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Process sustainability evaluation for manufacturing of a component with the 6R application

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Abstract

Sustainability in manufacturing can be evaluated at product, process and system levels. The 6R methodology for sustainability enhancement in manufacturing processes includes: reduced use of materials, energy, water and other resources; reusing of products/components; recovery and recycling of materials/components; remanufacturing of products; and redesigning of products to utilize recovered materials/resources. Although manufacturing processes can be evaluated by their productivity, quality and cost, process sustainability assessment makes it a complete evaluation. This paper presents a 6R-based evaluation method for sustainable manufacturing in terms of specific metrics within six major metrics clusters: environmental impact, energy consumption, waste management, cost, resource utilization and society/personnel health/operational safety. Manufacturing processes such as casting, welding, turning, milling, drilling, grinding, etc., can be evaluated using this methodology. A case study for machining processes is presented as an example based on the proposed metrics.

Keywords: Manufacturing; Machining process; Sustainability; Triple Bottom Line; 6R

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1. Manufacture of a product/component

The manufacture of a component starts with the extraction of the different materials needed and followed by a primary material processing method, for subsequent manufacture. These two steps, together with the design of the component or product, integrate the pre-manufacturing (PM) stage [1]. The manufacturing (M) stage will require several processes such as machining, welding, forming and assembly. The use (U) stage refers to the life time of the product while it is used by the customer, including upgrades, repairs and maintenance to prolong its life time. At the end, the post-use (PU) stage is the final processing of a product for disposal, including disassembly and sorting of different materials and components for further activities (i.e., reduce, recover, reuse, remanufacture, recycle, and/or redesign) [1, 2], depicted in Figure 1, which constitute the 6Rs. These end-of-life activities or processes identified within the post use (PU) stage of a product, help create sustainable values for end of life products/components and materials. Their definitions are the following:

- ***Reduce*** focuses on all stages of the product life-cycle, including the reduction on resources, materials and energy used, and the reduction of the waste generated [3].
- ***Reuse*** of products or components instead of new materials in new products can reduce, for instance, the energy and water used for the extraction [3].
- ***Recycle*** of products or components that otherwise are considered as waste can further reduce the use of new/virgin materials [3].
- ***Recovery*** of products involves disassembly, recollection and sorting processes for further shredding and recovery of the materials [4].
- ***Redesign*** of products or components involves the use of recovered materials and resources and the knowledge and information to streamline the design of a new generation product.
- ***Remanufacture*** of products or components involves reconditioning, repairs and subsequent manufacture of similar or different products for reuse.

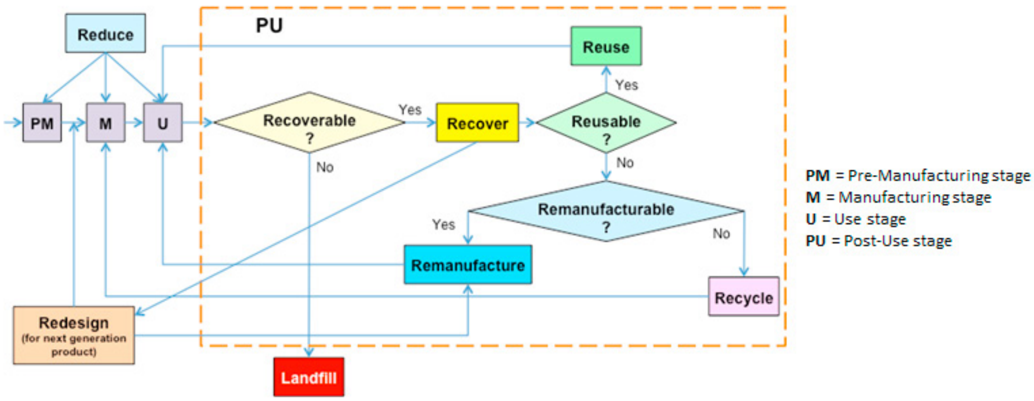

Fig. 1. 6R-based closed-loop product life-cycle, extracted from [5].

2. Manufacturing processes

Manufacturing processes will transform the initial raw materials into the final products, e.g.: casting, forming, machining, welding, additive manufacturing and assembly. Machining, in particular, is one of the most important manufacturing processes, which is estimated to contribute about 5% of the GDP in the developed world [3]. Thus, machining processes will be taken as the representative case in this paper.

Previous studies have identified six major sustainability elements in manufacturing processes such as: environmental impact, energy consumption, waste management, manufacturing cost, resource utilization, and operator safety and personnel health [6-8], as depicted in Figure 2.

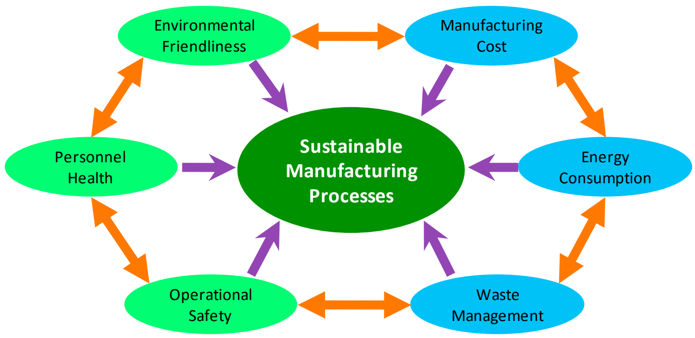

Fig. 2. Six major sustainable elements of the manufacturing processes [6].

3. Machining processes

Machining processes can be studied at different levels, such as component or product level; operation or process level; or at a performance level. The study presented here has been performed at the component or product level.

The machining process will use work materials, cutting tools, energy, water, coolant/lubricant and compressed air; and will produce finished products, chips, used cutting tools, used coolant, mist/leaks, scraps/defects, emissions, noise and other residues as by-products [9].

For instance, coolants or lubricants of the machining process are one of the main causes of environmental pollution [10], which makes them relevant and important at their PU stage during their end-of-life activities. In addition, the coolant/lubricant gradually dilutes during the machining process in form of mist, leaks, and adsorption in the chips [11]. However, recent advances in sustainable coolants/lubricants can help to reduce environmental emissions and consumption of natural resources; reduce health and safety risks; and potentially improve economic performance [12].

4. Process sustainability matrix: Component level

Previous studies have used 6Rs to improve product sustainability [13]. Zhang et.al. applied and presented the Product Sustainability Index (PSI) methodology by calculating individual sustainability metrics throughout the four life-cycle stages of the product [13].

This study uses an approach where the process sustainability matrix is presented at an overall component level, by applying 6Rs to each selected sustainability element: environmental impact, energy, waste management, manufacturing cost, resource utilization and society/consumer/personnel. Moreover, in analogy to what other researchers have done previously [14, 15], several metrics have been identified by the authors in order to evaluate the sustainability of the process. The application of the 6Rs to each selected sustainability element of the manufacturing processes is shown in Table 1. A marked box means that at least one metric has been identified, which will be further explained in Section 5.

To study the environmental impact of the manufacturing processes, the following sub-elements have been identified: the machine tool used during the process; the product/component; the work material; the cutting tools used including jigs and fixtures; the water consumed; and the emissions generated during the process, as described in Table 1.

Energy has three identified sub-elements: in-line consumption, facility environment maintenance and transportation. The 6R application to energy consumption in manufacturing processes is summarized in Table 1.

To study the wastes generated from the manufacturing processes, the sub-elements identified are the following: consumables; chips generated; mist/leaks; scraps/defects; used coolant/lubricants; used cutting tools; and other disposable residues. The application of the 6Rs to the management of the wastes generated from the manufacturing processes is shown in Table 1.

Table 1. 6R applications in all process sustainability elements

	Reduce		Reuse		Recycle		Recover		Redesign		Remanu-facture	
Environmental impact		Score		Score		Score		Score		Score		Score
Machine tool	√		√		√		√		√		√	
Products/components	√						√		√			
Work material	√		√		√		√		√			
Cutting tools	√		√		√		√		√		√	
Water	√		√		√							
Emissions	√											
		$\sum m_{1j}^1$		$\sum m_{1j}^2$		$\sum m_{1j}^3$		$\sum m_{1j}^4$		$\sum m_{1j}^5$		$\sum m_{1j}^6$
Energy		Score		Score		Score		Score		Score		Score
In-line consumption	√				√		√		√		√	
Facility environment maintenance	√				√		√		√		√	
Transportation	√				√		√		√		√	
		$\sum m_{2j}^1$		$\sum m_{2j}^2$		$\sum m_{2j}^3$		$\sum m_{2j}^4$		$\sum m_{2j}^5$		$\sum m_{2j}^6$
Waste management		Score		Score		Score		Score		Score		Score
Consumables	√		√		√		√					
Chips generated	√		√		√		√		√			
Mist / Leaks	√		√		√		√		√			
Scraps/Defects	√		√		√		√				√	
Used Coolant/ Lubricant	√		√		√		√		√			
Used Cutting tools	√		√		√		√		√		√	
Other disposable residues	√		√		√		√				√	
		$\sum m_{3j}^1$		$\sum m_{3j}^2$		$\sum m_{3j}^3$		$\sum m_{3j}^4$		$\sum m_{3j}^5$		$\sum m_{3j}^6$
Manufacturing Cost		Score		Score		Score		Score		Score		Score
Labor, incl. Training	√				√				√		√	
Product/Component/Materials	√		√		√		√		√		√	
Manufacturing process	√								√			
Energy	√				√		√				√	
Consumables	√				√		√		√		√	
Maintenance	√											
Indirect e.g.: Facility rent, Equipment, salaries	√		√		√		√		√		√	
		$\sum m_{4j}^1$		$\sum m_{4j}^2$		$\sum m_{4j}^3$		$\sum m_{4j}^4$		$\sum m_{4j}^5$		$\sum m_{4j}^6$
Resource utilization		Score		Score		Score		Score		Score		Score
Products	√		√		√		√		√		√	
Materials	√		√		√		√		√		√	
Tools	√		√		√		√		√		√	
Energy	√								√			
Equipment	√		√		√		√		√		√	
Facility	√		√									
People	√				√							
		$\sum m_{5j}^1$		$\sum m_{5j}^2$		$\sum m_{5j}^3$		$\sum m_{5j}^4$		$\sum m_{5j}^5$		$\sum m_{5j}^6$
Society/Consumer		Score		Score		Score		Score		Score		Score
Society at large	√											
Customer	√								√			
Operator safety	√		√		√		√		√		√	
Personnel health	√								√			
		$\sum m_{6j}^1$		$\sum m_{6j}^2$		$\sum m_{6j}^3$		$\sum m_{6j}^4$		$\sum m_{6j}^5$		$\sum m_{6j}^6$
										Overall Score		$\sum m_{ij}^k$

To study the cost of the manufacturing processes, the following sub-elements have been identified: labor, including training; product/component/materials; manufacturing processes; energy; consumables; maintenance; and indirect cost, such as facility rent, equipment or salaries. The application of the 6R to the cost of the manufacturing processes is also shown in Table 1.

To study the resource utilization in manufacturing processes, the sub-elements identified are: products; materials; tools; energy used; equipment; facilities and the people. The application of the 6Rs in resource utilization of the manufacturing processes is shown in Table 1.

To study the societal aspects of the manufacturing processes, four sub-elements have been identified: society at large; customer; operator safety; and personnel health. The application of the 6Rs to the society/consumer/operator of the manufacturing processes is displayed in Table 1.

Metrics for the Process Sustainability Matrix are presented in the next section. In addition, each sub-element will have a normalized score, which is further explained in Section 6.

5. Metrics for the Process Sustainability Matrix

The major purpose of the metrics is to establish a set of measurable factors to evaluate the manufacturing sustainability performance of a product based on the previously proposed factor matrix. The overall influence of the 6Rs can be measured by the system input and output. Thus, the following metrics are proposed, based on total system input and output per unit of product made.

5.1. Environmental impact

Work material consumption measures the materials that are used during the manufacturing of the product. This aims at the material that goes into the final product, including the parts that forms wastes streams such as machining chips. Waste generation measures collectible waste generated including both solid and liquid forms. Consumable consumption measures the material consumed that are used during the manufacturing process. Furthermore, emission measures the waste directly released to the environment in both liquid and gas forms. By internal capture and processing, emission can be turned into waste and sometimes resources.

Examples of metrics when applying *Reduce* are: machining time; number of components in the final product; mass of material to be removed; mass of emissions generated, and noise level outside of the factory. Similarly, examples of metrics when applying *Reuse, Recycle, Recover, Redesign and Remanufacture* are: percentage of cutting tools reused, percentage of recyclable materials, percentage of recovered products, information retrieval rate for future redesign of machines, percentage of virgin and recycled materials used and remanufacturing rate of products and cutting tools.

5.2. Energy

Energy consumption, measures all energies consumed during the manufacturing process. In practice, it can be further broken down into different energy forms and be normalized in consistent units such as kWh.

Machine energy consumption measures the energy consumed by the machine tools directly associated with the manufacturing process. It covers the manufacturing machines and in-line inspection, machine internal transportation, jig and fixtures, local environment maintaining, local accessories, etc. Plant facility energy consumption measures the utility equipment energy consumption. This equipment includes all equipment that are shared within the plant facility and maintains the manufacturing environment, such as lighting, heating and cooling, ventilation, cleaning, filtering, safety screening, etc. Transportation energy consumption measures the energy consumed by transportation units that connects machine groups and plant facilities.

The total energy consumption and energy consumption of the machine tool are two of the metrics identified when applying *Reduce.* Furthermore, percentage of recycled energy; percentage of recovered energy in terms of heat; percentage of renewable energy used; and energy used are examples of metrics identified when applying *Recycle, Recover, Redesign and Remanufacture,* respectively.

5.3. Waste management

Waste material generation measures the total amount of materials designed to go into the products but end up in the waste stream. Typical sources of such waste streams are residues from material removal processes, and defects/broken blanks or components. For instance, used consumable generation measures the total amount of materials, which are used as aid or intermediate part and do not form part of the final product, but forms part of the waste stream. Used coolant/lubricant generation measures the total amount of coolant and/or lubricant usage which goes into the waste stream. It is addressed separately due to its specific role and major influence. Mist and leakage emission measures the total amount of wastes that is not efficiently captured by the current waste management system. It forms direct material loss and breaks the closed material loop.

The following metrics are identified when *Reduce* is applied: mass of disposed consumables; mass of chips generated, mass of mist generation, mass of coolant loss, mass of hazardous waste; mass of disposed scraps and defects; mass of coolants used; amount of cutting tools used; and mass of restricted disposals. In addition, examples of metrics for the application of the other Rs are: percentage of consumables reused, recycling index of chips, percentage of coolants recovered, chip breakability and percentage of cutting tools re-sharpened.

5.4. Manufacturing cost

Hourly labor cost measures the labor directly and indirectly tied to the manufacturing of the product. It is usually measured in labor hours according to different positions and can be summarized as labor cost in local currencies.

Component cost measures the cost of sub-components which form part of the product. The components should be easily joined or added together to form part of the final product. Material cost measures the cost of raw materials which forms the final product. Energy cost measures the cost of various forms of energy during the manufacturing of the final product. This covers all the energy consumed at the facility. Consumables cost measures the cost of materials which do not form part of the final product. Capital tie-ups measures the cost due to capital investment, such as machine tool purchase, loans, land usage, etc.

Examples of metrics in the case of *Reduce* are: labor cost, employee education cost; cost of materials, number and cost of defects, disposal cost; total manufacturing cost, machining cost; cost of energy used; cost of consumables; maintenance cost; indirect labor cost, warehouse cost, storage cost, transportation cost and packaging material cost. Furthermore, other metrics identified for *Reuse, Recycle, Recover, Redesign and Remanufacture* are: sales of reused products, product disassembly cost, cost of energy during recovery and processing, redesign cost of consumables and remanufacturing cost of packaging materials.

5.5. Resource utilization

Product material consumption measures the materials directly or indirectly used in the product design. Consumable material consumption measures the materials used during manufacturing, but not as part of the product. Energy consumption measures total amount of energy consumed during the manufacturing of the product. Machine tools tie-ups, measures tie-ups due to machine usage, which needs to be normalized into monetary form. Facility tie-ups measures tie-ups due to facility usage. It also needs to be normalized into monetary form. Last, the man-power consumption measures the total amount of labor hours consumed both directly and indirectly during the manufacturing of the product.

Examples of metrics in the case of *Reduce* are: percentage of customized products; mass of materials used; number of tools used; energy used; machines used; fixture complexity; facility space; and percentage of man-force used. Furthermore, other metrics when applying *Reuse, Recycle, Recover, Redesign and Remanufacture* are: percentage of products reused; percentage of materials recycled; percentage of tools recovered; number of parts/components of the product; and percentage of fixtures remanufactured.

5.6. Society/Consumer

Metrics under these segments are difficult to normalize and integrate. Therefore, it is suggested to establish general guidelines and specific measurements can be structured for each case.

Examples of metrics in the case of *Reduce* are: number of consumers injured/affected; percentage of customers injured/affected, product pricing, number of societal awareness programs; exposure to corrosive/toxic chemicals, exposure to high energy components, injury rates, number of employees involved in hazardous operations; chemical contamination of working environment, mist/dust level, noise level inside the factory, physical load index, and health-related absenteeism rate. In addition, other metrics identified are: percentage of corrosive/toxic chemicals reused or recovered; percentage of high energy components recycled or remanufactured; and percentage of satisfied customers.

6. Sustainability evaluation

Sustainability evaluation can be done by scores. Each sub-element will have a normalized score (m_{ij}^{k}), where i represents serialized number of each sustainable element, and similarly, j for the sub-elements and k for each of the 6Rs. The scores can be added for each element and R applied. Furthermore, the overall evaluation of each sustainability element can be calculated as an overall score, which can be further added to the overall score of the manufacturing process evaluated, as shown in Table 1. Mentioned evaluation is obtained similarly to the Process Sustainability Index (*ProcSI*), [7], and can be extended to the entire the process sustainability matrix.

Consider the cutting tools used in a machining process as example, Table 2 presents the sustainability evaluation in terms of the environmental impact with focus on the cutting tools, including possible metrics examples.

Table 2. Sustainability evaluation of the cutting tools used, as a sub-element of the environmental impact

	Reduce		**Reuse**		**Recycle**		**Recover**		**Redesign**		**Remanufacture**	
Environmental impact		Score		Score		Score		Score		Score		Score
Cutting tools	No. Of cutting tools	m_{i1}^{1}	% of cutting tools reused	m_{i1}^{2}	Recycling index of cutting tools	m_{i1}^{3}	Recovery rate after first life	m_{i1}^{4}	Information retrieval rate for future redesign	m_{i1}^{5}	Remanu-facturing rate of cutting tools	m_{i1}^{6}
		$\sum m_{ij}^{1}$		$\sum m_{ij}^{2}$		$\sum m_{ij}^{3}$		$\sum m_{ij}^{4}$		$\sum m_{ij}^{5}$		$\sum m_{ij}^{6}$

7. Sustainability of the manufacturing processes

The manufacture of a product or component requires several manufacturing processes such as forming, machining, welding and assembly. Each process can be evaluated in terms of the productivity of the process, quality of the product and/or the overall production cost, as in the case of the machining process. The sustainability of the process can be considered as well. The amount, condition and potential end-of life activities that can be applied will greatly influence how sustainable the manufacturing process is. Therefore, 6Rs were applied to each sustainability element of the manufacturing processes using a process sustainability matrix. Different metrics have been identified and presented. Some of those metrics are deterministic in nature, thus it is possible to investigate them analytically. However, other metrics have a non-deterministic nature, thus their analysis might be more complex. For instance, using fuzzy logic, the fuzzy set obtained needs to be converted into a numerical value [14], which can be further used as a score in the process sustainability matrix.

Manufacturing companies continue to keep data about the potential end-of-life activities that can be applied to their machine tools or products; energy used in production; management operations performed; generated wastes; manufacturing cost; utilization of the equipment and facilities; operators' safety and the personnel health. Thus, an initial quantitative estimation of the overall sustainability of a manufacturing process can be made by using these data in a process sustainability matrix, as the combination of each sustainability element evaluated with respect to each R.

Thereby, the process sustainability matrix can facilitate visualization of the sustainability of a manufacturing process and its influence on the three main pillars: economy, environment, and society.

8. Conclusions

The manufacture of a component directly influences the end-of-life activities with respect to further reduce, reuse, recycle, recover, redesign and remanufacture of the product, its components and/or materials. This paper presents an approach to evaluate the sustainability of the manufacturing processes used for each component or product, based on the application of the 6Rs to each sustainability element by a process sustainability matrix.

The process sustainability matrix can ease the visualization and estimation of the process sustainability and aid the companies in different decision-making processes towards a more sustainable manufacturing in economic, environmental and societal terms.

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