order to automatize typical repetitive operations or tasks and to enhance the sustainability issue, for example [29]. The oldest one deals with the competency mapping, evaluation and match with manufacturing tasks for a specific Italian industrial sector [29-34], which is difficult to classify provided there were no specific topic or 6R class. Particularly, the investigation has been done for enterprises that are representatives of the 'Made in Italy' in the field of the textile and leathery luxury goods.

The Politecnico di Milano's pole (MI) developed a time-based control policy at machine level by considering a stochastic arrival process [35] and time-dependent transitory of equipment [36]. Most of the work is done here for Reducing the energy consumption of resources in manufacturing by controlling resource state during idle periods, thus addressing the topic 3 and 9. Also, they analyzed an off/on control policy based on buffer information [37]. These policies are formalized by modelling explicitly the energy consumed at each machine state (topic 4). The problem of controlling serial production lines with finite buffer capacities has been dealt with [38, 39], addressing again topic 9 of the Reduce class. De-Manufacturing Systems allow implementing optimized End-of-Life strategies and are necessary to support a sustainable and competitive Manufacturing/De-Manufacturing integrated paradigm [40]. This strategy is another key asset of the Italian approach to sustainable manufacturing, by proposing a more complex view of the end-of-life strategy, including disassembly, remanufacturing, recycling and recovery processes. De-manufacturing processes are in any case included into the 6R framework, but it is really hard to classify: both reuse, recycle were addressed, and encompassing topics 3,7 and 9. Also, the concept of frugal innovation has been proposed in [41] as a new process of adapting goods and their production, tailored to the target customers' requirements, which is lightly captured by the Reduce class an topic 1 and 11. The product service system paradigm is another possible way to face the sustainability, whose principles are hardly classifiable into the 6R's framework: the redesign was here used to include this aspect, and referring to topic 11. A particular focus on disassembly planning strategies [42] and on the development of new tools [43, 44] to speed up the disassembly characterized Pisa pole's (PI) approach. Mostly, these approaches belong to the recycle strategy. A 3 DoF robot was designed to grasp and manipulate RAEE as for example washing machines and to position the object properly to disassemble high value or dangerous components (reusable: motor; recyclable: cables and aluminum parts; dangerous: capacitor). The optimization of the disassembly sequence to maximize the value recovered from RAEE was studied also to improve the ergonomics and safety of the human operator. Nowadays Pisa team is still working on planning strategies in a disassembly environment where co-bots and humans collaborate [47], belonging to class Redesing and/or Remanufacture and topic 3 and 9.

By referring to the intersection of the 6R's classes with the topic model, which ideally form a matrix, it is quite clear from the above how the resulting picture of the sustainability issue is more clear than simply referring to 6R scheme. One cannot simplify the Italian enterprise strive for sustainability only reducing it to the resource consumption reduction. This picture obtained by mixing 6R classes and topic model provides a more complex view, which may allow to search different research directions: however, it is clear how recover and remanufacturing are still missing. It is also clear, on the other hand, how the picture emerging from the intersection of 6R classes and topic model provides the flavor of the Italian technologist approach with respect to the general stream on sustainable manufacturing. A deeper analysis may deploy the specific approaches (e.g., tools, methodologies, technologies adopted, etc.), which is out of the scope of this paper of providing a wider frame to understand and deploy the meaning of SM. Empty 6R/topic (cells of the ideal matrix above) represents missing research opportunities or industrial applications, thus having an indication of what SM may be in the next future.

3. Discussion and future developments

One point to highlight is that, the enhanced scheme here proposed with respect to 6R's requires to solve the problem of an accurate description mixing one or more dimensions: a criterion should be stated clearly, so as to derive a good image of the reality of the applications and of the essence of the sustainable ideas pursued. This point resulted almost clear by the above, where one can find more repetition at different topics and 6R's classes. Finding correlations between 6R's classes can be an interesting attempt to overcome this limitation, and thus also refine the possible definition of sustainable manufacturing, provided that real applications rarely fall within only one single class alone, as it was evident in this study. The nature of applications and the features of tools adopted in the sustainable manufacturing cases are aspects considered, beyond the principles (i.e., the scopes) of the 6R framework, by the topic model. As a final remark, still the true meaning of sustainable manufacturing is unrealized so far, hopefully because of its infinite way of deploying it into the reality or even because the same sustainability is multifaceted per sé. The different point of view offered by the paper, born from a scientific network of researchers deeply involved into the sustainability issue in manufacturing by the technological point of view, can be another step toward a commonly agreed statement of its true meaning.

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