Some trends and proposals for the inclusion of sustainability in the design of manufacturing process

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Abstract. Production processes are designed to meet requirements of three different natures, quality, cost and time. Environmental concerns have expanded the field of conceptual design through the introduction of sustainability requirements that are driven by the growing societal thoughtfulness about environmental issues. One could say that the major concern has been the definition of metrics or indices for sustainability. However, those metrics usually have some lack of consistency. More than ever, there is a need for an all-inclusive view at any level of decision-making, from the establishing of the design requirements to the implementation of the solutions. According to the Axiomatic Design Theory, sustainable designs are usually coupled designs that should be avoided. This raises a concern related to the very nature of sustainability: the cross effects between the actions that should be considered in the attempt to decouple the design solutions. In terms of production, one should clarify the characterization of the sustainability of production systems. The objectives of this paper are: i) to analyse some trends for approaching the sustainability of the production processes; ii) to define sustainability in terms of requirements for the design of the production processes; iii) to make some proposals based on the Axiomatic Design Theory, in order to establish the principles with which the guidelines for designing production processes must comply; iv) to discuss how to introduce this matter in teaching both manufacturing technology and design of production systems.

1. Introduction

Environmental sustainability has become a concern to the human society. The natural way in that a part of the world population already separates and discard the trash they produce at proper places is a good example of the collective consciousness. This kind of concerns also began to be reflected in the designing actions, mostly concerning to the type of raw materials and the energy consumption through the entire life cycle of the design objects, which includes decommissioning and disposal [1]. Thus, the concept of eco-design was born, which ultimately consists in seeking to design to minimize the environmental impacts throughout the products’ life cycle. This characteristic turns out to become more important regarding the traditional balance performance vs. cost, as well as the available options for the products. Nowadays, the adoption of the development concept by corporations is already regarded as business value. Some authors developed design concepts on sustainability. According to them, the design of new products should also accomplish environmental aspects besides the economic
and societal ones [2]. In this threefold concept, profit, planet and people are considered simultaneously (see figure 1). Thus, sustainable design is a kind of design that accomplishes the expected functionality that generates profit, that is socially acceptable and that uses reduced raw materials and energy, while generating minimal waste.

Figure 1. The triple bottom line of sustainability [2].

Sustainable design is applicable not only to product design but also to systems design, namely to industrial manufacturing processes. How do the companies know if they are using sustainable manufacturing processes? What should they do to move in the right direction? On which metrics should they support the sustainability assessments? This paper will try to contribute to the answers for those questions. First, some trends for sustainable manufacturing processes are presented and discussed (section 2), followed by the presentation of some metrics to assess sustainability (section 3), from which one concludes the coupled nature of sustainable design (section 4). Section 5 proposes an approach to deal with sustainability in the design of manufacturing processes. In the end, some suggestions are made for teaching sustainable manufacturing in engineering schools (section 6), followed by concluding remarks.

2. Some trends for approaching sustainability of manufacturing processes

Sustainability is a broad concept that involves materials, energy, waste and pollution. Considering all these aspects in manufacturing design is a hard task. So far, many authors have been working in the development of approaches for the inclusion of sustainability in the design of manufacturing processes. Those approaches usually have in common the use of suitable indicators in order to measure, compare or access sustainability.

Shuaib et. al. have built a global product sustainability index [3]. Their goal was to achieve a figure that describes the sustainability of manufactured products through their complete life cycle. They called it “Product Sustainability Index (ProdSI)”. They used a top-down approach to identify which are the elements of the product that should be evaluated for sustainability. The approach seems more appropriate than the reverse one, where the metrics are established without knowing a priori how to aggregate them. They developed a five-level hierarchical structure:

- ProdSI – the overall aggregated product sustainability performance index;
- Subindex – the three aspects of TBL (economy, environment and society);
- Cluster – major elements or factors of product sustainability in the three TBL categories;
- Subcluster – decomposition of clusters to more-specific elements of product sustainability;
- Individual metrics – a quantifiable and measurable attribute or property related to a single parameter or indicator of product sustainability that is measured through the total product life cycle.

Table 1 partially depicts this structure. Each subcluster has one or more than one metrics that are not shown in the table. The procedure starts with the measurement of the individual metrics and the
corresponding data collection, which is followed by data normalization (in a scale 0 - 10), the choice of weighting factors (based on experts’ opinion that are gathered through surveys) and the data aggregation.

Table 1. Top down approach for individual metrics [5].

| Subindex                        | Cluster                              | Subcluster                                      |
|---------------------------------|--------------------------------------|-------------------------------------------------|
| Economy                         | Industrial investment                | Capital cost                                    |
|                                 |                                      | R&D cost                                        |
|                                 |                                      | Employee training                               |
|                                 | Direct/indirect costs and overheads  | Labor cost                                      |
|                                 |                                      | Materials                                       |
|                                 |                                      | Energy                                          |
|                                 |                                      | Logistics                                       |
|                                 |                                      | Product operational cost                        |
|                                 |                                      | Legal costs                                     |
|                                 | Benefits and losses                  | Market value                                    |
|                                 |                                      | Quality losses                                  |
| Environment                     | Material use and efficiency          | Product material content                       |
|                                 |                                      | Material utilization                            |
|                                 |                                      | Regulations and certification                   |
|                                 | Energy use and efficiency            | Energy from renewable sources                  |
|                                 |                                      | Energy from nonrenewable sources                |
|                                 |                                      | Energy regulations/certification                |
|                                 |                                      | Energy efficiency                               |
|                                 | Other resources use and efficiency   | Water use                                       |
|                                 |                                      | Recycled water use                              |
|                                 |                                      | Other natural resources                         |
|                                 |                                      | Natural resource regulations/certification      |
|                                 | Wastes and emissions                 | Gaseous emissions                               |
|                                 |                                      | Solid waste                                     |
|                                 |                                      | Liquid waste                                    |
|                                 |                                      | Other waste and emissions                       |
|                                 |                                      | Waste management/certification                  |
|                                 | Product end of life (EOL)            | EOL product/material recovery                   |
|                                 |                                      | EOL product reuse                               |
|                                 |                                      | EOL product remanufacturing                     |
|                                 |                                      | EOL product recycling                           |
|                                 |                                      | Product EOL regulations/certifications          |
| Society                         | Product quality and durability        | Product repair and maintenance                  |
|                                 |                                      | Product reliability                             |
|                                 |                                      | Return and recall                               |
|                                 | Functional performance               | Major product specifications                   |
|                                 |                                      | Product customizability                          |
|                                 |                                      | Product functional effectiveness                |
|                                 |                                      | Ease of operation                               |
|                                 | Product EOL management               | Ease of EOL activities                          |
|                                 |                                      | Product EOL societal impact                     |
|                                 | Product safety and health impact     | Safety                                          |
|                                 |                                      | Health                                          |
|                                 | Product societal impact regulations  | Product EOL regulation compliance               |
|                                 | and certifications                  | Product EOL certification                       |
In the end, they succeeded to create a representative index to compare product sustainability. The weakest point of the method is the use of weighting factors that induce subjectivity. Indeed, weighting is a very sensitive process that affects the result of the sustainability assessment.

In what to the sustainability characterization of manufacturing processes concerns, many works have been produced in recent years. Mani et. al identified the following challenges to develop the measurement for sustainable manufacturing [4]:

- uncertainties in manufacturing environment;
- dramatic changes in customer requirements;
- innovation in production technology;
- uncertainties in internal operating environment;
- inadequate approaches to overcome uncertainties;
- inadequate and unstructured information;
- inadequate decision models;
- undefined scope and boundaries within manufacturing unit processes;
- multiple unverified measurement methodologies.

The same authors presented a methodology for the evaluation and the improvement of sustainability in manufacturing industries. Based on unit manufacturing processes (UMP) (i.e., injection molding, casting and machining and surface treatment), modeling information is made by considering inputs, outputs, operation rules and resources, as well as the dataflow between operations. The goal is to make the UMP sustainable characterization, in order to create essential information to support decision-making related to sustainability. This characterization is made extracting key information of manufacturing processes from all the data available in handbooks, catalogues or metrics. Such information includes, but is not limited to, energy, emissions, pollutants, waste, scrap, alternative raw materials, cycle time and productivity. The main purpose of the characterization of the sustainability is to formulate strategies for evaluation and improvement of sustainability. The methodology is depicted in figure 2.

![Figure 2. Sustainability evaluation and improvement methodology [4].](image)

The two above cited works [3, 4] are representative of the state-of-art concerning to the sustainability approach to manufacturing processes. The current situation can be characterized by:

- General acceptance for the inclusion of sustainability concerns;
- Inexistence of a global and well-defined framework to characterize sustainability in manufacturing;
- Use of representative indices as a basis to design decision-making.
3. Sustainability requirements and metrics for the design of production processes

Within the Triple Bottom Line concept, economic, environmental and societal requirements must be considered together in a sustainable design of any manufacturing process. Regardless of the many works already carried out, sustainability stakeholders agree on the absence of a well-defined approach to characterize sustainability in manufacturing. The difficulty is related to the huge quantity of design requirements, as well as to the relations between them. Usually, the manner to deal with this drawback is to use indices to support decision-making.

Several indices have been proposed and used. Labor cost, energy consumption and return rate of faulty products are just a few examples.

In a sustainable design of any manufacturing process, the three types of sustainability requirements (economic, environmental and societal) should be considered together. Each type of requirement could generate many lower-level requirements, which turn sustainable designs into complex designs. Furthermore, many of the sustainable requirements depend on the same design variables. For instance, it is easy to realize that economic and environmental requirements likely depend on the same design variables that govern the functional requirements. According to the Axiomatic Design terminology, most of these designs are of the coupled type [5].

This difficulty is often avoided by considering some design specifications as input constraints, and not as requirements, but this expeditious tactic usually hampers the designer’s freedom.

4. How to deal with sustainability in design of manufacturing processes

Sustainable design of manufacturing processes is being studied through several approaches and promising results have been achieved. However, an overall method for the sustainability assessment was not found so far.

Axiomatic Design theory (AD) provides a useful framework to deal with any type of design process because it allows distinguishing “good designs” from “poor designs”. In addition, AD also allows identifying the best design among several “good designs”. Therefore, AD seems to be an appropriate tool to deal with sustainable designs.

Since the Brundtland Report [6], sustainability became a compulsory part of the development strategies of organizations. Whatever is the way that is chosen to achieve sustainability, its implementation unavoidably involves engineering decisions, in which one would have to cumulatively meet functionality, cost-effectiveness and safeguard the environment. Specifically, manufacturing technology and production systems are crucially important. Engineering professionals are actors of sustainable development, but as said Broman et. al., “an essential aspect of sustainable development is to include knowledge about it in the education of professionals” [7]. With an exception to what to the legal details concerns, an issue for discussion is if the development of an attitude toward sustainability in engineering education should be based on the inclusion of the theme in different disciplines, or if the matter should be regarded as an autonomous subject.

A possible approach to this theme is as follows: students should understand sustainability as an important goal to fulfill that should not be regarded as a constraint to the engineering solutions. Therefore, sustainability should be expressed by a set of functional requirements at each level of abstraction of the designing process, which in turn should be decomposed in a basis of suitable design parameters and process variables that cumulatively satisfy functionality, cost-effectiveness and environment. This implies that the evaluation of sustainability must be made in the conceptual stage of decision, instead at the detailed design. This approach implies that modern-day engineering education should encompass state-of-art technology, and should take into account that global sustainability entails concerns about “appropriate technology” [8]. The so-called “appropriate technology”, as well as the corresponding design solutions, should therefore be taught. A basic concept that is comprised in the definition of sustainability is the concept of 'needs', which engineers must know to transform into functional requirements. As mentioned in the UNESCO Report, “the key factor is that all technology should be appropriate to economic, social and cultural contexts, as it once was when most technology was developed locally or when most situations were fairly similar in smaller scale pre-industrial days.
Problems arise when technology is transferred between different economic, social and cultural contexts, even within the same country, but especially between the developed and industrial to less developed and more traditional situations.” [8]. Based on this reasoning, engineering education, specifically in the field of manufacturing engineering, should foster the attitude of students toward creating new sustainable solutions.

5. Conclusions

There is no global and well-defined framework to characterize sustainability in manufacturing and Axiomatic Design could yield to a suitable solution for design for sustainability, because AD allows identifying the existing couplings and trying to remove at least some of them. The current trends seem to be the inclusion of the theme sustainability in different disciplines, or as an autonomous subject. Whatever would be the solution for teaching, education in manufacturing engineering should foster the attitude of students toward creating sustainable solutions.

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