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Sustainable Manufacturing as a Game: A Proposal of Framework

M.Dassisti

Politecnico di Bari, D.M.M.M.,Bari, Italy

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Abstract

The aim of this paper is to provide a systemic view on the recent sustainable-thinking wave in manufacturing with regards to conceptual approaches. The methodology is based on a wide scientific literature analysis reflecting the most up-to-date achievements in different sectors for sustainable manufacturing. The findings include a new classification of most of the recent scientific results on conceptual approaches to sustainable manufacturing according to theory of games. The novelty is in considering two players – namely the earth and the mankind – that rarely are involved in the approaches available in the recent scientific literature.

Keywords: Sustainable manufacturing; framework; eco-approaches; game theory

1. Forewords

Deeply embedded in the last century culture is a belief in the desirability, indeed of the necessity, of welfare as continual growth. Nowadays a new "ecological sensitivity" is growing as an answer to the consciousness of the limitedness of resources <<If human population was smaller and human activities were not intensive and continuous, if nobody was anxious about the statistics of production and consumption growth, nobody would have talked about the environment.>> [1]. Sustainability has assumed only recently a different meaning of the old verb "to sustain" deriving from Middle English <<To keep in being; to continue in a certain state; to keep or maintain at the proper level or standard; to preserve the status of>> [2]. But the true point is to deploy this concept into manufacturing, to understand what really can it look like; a possible defis provided in [3]: <<Sustainable manufacturing adds value to materials, components, or products while maintaining the availability of natural resources and environmental quality for future generations.>>. It is thus clear that the true big point to deal with when talking about sustainability is to address the ancient philosophical debate about the relationship between mankind and the mother Earth. According to this, we can put the sustainability question in manufacturing as an "optimization game" where it is appropriate to search solutions where both of them succeed. That means mankind try to search for the best living condition (not only surviving, but also a real state of wellness) while the Earth tries to reach those perfect conditions useful to the mankind survival. Despite this position might seem absurd, since we are talking about one player with no decisional power, one can nevertheless think the Earth as a true mother wishing to survive: in doing so, as an axiom, the mankind can only derive benefits and thus this explains the rationale behind a search of a win-win strategy. To summarize, one can think of the player "Earth" following a global optimum search, while for the player "mankind" as searching a local optimum in the game they play. Whenever the best condition is reached, one will realize that a sustainable approach is positive to the environment (symbolism: E+) and positive to the economy (symbolism: M+). If an approach is not positive, then it will be assumed either neutral (symbolism M=, E=) or negative (symbolism M-, E-) for simplicity of reasoning in the present framework. Research in sustainable manufacturing is an important activity that informs product development from a life cycle perspective; it provides a multi-view perspective of sustainability problems and the efforts required to face these [4]. The scope of this paper is to propose a different and useful view of the scientific efforts devoted so far on sustainable manufacturing (former "clean technologies"), with the aim to highlight best practices as well as lacking points for future research developments. When talking about sustainability, one should consider also the consumer's attitudes: an unnecessary product that is not manufactured can be the best one. Despite the most important chance to support the ecological sensitivity is the reshaping our attitudes and habits, here we will concentrate on technical matters, i.e. researches concerning sustainability of manufacturing processes. The shape of the paper is as follows: paragraph 1 provide an introduction to the scope of the paper and the context it operates. Paragraph 2 provides a state of the art of the overviews and conceptual approaches to the subject. Paragraph 3, on the other hand, provides an overview of the quantitative approaches with the aim to recognize the advantage of the two players before recognized (namely Earth (E) and mankind (M)). Paragraph 4 then provide the frame to classify approaches and derives some clues to decide if a quantitative approach to sustainability is a really positive strategy or not. Finally,

* E-mail address: m.dassisti @poliba.it
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paragraph 5 presents some final discussion and conclusions. The practical implication of the paper lies in the new cultural framing of approaches and the highlighting of unexpected emerging concepts from the analysis. The value added is thus an effective systematization of concepts and recognition of lacking research topics in the field of sustainable manufacturing.

2. The Sustainable Manufacturing paradigm

Manufacturing has been and hopefully will remain a key component of modern societies, where production of manufactured goods is intended to meet direct demand or provide services as a sign of wellbeing. At the same time, as always, manufacturing activities performed by mankind represent a significant burden on the environment [4]. The new paradigm of manufacturing sustainability seems to conciliate two terms which seemed opposite up to now, to form an unique set of approaches that can open a new era.

Clearly defining environmentally sustainable process is not easy at all; in a strict sense, there is no such thing as a truly sustainable or green process (the same has been asserted for products [5]). Any process we perform will perturb the environment at some stage in its lifecycles: the fundamental question is here if we can determine the way the world goes. Accordingly, the following statement can be asserted, with no fear of contradiction from the whole set of contributions analyses, to clarify the meaning of manufacturing sustainability: taking as reference point the natural processes, the lower the impact on environment of an artificial transformation process the higher its sustainability, provided it satisfies the economical or social scope it was intended for. This statement might allow to set an ideal comparative scale, useful at least to benchmark different approaches and/or technologies. Several scientific works have been devoted to provide conceptual frames for sustainability and the related implications from a scientific or a pragmatic point of view; we will refer here to this as qualitative contributions. General criteria for sustainability come from the four principles of "The Natural Step" framework [6], strongly related to social aspects: intra-generational equity (spatial scale), inter-generational equity (temporal scale), flexibility to include all the stakeholders [7]. The stress on the strong role of technology as an innovation driver added to the classical triple bottom-lines of economy, society and environment, is suggested in [8] as a sustainable enabler. Implications of these scientific outcomes are hard to see in the immediate scenarios, neither to implement these is easy. To a certain extent the value of such a general reflections is in their enlightening a potential path, even though they are hard to deploy in manufacturing per sé. The systemic view is often claimed as critical to assess the true impact of manufacturing processes against the danger of piecemeal efforts effects, de-synergy, i.e. strong waste of efforts with low overall benefits [9]. Several interesting examples there are on green investments [10], whenever the spillover gap between public social return on investment and private return should be maximized. This claims for the importance of a systemic view for any strategy for sustainability ([11]), as the idea taking care of introducing the concept of footprint induced by present delocalized production (spatial dimension). At the same time, it is interesting the idea of evaluating the impact of some sustainable action of one stage of the product life-cycle on the other stages, which might turn to be dangerous (temporal dimension), as in cases presented in [12] for the automotive sector. Other general approaches to sustainability are much more based on "prescriptions", even though not strictly technical, stressing on environmental-adapted business thinking. Challenges were set to integrate into the corporate culture "the factor 10 approach" [13], where the industries is asked to produce the actual growth with only one-tenth of resource consumption. The achievement of such ambitious objectives would require a radical re-think of many of industrial practices, where continuous improvement is not enough and a step change in environmentally related performance is required. This brings to an interesting question, i.e., if sustainability nowadays resemble to the quality concept of yesterday: environmental issues are in fact increasingly seen as an integral component of continuous improvement processes in both the corporate and environmental fields. The Total Quality Environmental Management (TQEM) movement, which extends traditional quality tenets to the management of corporate environmental matters - as well as those of process efficiency and product performance – is an attempt to deploy transcription into more technical matters. Having the environment as a customer, TQEM focuses company attention onontinuously improving environmental performance [14]. Other frameworks for sustainable manufacturing are based on requirement analysis, to evaluate innovative technologies from a sustainable manufacturing point of view.

Requirements for product/processes, are mainly based on the idea of flexibly adaptation to true customer needs [15]: modularity, convertibility, diagnosability, customer-driven adaptability, integrability. The same author stresses on the fact that up till now only the "reduce" strategy has been settled, noting that an enhancement is required in searching for innovations in use-productivity. Other studies presents principles and practices that should be followed (or has been successfully applied), the most of the time based on simple first order logic inductive reasoning. In [16] for instance pushes on "pick-the-low-apple" principle in working towards sustainable production based also on some success stories. The same stress on resource depletion is in [13] and [17], stressing the importance of a closed-loop material cycle in several fields. Sustainability based on a resource consumption depletion is, at the end, nothing that asserting the mass conservation principle. Simply to implement, are on the other hand effective to our scope of sustainability? More technical based solutions, but still qualitative, are those proposed in the "green chemistry" as an innovative, non-regulatory, economically-driven approach toward sustainability: as such these have the potential to be self-maintaining on the reduction of pollution and resource consumption. A significant point is the distinction between molecular level (or product level) and the system level (or process level) of potential impact of green engineering, based on the 12 principles that consider environmental, economic and social factors [18].

All these approaches reaffirm the mother Nature as a master of sustainability, with no side effects as for human activities, specifically economic activities, on the environment. It is thus clear that, starting from the concept of finite resource of the Earth, new conceptual models on best practices need to be devised, to interpret the relationship between manufacturing activities (performed by mankind - M) and the whole living planet (E). In the paper, only the quantitative scientific approaches devoted to sustainable manufacturing are arranged to form a sort of framework, derived from the accurate analysis of the contents and results derived from bibliometric data collected through searches in databases (primarily SCOPUS and Web-of-Science, with their broad coverage of engineering conferences and journals) which register a significant number of publications for the 1990 – 2012 period on the field. Papers were selected according to their pertinence to the subject of sustainable manufacturing in a broader sense, but mainly related to physical processes of transformation.

The technical focus here adopted brought to a narrow subset of the huge class of scientific contributions available under the "sustainability" umbrella. In the following subparagraphs several approaches are commented, classified into three different main approaches, to build one dimension of the framework proposed.

3. Quantitative contributions to Sustainable Manufacturing

Apart general concepts and qualitative suggestions, there is a mass of scientific contributions devoted to technical matters, with a practical outcome in the real life. These can be classified as quantitative contributions, as follows.

3.1 Assessing sustainability

Several scientific works have been devoted to the assessment of the true effect of human activities on the environment, hopefully to better understand the cause-effect relationships and also possible directions for improvement from the present condition. Several specific applications for different industrial sectors are available assessing environmental performance (e.g. [19], [6], [20]). Also general assessment frameworks have been developed so far (see. E.g.[21]). All these approaches can be encompassed in a (M=,E=) solutions to sustainability, since they are only indirectly involved in an improvement. The enormous diffusion of the assessment of environmental impact of service companies witness this trend (see, e.g. [22]). A variety of applications for different technologies in different sectors of manufacturing are available (see, e.g., [23], casting in [24]). A mention apart is for [25] that concentrates, very interesting indeed, on biotechnological processes. The major limit of LCA approaches (independently of the methodological distinction between the so-called attributional [26] and consequential LCAs) is the scarcity of sound data [27]: allocating elementary product flows, crossing the system boundaries - between different product systems - or quantifying the environmental impacts of a change in the product systems, always is a matter of a profound knowledge of the processes and also of a specific knowledge of its implementation. Some author address the problem of environmental performance assessment for products by defining environmentally problematic phases though an Environmental Quality Function Deployment approach [28], where the environmental engineering parameters and stakeholder requirements are linked though the relationship matrix.

Assessment inspired to the second law of thermodynamics may well turn out to be the central scientific truth of the 21st century, such as those using the concept of exergy, the 'ordered motion', based on entropy that fuses energy and material quality information in a measure that is both descriptive and of physical significance. Exergy could be a suitable concept in the development of a sustainable industry, as it clarifies quantification of resource depletion, waste emissions and process losses [18]. Other interesting approaches are the thermo dynamical analysis presented in [29]. Other authors propose an accurate estimation of the energy requirements for manufacturing processes: such as in the embodied product energy framework in [27] for estimating the energy consumption in injection-molding at the design stage, showing the potentialities for improving LCA analyses. Finally an interesting perspective in forecasting the effect of sustainable technologies on manufacturing systems by borrowing concepts of evolutionary theory has been proposed ([30]). None of these efforts address the matter of a systemic view as proposed in this paper; they simply concentrate on the absolute values of flows more than on their relative meaning in the context of the game here referred to. What is the meaning of measuring an impact if the only benchmark available is "zero"? It is not reasonable to simply assess a processes without clearly stating the true reference system of it; for instance, measuring the footprint of the mankind action means to set the win condition for the earth (E) at the zero value where, on the other hand, mankind (M) loss because only a non-performed manufacturing process can have such a figure, with this angle of observation. 3.2 The R's approaches. Let's us to recall the 6R's criteria presented in [31] : Reduce, Reuse, Recycle, Redesign (or Rethinking), Recover and Remanufacture (or Renovation). Another golden rule has been added (the Regulation) [32].

Sustainable technologies following the 6R's rules can be classified as ""Re-X" strategies: Re- prefix means again, i.e. once more or, in a word, extend the use of. When applied to manufacturing, these strategies are evidently aimed to renovate functions of products (or processes) thus focusing on the impact of the use of resources of the Earth (E). Embedded into eco-approaches that follows Re-X's philosophy, there is the concept of cycling, i.e. lowering consumption of resources. It is possible to state that these Re-X criteria address a sort of "neutral sustainability", because these represents efforts to minimize impact, i.e. allowing an advantage to mankind (M+) while slightly reducing the impact on earth (E=). By extending the idea of minimization according to the input/output analysis applied to manufacture up to its extreme consequences, it is obvious to dream of a systemic "zero-waste industrial cycle", which would have a double win effect because producing (M+) while not impacting on the environment (E+): ideally symbiotic chains between industries belong in principle to this category (see, e.g. [33]).

3.2.1 Reducing

The "reduce" approaches in sustainability research are typically the most frequently addressed; the most of these approaches are a (M+, E-) or (M+,E=) solutions. Belonging to the natural instinct to assure resource preservation, it is not so obvious this might assure sustainability per sé. Reducing may pertain to resource consumption ([34]), to resource pollution [35] or even toxicity [36]: examples are available in aluminum pressure-die casting [35], pulp manufacturing [37], tile industry [38].

Concerning metal removal processes, reduction is always declined for lubro-refrigerating fluids: here, the main efforts devoted seems to be to nearly dry the cutting process, to avoid toxicity and pollution. The are plenty of testimonials in this field ([39], [40], [41], [42]), which to a certain extent can be classified as M+ but neutral to Environment (E=), since it is clear that avoiding cooling eliminate toxicity, but not necessarily induce a positive effect on the environment. A benchmark analysis is presented in [3] showing how in some cases the use of metal working fluids is more sustainable, stressing on the importance of innovating materials. Other studies are based on the search for the optimal conditions trough different approaches: searching optimal parameters ([31]), using different chemical compositions ([43], [3], [44], [45]), using appropriate lubricating strategies ([46], [47]) or even changing tool coatings ([48], [49], [50]). The same reduction is considered also for minimizing waste production, trying to reach the zero-discharge limit such as in [51] for crystal glass industry or in [52] in food industry. An interesting concept of the design for degradation has been recently proposed [53], [54]. Another reduce branch us for energy consumption, where usually the simple additive approach is used to assess balance of flows (energy analysis) [55]. In [56] the stress is on the poorness of linear thinking ("pinch based rules") proposing the idea of integrating hybrid sources of energy to get significant savings, as in [57]. No mention at all is made about the overall effect of these strategies: an LCA analysis would be, for instance, greatly adequate to understand the true efficacy of the soltion posed. Reduction should be a never ending process, a result of a continuous improvement process to be truly effective. This means systemic view should always be adopted to assess the overall ecological effect on the environment of each solution.

3.2.2 Re-using and Recycling

Reusing in manufacturing is almost trivial concept in principle, but very difficult to put into practice, as in the examples truly applied in [58] for clinker production and for cutting tools. Recycling is less efficient in general: it is a really (M+, E=) solution. Since it is slightly simpler than reusing, this is why recycling is almost widely experienced: in the automotive sector [12], in building industry ([59], [60]). As shown also by different studies, recyclability is the most on-hand strategy for sustainability: see studies on plastic recyclability [61], reverse logistic and recycling networks [62].

3.2.3 Redesign

To redesign processes is another step toward optimization for sustainability, since it might provide stronger effects in terms or impact reduction on environment (E+). Redesign means to devise new solutions or technologies, as well as to reshape products. Some authors address decision support techniques to approach the sustainability, scenario analysis [63], principle based approach for greening processes [64] and [55], non linear thinking or simply systemic analysis. These solutions are addressd as neutral for Man, since these are much more concentrated on the environment than on requirements of mankind. Other authors face the problem of greening processes by appropriate modeling or by approaching the problem using a Life Cycle Approach view ([65]). In any case, redesign means to know the potentialities of technologies, the logic behind greening products as well as the effects of changes for sustainability. Much more efforts will be thus required in the next future to enlarge the horizon of knowledge on sustainability.

3.2.4 Remanufacturing

The remanufacturing is the process through which a technological equipment, that has been in a certain state of wear or definitively inoperable, goes through a transformation process into a new technological equipment, with the same capability or a different one, reusing under different ways as many parts of the old equipment as it is possible ([66]). Despite the intense economical opportunities for product internalization, the so called "double dividends" [67], few success case are available so far, as in [68] where remanufacturing was incorporated into a product system. Several metrics for remanufacturability have been addressed (as in [69]), but rarely sound data are available for truly significant decisions. Opportunities often came from different experiments, such as for cryogenic machining, where sustainability is reached because of the reduction in use of polluting lubricants, the prolongation of tool life and the improvement of the working energetically favorable (E+); see, e.g. [70], [71].

3.3 Innovative approaches

This paragraphs aims at recognizing all the other scientific contributions that does not belong to the two categories before mentioned, i.e. assessment, Re-X.

The efficiency efforts belong to the realm of optimization of a functional problems, i.e. trying to minimize the effect while maximizing the results. This not necessarily means at true win-win strategy in our game, but it can looks like a (M+,E=) solution or even an (M+,E+) one. Such a kind of problems require a clear modeling of the process ([72]) and the identification of all the critical variables. Several approaches tries to decompose the whole production chain into steps (process view) where to identify inefficiencies and wastes ([73], [74]). The identification of the Best Available Technology ([75]), is a further constructive step to be pursued in this direction.

It would be interesting to address the relative improvements more than the absolute ones when dealing with optimization problems for sustainability, i.e. adopting a more comprehensive approach. An interesting approach in line with functional reasoning about the product is introduced by the so called Product-Service systems (see, e.g. [76], [77]), where manufacturing companies propose a paradigm shift from the true object toward its intrinsic value, the capability to satisfy needs by performing one or more functions: this solution can be really a (M+,E+) solution. Interesting to this regard is the concept of "sale for capability", a new paradigm critical to sustainability, which is close to the use of the concept of "function" to characterize a product or process. This last approach is a candidate for reaching the (M+,E+) condition. The best strategy from ecological (E+) and economical (M+) performance would be the condition where all materials contained in the product are completely recovered and recycled (zero land filling). As an opposite to this, the worst case is that of ecological (E-) and economical (M-) performance, where all materials contained in the product are sent to landfill [27]. The future approaches to sustainability has been already devised, based on bio-mimicry; examples of this are the bio-based sustainable industrial chemistry as the new trend for the future of sustainability. The same is for the concept of industrial metabolism, as a fit of the new emerging theory of industrial ecology (see [78]). A new concept of line remanufacturing is addressed in [79] conceived by simulation modeling, which is a quite technical point of view of industrial ecology. A final note is for the new emerging fields of research, such as for nano-product and nano-manufacturing, where brand new problems will rise to challenge the present research trends on manufacturing [80]. To tell as in [81] if there are concerns over the impacts of nanomaterials in the environment, then this provides an incentive for one of themain goals of industrial ecology: “closed loop” use of materials.

4. The Game framework

The aim of the present framework is to provide a new point of view to recognize efforts made by scientific research on sustainability, to realize directions and, hopefully, lacking points for future researchers in the field. The frame does not include other frameworks on sustainable manufacturing, as reviewed in paragraph 2, but takes into account the concept borrowed from the game theory (see, e.g. [82]) so as to provide also a practical support to decisions in selecting or developing new scientific contribution to this subject.

First of all, let us refer to figure 1, which illustrates the three main axes of the framework, namely: approaches, concerns and barriers. Approaches are those recognized and discussed in paragraph 2, i.e.: i) assessment, that means those contributions that claim that measuring is one important step toward sustainability of manufacturing; ii) Re-X, i.e. those approaches that tries to reduce impact or minimize effort, as summarized in §2; iii) innovation, means those approaches that are complementary to the before mentioned ones.

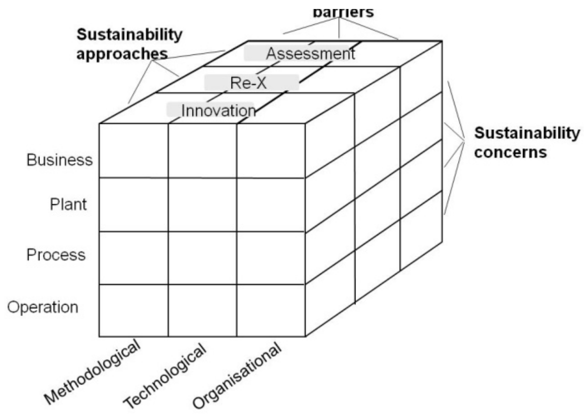

Fig. 1. The framework to classify scientific contributions for sustainable manufacturing

The second dimension of the framework is the concern, meaning the context of application of the scientific contribution, which might significantly change depending the scale (or granularity) of it; i.e. if it belongs to the overall business process, if it impacts at level of plant, or if concern a specific process or even an operation. The narrower the domain, the difficult is to apply the solution tout court, even though this can inspire new ideas and innovations.

Finally the third dimension highlights the barriers that can really impede to reach a true sustainability: barriers can be viewed as future opportunities for research and innovation, since methodological, technological or organizational area pertain to different fields of application. Namely, methodological represents a systemic approach, i.e. refers to all those approaches where a wider view is appropriate; in these cases research is much more related to system theory and interfaces. Technological problems, which are not necessarily the most critical one, represents nevertheless an opportunity, even though faster and stronger effects can be reached addressing the other two dimensions.

Organizational approach is much more related to a local systemic view, i.e. pertains much more to human aspects.

The real effectiveness of the framework is in considering the three dimensions within the game theory frame, i.e. to classify approaches under the E/M relationship and see their potentialities for the other two dimensions: barriers (i.e. opportunities) as well as concern (i.e. the context of application). Whenever a (M+,E+) approach is devised, it is an interesting indication to concentrate over the related barriers and also to address the possibilities of extension toward other wider concerns. In doing so, we tried to summarize the classification emerged from the framework proposed, based on the simple assumptions on game theory. Only the quantitative scientific contribution addressed in the paper was considered as in the following table.

Table 1. Classification of scientific contributions according to the game theory and the framework proposed

	E+	E=	E-
M+	[33],[51],[52], [53], [54],[70],[71], [75],[76], [77],[78],[81]	[31],[39], [40], [41], [42],[56],[57],[58], [12],[59], [60],[61],[62],[66],[72],[73], [74],[79]	[34],[35], [36], [37], [38], [31], [43], [44], [45], [46], [47], [48], [49], [50],[55]
M=	[63],[64],[55], [65],[68]	[19], [6], [20], [21], [22], [23], [24],[25], [26], [27], [28], [18],[29], [27], [30], [3],[67],[69],[80]	
M-		[32]	[27]

5. Conclusions

The aim of the work is to provide a new perspective to classify scientific contributions devoted on sustainable manufacturing, to realize directions and, hopefully, lacking points for future research in the field. It is behind of the scopes of this paper to provide an extensive state-of-the-art analysis, but rather it was to show how the frame might contribute to provide a clear picture on sustainability, which is not yet a truly science. Limits of the research is the wideness of the database adopted, as well as the classification methods, based on author’s personal intuition and judgment. From this initial analysis, a few approaches tries to explore potentialities for a true change by reading the sustainability as a innovation challenge (M+,E+) solutions of table 1. And indeed, what can be stated without fear for errors is that there are two kinds of approaches: reactive (i.e. M+,E=/-), trying to slightly change, and a few pro-active (M+,E+,). Amongst the win-win approaches (E+,M+), still there is an unsolved question: to which extent is it possible to fully reuse materials and/or products with the present manufacturing technologies and also if it is important to develop different product concepts or different technologies. It should be said that <<the idea of `zero emissions´ is based on the (false) idea that every biological waste is `food´ for some other organism. Hence, the idea that some industry can always be found (or created) to consume another industry's wastes, or even just its solid wastes, is naive>>[83]. The reasoning of Ayres, refusing the reasoning of zero-wastes, reminds that even in natural processes alone (i.e. the other two components of the Global System without mankind) does not exists with zero-impact from the transformation processes.

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