Design for Sustainable Mass-Customization:

Design Guidelines for Sustainable Mass-Customized Products

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Abstract—This paper presents a new product design approach based on a unified set of Design for eXcellence (DFX) guidelines applied to the design of sustainable mass-customized products. In order to gather the main product design requirements for developing a sustainable mass-customized product, an integrated product design process guideline is introduced to go beyond conventional engineering product requirements and consider new sustainable and mass-customization ones. The integrated product design process guideline proposed takes into account all product lifecycle phases in order to assess and identify all possible impacts of product design decisions in further lifecycle phases.

Keywords—Product Design, Design for eXcellence, Product Development, Sustainability, Mass-Customization.

I. INTRODUCTION

Today's industrial design engineers are required to be top experts in a large number of engineering disciplines regarding the new products they are designing and/or re-designing. With new product features, functions and upcoming high-quality (e.g. Design for Six-Sigma) and environmental (e.g. Design for the Environment) requirements emerging and/or evolving, industrial designers must start providing a formal assurance - guarantee - regarding manufacturability and other product attributes (e.g. environmental-friendly) when sketching a new product design or re-designing an existing one. This sustainable product design vision is synthesized as the importance of *designing for all* desirable attributes according to Mottonen et al. (2009) [1]. Hence, the goal-specific design methods such as *Design for eXcellence* (DFX) represent such product design vision for answering to the up-surgings necessity of collecting specific design guidelines and requirements (rules) to address a particular issue or set of issues in relation to the achievement of desirable sustainable product characteristics [2]. Moreover, the advantage of DFX design guidelines is their direct approach and corresponding methods and techniques with the main purpose of generating and applying technical knowledge in order to control, improve or even invent particular product traits. Therefore, every design guideline represents the transformation of an abstract form of knowledge for designing, proper of specialized designers, to an explicit method that contains the "knowing-how-to-design"; in other words the procedural knowledge needed for immediate implementation in a new product design and/or re-design process [3] [4] [5] [6].

Nevertheless, current DFX design methods (e.g. Design for the Environment) may be limited when it comes to the fact that the proper achievement of sustainable products, considering their entire lifecycle, requires a complete comprehension of the whole value system of the new product to be designed or re-designed. This issue leads to the point that any product manufacture has a finite life, which always implies the depletion of resources, and to the ideal that long-term shareholder value must be a priority to ensure future generations' access to certain products by embracing the ecological, social and economic aspects of the sustainable manufacturing of any product [7]. Hence, *sustainability* is as a result a new *must* product design requirement, and therefore product development requirement, which should be taken into account when designing and re-designing any new product.

Along with a *sustainability* design requirement for new products, *Mass-Customization* (MC) can be considered as a production paradigm, as well as a *design for* requirement, to deliver products to the market with sustainable added-value by meeting individual customers' needs [a social sustainability contribution] with a near mass-production efficiency [an economic sustainability contribution] based on manufacturing operational models such as assembly-to-order (ATO), configure-to-order (CTO), or engineer-to-order (ETO), which make a more intelligent use of manufacturing resources [an environmental sustainability contribution]. e.g. "Delivering not what the market wants, but what specific customers want"... "Producing products just when the customer need them and only in the quantity they are needed" (Adapted from Tseng & Jiao, 2001 [8]).

This paper aims to introduce a novel product design approach oriented to *sustainable mass-customized products*, and contribute to their sustainable manufacturing, by linking *mass-customization* and *sustainability* principles with DFX design guidelines in order to provide industrial designers with a new process for designing and/or re-designing next-generation products.

The research work is presented as follow: An introduction to the sustainable mass-customization paradigm; a formal definition for a sustainable mass-customized product and its requirements, a collection of DFX design guidelines relevant for the design of sustainable mass-customized products, and finally a new integrated DFX guideline for Sustainable Mass-Customization (DFS_{MC}).

II. SUSTAINABLE MASS-CUSTOMIZATION PARADIGM

In order to define a product design approach to fulfill all the product design requirements of the *sustainable mass-customization paradigm*, it is important to understand its main features or characteristics for the design and re-design of products. This is referred to how a product can be characterized within the frame of current sustainable and mass-customized product categories.

A. Sustainable Products

The continuous development of sustainable product designs have reached important results in the past decades in terms of environmental quality indicators (e.g. degradability, minimal resources use, minimal pollution generation, etc.), social profits (e.g. social responsibility, health and safety) and economic improvements (e.g. minimal costs, conquering of new markets segments, etc.) [9]. Therefore, systematic approaches to *Design for the Environment (DFE)* started to emerge in the 90s, known as *eco-design* or *lifecycle design* methods [10] [11]. These approaches were developed with the aim to reduce and balance the adverse impact generated by a product to the environment considering its entire product lifecycle - from raw materials extraction and acquisition, thru manufacturing, distribution and use, to reuse, recycling and final safe disposal [12]. Therefore, nowadays it is possible to list the requirements for *eco-designing sustainable products* according to Keoleian & Menerey (1994) [10]: (a) Selection of low-impact materials (e.g. renewable, recycled), (b) Reducing the weight or volume of materials in the product (e.g. dematerialization), (c) Using cleaner techniques for product manufacture (e.g. less wasteful, polluting), (d) Reduction of environmental impacts arising from the product packaging and distribution processes, (e) Reduction of environmental impacts arising from the use (e.g. energy consumption) and maintenance of the product, (f) Optimizing the product lifecycle (e.g. by creating durable-classic designs), and (g) Reuse, remanufacture, recycling or safe disposal at the end of the product's life.

Since the *eco-design* concept was introduced as one of the methods to develop *sustainable products*, other methods and methodologies have been proposed in order to achieve products capable to fulfill environmental, social and economic aspects as well, among ones it is important to recognize the work by Ranky (2010) [13] around the Japanese principle: '*Monozukuri*', which means: sustainable, environmentally friendly, green factories and products with simultaneously integrated product and process designs. This principle is applied to the different stages of a product development, especially to its design, in order to achieve products as sustainable as possible.

B. Mass-Customized Products

Mass-customization has been defined by many authors [14] [8][15][16], and some of the commonly accepted characteristics and issues associated to *mass-customized (MC) products* are: (a) A product deployment concept that combines low price with extensive variation and adaptation in order to impact the customer's perceived value of a product, (b) A production of custom products at mass-production speed and efficiency, (c) A production system characterized by stable but still

flexible and responsive manufacturing processes that provide a dynamic flow of products, (d) A production paradigm that combines the low unit costs of mass-production processes with the flexibility of individual customization; producing goods and services to meet individual customers' needs with near mass-production efficiency, (e) A production method for effectively postponing the task of differentiating a product for a specific customer until the latest possible point in the value chain.

Mass-customization uses flexible design processes and manufacturing systems to produce a variety of *customized products* at a lower cost than standardized mass-production systems; it can provide customers with products capable to fulfill most of their individual needs. The implementation of *mass-customization* has then the following characteristics according to Svensson & Barfod (2002) [15]: (a) It influences and affects design, manufacturing and ramp-up production processes, (b) It is not only a matter of money; it is mostly a matter of people (customers), (c) Often it is an idea that comes from the sales/planning department and is forced up on the rest of the company, and (d) It "takes a steady hand at the helm", which means, if an overall management commitment is not present, most manufactures would be better without *mass-customization*.

The added value of *customization* must be balanced among the product costs, manufacturing costs and product development times. Hence, *mass-customized products* have to be manufactured at a cost comparable with those items manufactured using mass-production techniques [17]. Moreover, thru *mass-customization*, producers are able to reduce their inventories and manufacturing overhead costs, eliminate waste in their value chains, and obtain more accurate information about demand. Customers, on the other hand, get reasonably priced and tailor made products according to their personal preferences of style, features, colors and/or functions. Thus, *mass-customization* has to be so efficient at price that customers will be willing to pay, and at cost that allows producers to reach profitable margins.

The requirements of *mass-customization* as a product design principle are based on three main aspects: (a) time-to-market (quick responsiveness), (b) variety (customization), and (c) economies of scale (mass-efficiency); so in order to achieve such balance between these aspects, four major technical challenges are identified: (i) product parts reusability, capturing repetitions in design and manufacturing to maximize reusability so as to achieve low costs and high efficiency, (ii) product platform, providing a technical basis for accommodating customization, managing varieties and leveraging core-capabilities to optimize product flexibility and foster a customer focus and product-driven business model, (iii) process platform, providing a customizability analysis in *design for mass-customization*, where customers' preferences are evaluated and optimized with different design alternatives, and (iv) integrated product lifecycle, facilitating a coherent integration context throughout the product development process and over the product lifecycle to achieve quick responsiveness.

Furthermore, in order to understand the possible *mass-customization* implementation types, three customization categories have been defined by Anderson & Pine (1997) [18]: (a) Modular - modules are building blocks that can customize a product by assembling various combinations of modules, (b) Adjustable - Adjustments are a reversible way to customize a product, and (c) Dimensional - Dimensional customization involves a permanent cutting to fit, mixing or tailoring.

The implementation of any of these *mass-customization* categories depends on what kind of product is going to be developed. Product characteristics (functional specifications, geometry, etc.) are related with manufacturing processes and production planning in order to define constraints, aided techniques and/or tools to be implemented for a product design and development. *Customized products* are not easy to address, because several features, implications, techniques and tools are needed to be implemented with the aim to design efficient products. *Mass-customized products* do not have a lifecycle or become obsolete; they are always evolving to satisfy the market demand.

C. Sustainable Mass-Customized Products

The characteristics identified for *sustainable* and *mass-customized products* from an extensive literature review are synthesized in the Tables 1 and 2.

Table 1. Sustainable Products Characteristics

<ul style="list-style-type: none"> • Integration of workflows with visual control. • Developing and manufacturing products under a sustainable frame. • Reconfigurable and flexible assembly lines. • Green technologies. • Sustainable design. • Material recovery and reuse avoiding composite materials. • Manufacturing and assembly for the purpose of reducing waste. • Using of advanced digital manufacturing, assembly, packing and flexible manufacturing. • Green engineering. • Simulation in the virtual domain. • Value chain plays a crucial role in the design of sustainable products. 	<ul style="list-style-type: none"> • The production of sustainable products must be integrated into green value chain. • Disassembly-easiness - easy component separation; avoid permanent attachments of dissimilar materials such as welds. • Simplicity-develop - common designs for multi-functional parts. • Waste minimization - reduce product size and weight, reduce packaging. • Energy conservation - reduce energy used in production and product power consumption. • Material conversation - design multi-functional products and parts; specify recycled and renewable materials; use remanufactured components; design for product longevity and performance; design for closed-loop recycling.
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It is possible to note in Table 1 and 2 that *sustainable products* have some characteristics unlike *conventional* and *mass-customized products*, since *sustainable products* satisfy threefold requirements (economic, environmental and social), which are not a steadfast rule of *mass-customized products*.

Hence, *sustainable mass-customized products* are defined as: “products capable to fulfill engineering and customers’ requirements including environmental, economic and social constraints”.

Table 1. Mass-Customized Products Characteristics

<ul style="list-style-type: none"> • Affordable, high-quality and customized products. • Low management cost for product variation. • Purchase emphasis on strategy cooperation. • Financial emphasis on value chain management. • Introduce product proliferation while taking advantage of mass-production efficiency. • Product efficiency. • Variety and customization through flexibility and quick responsiveness. • Total process efficiency premier. • Direct marketing, “blue ocean” relationship with suppliers, and other partners. • Logistics is outsourced to 3rd partners. • Supplier interdependence. • Heterogeneous markets and segments of one. • Fragmented demand. • Economies of scale and economies of scope. • Lot sizes of one. • No inventories: Make-to-Order (MTO). • Production plan and execution is based on customer order: “zero” storage. • Effectively postponing the task of differentiating a product for a specific customer until the latest possible point in the value chain. • Short product development and lifecycles. • Pull production mode. • Low overhead. • Dynamic flow. 	<ul style="list-style-type: none"> • Flexible processes, production and organizational structures. • Production emphasis on outsourcing, core-capability and fast response. • High utilization of and investment in worker skills. • Integration of thinking and doing. • Integration of innovation and production. • Coordination of R&D and continuous improvement. • Sense of community. • Customer co-designs the process of product and service. • Product development is mainly carried out by design engineers who define the degrees of freedom in product design that customers can exploit in order to create individualized product variants (solution space). • Provide products that best serve customer needs while maintaining near mass-production efficiency. • Developing, producing, marketing, and delivering affordable products with enough variety and customization that nearly everyone finds exactly what they want. • Fast response for customer’s requirements. • Interaction with the manufacturer who is responsible for providing the custom solution. • Changes over activities from a product to another must be minimized.
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Moreover, based on the previous *sustainable* and *mass-customization* products characteristics, it is important to point out that *sustainable mass-customized products* will need to integrate a ‘process analysis’ paying attention to environmental impacts, and calculating the emissions generated during the product design process, while controlling times and costs involved in the product development as well as ensuring fair work conditions and the ability to adapt to the changes required for a *mass-customized product design process*.

III. SUSTAINABLE MASS-CUSTOMIZED PRODUCT DESIGN REQUIREMENTS & GUIDELINES

Engineering design is the process of developing a system, a component or a procedure to meet desired needs. *Design for eXcellence (DFX)* research emphasizes the consideration of all design goals and related constraints in the early product design stage [19]. By considering all goals and constraints early, companies can produce better products. Furthermore, the product will enter the marketplace earlier because an inherently simpler product is designed correctly the first time without the introduction of problems, delays and changes of orders.

DFX guidelines implementation have led to enormous benefits including simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time-to-market. More recently, environmental concerns required that disassembly and recycling issues should be considered during the product design phases. The effort to reduce total lifecycle cost for a product through design innovation is becoming an essential part of the current manufacturing industry [20].

Design for Disassembly (DSD), Design for Recyclability (DFR) and Design for Lifecycle (DFL) allow the designers to plan ahead for product re-processing after its useful life. Design for the Environment (DFE) focuses on environmental, safety and health related issues and thus can help to reduce the indirect cost of a product. Design for Quality (DFQ), Design for Maintainability (DFM) and Design for Reliability (DFR) can also be assured by design and process controls rather than by expensive testing, diagnostics and re-work.

In order to define a - “Design for Sustainable Mass-Customization (DFSMC)” - DFX guideline, each of the DFX guidelines depicted in Table 3, were preliminary studied individually in order to take those useful requirements that will be integrated to achieve the proposed *DFSMC guideline*.

Table 3. DFX Guidelines studied towards DFSMC Guideline

<ul style="list-style-type: none"> • DFA - Design for Assembly • DFD - Design for Disassembly • DFM - Design for Manufacturing • DFSS - Design for Six Sigma • DFT - Design for Testing • DFQ - Design for Quality • DFSC&L - Design for Supply Chain & Logistics • DFR - Design for Recycling • DFMN -Design for Maintenance 	<ul style="list-style-type: none"> • DFE - Design for Ergonomics • DFC - Design for Cost • DFR - Design for Reliability • DFSTM - Design for Short-Time to Market • DFS - Design for Safety • DFMR - Design for Minimum Risk
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From each *DFX guideline* studied, their main product design requirements were taken in order to relate them to the *sustainable mass-customized (S-MC) product characteristics* depicted in Tables 1 and 2. The main idea behind this research work was to develop a new *integrated DFX guideline* that combines all the *DFXs design guidelines* enlisted in Table 3 in order to guarantee the fulfillment of all the design requirements of *sustainable-mass customized products*.

Table 4 presents the “novel” - *Design for Sustainable Mass-Customization (DFSMC)* - integrated DFX guideline, and the design requirements that are supported for *sustainable mass-customized products*.

Table 4. Design for Sustainable Mass-Customization (DFSMC) Product Requirements & Guidelines

DFSMC Guidelines	S-MC Design Requirements
Affordable, high-quality and customized products.	<ul style="list-style-type: none"> • Reduce the number of parts for simplified operations in order to reduce cost. • Standardize common parts for facilitating design activities in order to reduce cost. • Determine the relationship between customer requirements and technical requirements for increased robustness of product performance in the consumers' hand in order to improve product quality and customer satisfaction. • Identify critical customer requirements and translate them into design requirements to develop the product exactly how the customer needs it in order to improve customer satisfaction and reduce number of design changes or iterations.
Low management cost for product variation.	<ul style="list-style-type: none"> • Use common materials for facilitating design activities in order to reduce cost. • Standardize common parts for minimize the amount of inventory in the system in order to reduce cost. • Use common materials for minimizing the amount of inventory in the system in order to reduce cost. • Elaborate a systematic approach for the product design analysis in order to reduce economic risks: minimum risk-minimum cost.
Financial emphasis on value chain management.	<ul style="list-style-type: none"> • Identify logistic design constrains and support risks in order to ensure their consideration into the design and logistic capabilities, into the product design as cost-effective as possible, and into the full supportable system throughout a product's life. • Identify all viable design and support system alternatives and risks associated with each one in order to meet the company's cost goals and to meet the customer requirements. • Devise and verify measurement methods and metrics for improving internal processes as well as customer relationships and business performance across the value chain in order to improve quality product.
Variety and customization through flexibility and quick responsiveness.	<ul style="list-style-type: none"> • Identify all the activities involved in the design process for costs specification in order to produce efficiently in all phases of the product lifecycle. • Evaluate the design for minimizing complexity in order to have few production processes. • Evaluate the design for minimizing complexity in order to reduce numbers of parts. • Reduce time-to-market products, for planning time, for change management, in order to reduce manufacturing costs.
Direct marketing, “Blue Ocean” relationship with Suppliers/Partners.	<ul style="list-style-type: none"> • Gather market and marketing competence information for integrating simultaneous engineering processes in order to achieve shorter delivery times to market. • Plan for reuse and recycling by selecting vendors with good environmental histories for a good control of the system in order to improve quality of processes and products and help the environment.

Short product development and lifecycles.	<ul style="list-style-type: none"> Conceive a product with a long-term view of how its components can be effectively and efficiently repaired, refurbished, reused and/or safely disposed in an environmental friendly manner at the end of the product's life. Create program schedules and test plans for identifying and managing risks throughout the development lifecycle, from product conception through launch, in order to increase customer satisfaction, operational efficiencies and revenue, thus impacting shareholder value. Develop a test flow chart and identify the best process and equipment for test and inspection for discovering errors to determine the predicted life of a part/product in order to report how the product will fail or wear out. 	Products can be easily manufactured, assembled and disassembled in a quick and efficient way in response to the customer specifications.	<ul style="list-style-type: none"> Minimize flexible parts and interconnections for ease assembly in order to avoid errors in the assembly process. Design the part to be rigid enough to withstand the forces of clamping and machining without distortion in order to prevent breakage. Standardize common parts for standardize handling and assembly operations in order to reduce cost. Design parts for easy reassembly by using existing tools from one-off and small batch production in order to facilitate reconditioning process. Design parts for easily adjustable or extendible parts in order to reduce the number of new parts.
Production plan and execution is based on customer order: "zero" storage.	<ul style="list-style-type: none"> Reduce the number of parts for minimize stock in order to reduce cost. Verify and validate that the product design will meet customer needs with: peer reviews, check-lists, design reviews, simulation and analysis, qualification testing, production validation testing, focus-groups and market testing - in order to increase customer satisfaction, operational efficiencies and revenue, thus impacting shareholder value. 	Product processes should be organized in loosely coupled modules.	<ul style="list-style-type: none"> Define clearly the product design requirements by listening to the voice of the customer for reducing the number of design changes or iterations, and hence reducing the number of prototypes made during the design stage in order to reduce costs. Apply modular principles to reduce service and inspection effort for easy maintenance.
Effectively postponing the task of differentiating a product for a specific customer until the latest possible point in the value chain.	<ul style="list-style-type: none"> Determine the relationship between customer requirements and technical requirements for increased robustness of product performance in the consumers' hand in order to improve product quality and customer satisfaction. Identify critical customer requirements and translate into design requirements to develop the product exactly how the customer needs it in order to improve customer satisfaction and reduce number of design changes or iterations. Make direct interviews to potential customers, focus groups, analysis of the characteristics of similar market products and observation of their real use for identifying customers' needs in order to define a structured set of quality elements that will be successively classified and evaluated. 	Use modular components that can be combined to create a wide range of different products.	<ul style="list-style-type: none"> A product should be designed in a way that it consists of independent modules that can be assembled into different forms of the product easily and inexpensively. Apply modular principles to reduce service and inspection effort for easy maintenance.
Customer co-designs the process of product and services.	<ul style="list-style-type: none"> Determine the relationship between customer requirements and technical requirements for increased robustness of product performance in the consumers' hand in order to improve product quality and customer satisfaction. Identify critical customer requirements and translate into design requirements to develop the product exactly how the customer needs it in order to improve customer satisfaction and reduce number of design changes or iterations. 	Integration of workflows with visual control.	<ul style="list-style-type: none"> Stored the information of the specific test of the design to take a control in order to improve quality of processes and products.
Changes over activities from a product to another must be minimized.	<ul style="list-style-type: none"> Standardize common parts for standardize handling and assembly operations in order to reduce cost. If possible, avoid machining operations for reducing time operation in order to reduce cost. Minimize numbers of fasteners and connectors to increase speed of disassembly for saving time in order to reduce cost. 	Reconfigurable and flexible assembly lines.	<ul style="list-style-type: none"> Use suitable joining techniques in those parts for disassembly and reassembly in order to easily re-processing and reconditioning. Use suitable fastening techniques in those parts or modules for disassembly and reassembly in order to easily re-processing and reconditioning. Design parts for easy reassembly by using existing tools from one-off and small batch production in order to facilitate reconditioning process.
		Green engineering and technologies.	
		<ul style="list-style-type: none"> Required guideline to design SMC products. 	
		Sustainable design.	<ul style="list-style-type: none"> Choose recycling-compatible materials, so no extra time is required to separate the components to be recycled in order to reduce time and help the environment. Avoid using materials that require separating before recycling in order to help the environment.

Manufacturing and assembly for the purpose of reducing waste.	<ul style="list-style-type: none"> • Avoid parts that can become tangled, wedged or disoriented in order to prevent component damage, remanufacturing and loss of time. • Design with careful considerations in very aspects from design to manufacturing in order to avoid design changes in the later stage, thus reducing the chances of cost incurred by design changes. • Avoid holes and tabs and designed closed parts to minimize the use of automation in parts handling and assembly such as: vibratory bowls, tubes, etc. in order to avoid extra costs. • Use suitable fastening techniques in those parts or modules for disassembly and reassembly in order to easily re-processing and reconditioning. • Execute assembly operations simultaneously in order to reduce time • Standardize common parts for standardize handling and assembly operations in order to reduce cost.
Manufacturing and service processes should be designed in a way that they consist of independent modules that can be moved or rearranged easily to support different distribution network designs. <ul style="list-style-type: none"> • Required guideline to design SMC products. 	
Use of advanced digital manufacturing, assembly, packing and flexible manufacturing.	<ul style="list-style-type: none"> • Minimize flexible parts and interconnections for ease assembly in order to avoid errors in the assembly process. • Design with careful considerations in very varying aspects from design to manufacturing in order to avoid design changes in the later stage, thus reduce the chances of cost incurred by design changes. • Use near net shapes for molded and forged parts to minimize machining and processing effort in order to reduce manufacturing costs.
It requires simulation in the virtual domain.	<ul style="list-style-type: none"> • Verify and validate that the product design will meet customer needs with: peer reviews, check-lists, design reviews, simulation and analysis, qualification testing, production validation testing, focus groups and market testing - in order to increase customer satisfaction, operational efficiencies and revenue, thus impacting shareholder value.
The supply network plays a crucial part in the design of sustainable products.	<ul style="list-style-type: none"> • Identify logistic design constraints and support risks in order to ensure their consideration into the design and logistic capabilities, into the product design as cost-effective as possible, and into the full supportable system throughout a product's life. • Provide cost effective packaging and handling protection, compatible with storage, shipping and recycling for guaranteeing the safety of products in order to avoid extra costs. • Plan for reuse and recycling by selecting vendors with good environmental histories for a good control of the system in order to improve quality of processes and products and help the environment.
The production of sustainable products must be integrated into green value chain. <ul style="list-style-type: none"> • Required guideline to design SMC products. 	
Facilitate means of component separation by avoiding permanent attachments of dissimilar materials such as welds.	<ul style="list-style-type: none"> • Maintain good access to components and fasteners considering plane of access in order to save time when disassembling, re-processing and reconditioning. • Reduce the number of parts to minimize number of disassembles in order to reduce time (cost). • Minimize numbers of fasteners and connectors to increase speed of disassembly to save time in order to reduce cost.

Material recovery and reuse, avoiding composite materials.	<ul style="list-style-type: none"> • Design for easy identification of the state of wear of a part to decide whether it can be reused in order to reduce the number of new parts that are need. • Conceive a product with a long-term of view of how its components can be effectively and efficiently repaired, refurbished, reused and/or safely disposed in an environmental friendly manner at the end of the product's life. • Select materials that do not conflict with reprocessing and minimize corrosion. • Select compatible materials for those parts to be reprocessed in order to easily reprocessing. • Design parts and modules to be cleaned easily and without damage for those parts to be reusable in order to facilitate reconditioning process. • Label those parts and modules in order to specify the proposed recycling strategy including recycling properties and required recycling procedures for easy recycling. • Marking parts with international recycling symbols to allow recyclers confidently sort items into the correct material stream in order to help the environment.
Develop common designs for multi-functional parts.	<ul style="list-style-type: none"> • Prefer simple adjustments or provide positioning guides in order to prevent component damage, incorrect assembly and loss of time. • Standardize common parts for minimizing the amount of inventory in the system in order to reduce cost. • Reduce the number of parts for simplifying operations in order to reduce cost.
Reduce product size and weight to reduce packaging.	<ul style="list-style-type: none"> • Evaluate dimensions for reducing overall dimensions in order to reduce material.
Reduce energy used in production and product power consumption. <ul style="list-style-type: none"> • No DFX guidelines available. 	
Design multi-functional products and parts, specify recycled and renewable materials, use remanufactured components, design for product longevity and performance, design for closed-loop recycling.	<ul style="list-style-type: none"> • Select compatible materials for those parts to be reprocessed in order to easily reprocessing them. • Choose recycling-compatible materials, so no extra time is required to separate the components to be recycled in order to reduce time and help the environment. • Marking parts with international recycling symbols to allow recyclers confidently sort items into the correct material stream in order to help the environment. • Label those parts and modules in order to specify the proposed recycling strategy including recycling properties and required recycling procedures for easy recycling.

IV. SUSTAINABLE MASS-CUSTOMIZED PRODUCT DESIGN CONSTRAINTS

Product design constraints are important to take into account when designing *sustainable mass-customized products*. A product design constraint is a negative correlation that can appear among different *DFSMC guidelines*. Some individual design guidelines defined for *sustainability* can affect in a negative way *mass-customization* and vice-versa. Thus, these correlations and other *DFSMC guidelines* relations are assessed in Figure 1 considering positive, negative and neutral correlations

and relations among *sustainable mass-customized products requirements*. Figure 1 has been designed and utilized based on the functionality of the QFD's roof in order to allow observing the correlations and relations among the *DFSMC guidelines*.

The following symbols are used to represent what type of impact (correlation/relation) each product requirement has on the other: Positive +, Negative −, and Neutral ●.

The 2nd negative correlation is among: “Develop common designs for multi-functional parts vs. Reduce product size and weight, reduce product packaging”. The challenge faced here is to include multi-functional product parts vs. reducing product size and weight. Customized products design is based on characteristics like modularity and commonality, so products are made by several parts or components. So, the industrial

Figure 1 presents positive, negative and neutral correlations and relations among product design requirements concerned with *sustainability* and *mass-customization*. The negative correlations are very important, because those contradictions among certain product design requirements related to sustainability or mass-customization need to be taken into account for designing *sustainable mass-customized products*.

Hence, the negative correlations identified are carefully analyzed and discussed in the following paragraphs.

The 1st negative correlation is among: “Affordable, high-quality and customized products vs. Material recovery and reuse avoiding composite materials”. The two guidelines listed above are related to *mass-customization* and *sustainability* respectively. The challenge faced here is to achieve affordable high-quality and customized products with a high-degree of recyclable materials content, which implies new procedures to assess product quality. Thus, depending on the product design requirements, the industrial designer has to define the product quality level needed when following these two *DFSMC guidelines*. This decision means defining which requirement is mandatory rather than the other (e.g. it is most important to reuse and use recyclable materials rather than to reach a high-quality product?).

designer has to define how many components are needed to be added in a product seeking to address the functionalities for which the product was designed. Hence, tools like IDEF0 (Integration Definition for Function Modeling) could be implemented to solve this kind of problem and define product function(s) allowing the designer to link functions-product parts with the intention to define the proper number of components. Based on the proposed *DFSMC guideline*, the designer is allowed to define product size and weight when tools or techniques capable to link functions-product parts are implemented, so under such circumstances the designer can decide how much affects product size and weight when new components are added.

The 3rd negative correlation is among: “Reduce product size and weight, reduce packaging vs. Design for longevity, performance, multi-functional and closed-loop recycling, specify recycled/renewable materials, and use remanufactured parts”. The industrial designer must define how much benefit is in reducing product size without affecting product performance and also take into account recyclability and remanufacturing. In this negative correlation, the two guidelines involved are related to *sustainability*, so this implies that is necessary to define which requirement is going to have a bigger impact in

terms of sustainability performance (e.g. it is necessary to have a better product performance and to implement recyclable materials rather than to reduce product size and weight?).

The 4th negative correlation is among: “Reduce product size and weight, reduce packaging vs. Use modular components that can be combined to create a wide range of different products”. The problem with the product size reduction is to define how much the product weight can be reduced without affecting modularity. Thus, like the 2nd negative correlation analyzed before, the industrial designer has to define if the reduction in the product size and weight can or cannot affect product modularity.

It is possible to note from the negative correlations analyzed that the designer criterion is quite important to lead the product design process through an *integrated sustainable mass-customized frame*. In other words, *DFSMC guidelines* implementation involves *sustainability* and *mass-customization* requirements, therefore during the product design process, depending on the product applications and constraints, contradictions can often appear. This is where industrial designers must do an evaluation among guidelines and then choose which guideline is more important to be accomplished.

Positive relations among *DFSMC guidelines* are useful for both *sustainability* and *mass-customization* product design requirements, that is to say, that it could be possible to apply any of them or both of them in order to obtain positive results and it will not have a contradictory result.

Neutral relations are those in where there is no negative or positive effect with the implementation of one or the other *DFSMC guideline*, hence depending on the product design requirement the industrial designer can implement one or the another *DFSMC guideline* with neutral relation.

All the correlations and relations represented in Figure 1 established the bases to define the *DFSMC guidelines*.

V. DESIGN FOR SUSTAINABLE MASS-CUSTOMIZATION (DFSMC) DFX GUIDELINES

In order to reach the definition of a new integrated DFX guideline named: *Design for Sustainable Mass-Customization (DFSMC)* in a complete product lifecycle environment, two important research activities were conducted. First, it was studied the design requirements of *sustainable mass-customized products* and several *DFX guidelines* in order to define the *integrated DFSMC guidelines* to *fulfill sustainable mass-customized product design requirements*. Second, an evaluation of the correlations and relations among *DFSMC guidelines* where studied in order to provide a useful way for industrial designers to implement the *DFSMC guidelines* (e.g. a process guideline).

Table 5 introduces the implementation of the *DFSMC guidelines* thorough the six product design and development phases to achieve a *sustainable mass-customized product*. Each phase is explained in detail and synthesized.

Table 5. Design for Sustainable Mass-Customization (DFSMC) DFX Guidelines Implementation

S-MC Product Design and Development Process	
Planning Phase	<ul style="list-style-type: none"> • <i>Corporate strategy</i>: products must be affordable, high-quality and customized. • <i>Assessment of technology developments</i>: this requirement addresses the technologies of visual control, reconfigurable and flexible assembly lines, and manufacturing and assembly for the purpose of reducing waste, digital manufacturing, assembly, packing and flexible manufacturing and simulation. • <i>Market objectives</i>: customized products have to be achievable for large market segments, and not only for a few premium customers.
Concept Development Phase	<ul style="list-style-type: none"> • <i>Generate alternative products</i>: the alternative products must be affordable, high-quality and customized; short product development and lifecycles (customer needs and wants change quickly and constantly), and integrate green technology development have also to be considered. Developing common designs for multi-functional parts, design for longevity, performance, multi-functional and closed-loop recycling, specify recycled/renewable materials, must be considered too. • <i>Evaluate alternative products</i>: simulation in the virtual domain is required. • <i>Development and testing</i>: The most sustainable concepts are selected.
System Level Phase	<ul style="list-style-type: none"> • <i>Define product architecture</i>: short product development and lifecycle should be considered. The architecture have to be developed in order to be easily manufactured, assembled and disassembled in a quick and efficient way in response to the customer specification. The designer reduces product size, weight and/or packaging as much as possible. The designer has to take into account aspects like modularity, product functionality, costs, among others; and then define how much benefit is in reducing product size, weight and/or packaging. All these activities are supported by simulations in the virtual domain. • <i>Decomposition of the product into subsystems and components</i>: modular components are used in order to be combined and to create a wide range of different products. This activity conceives how parts can be easily assembled considering structuring, reducing, standardizing and simplifying the assembly operations (also disassembled). • <i>Final assembly scheme for the production system</i>: it has the purpose of reducing waste, avoid permanent attachments of dissimilar materials such as welds, and integrate flexibility and quick responsiveness to achieve variety and customization.
Detailed Design Phase	<ul style="list-style-type: none"> • <i>Complete materials specification</i>: it addresses to the material recovery and reuse-avoid composite materials, to standardize materials and fasteners, to specify recyclable materials and evaluate them to be used in product complying with functional requirements. • <i>Standard parts to be purchased from suppliers</i>: in order to achieve variety and customization through flexibility and quick responsiveness, a relationship with suppliers and other partners is essential; the supply network plays a crucial part in the design of sustainable products. • <i>Process plan</i>: it is based on customer order, “zero” storage; it should also integrate workflows with visual control, reconfigurable and flexible assembly lines integrating green technologies and simulation in the virtual domain. • <i>Tooling is designed for each part to be fabricated within the production system</i>: products can be easily manufactured, assembled and disassembled in a quick and efficient way in response to the customer specifications. Activities that are necessary to change parts, fixture, tooling, equipment programming from a product to another must be minimized.

Testing and Refinement Phase	<ul style="list-style-type: none"> • <i>Construction and evaluation of multiple reproduction versions of the product</i>: the use of modular components that can be combined to create a wide range of different products is very important. Green technologies and simulation in the virtual domain may be used. • <i>Component separation has to be facilitated</i>: it has to be avoided permanent attachments of dissimilar materials such as welds.
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VI. CONCLUSIONS

DFSMC guidelines are a “process guideline” by which products can be designed based on sustainability and mass-customization requirements in mind. However, it is important to consider that the development of *sustainable mass-customized products* includes a concurrent work for the correct *sustainability* and *mass-customization* requirements coupling. In other words, *sustainable mass-customized products* need to accomplish several design requirements that have to be coupled in order to satisfy customer’s needs, sustainability needs and mass-customization needs. Hence, a concurrent work is needed with the intention to cover all product design phases.

Furthermore, during the *DFSMC guidelines* development, the following remarks were noted: (a) A sustainable mass-customization product design process, dealing with several design requirements, might lead to certain negative correlations, therefore in order to solve these possible contradictions different tools and/or techniques for decision support may be applied in order to facilitate decision-making about the level of sustainability and mass-customization for example that a product has to reach, and (b) During the product design planning process it is crucial to clearly identified which parts over the whole *sustainable mass-customized product lifecycle* are going to be affected by the sustainability and/or mass-customization principles/parameters, since for some processes (e.g. manufacturing, packaging and testing to mention a few), the application of sustainability or mass-customization can increase costs and time-to-market. For example, when number of product parts affects the packaging process, the designer must decide if it is needed to use more material to achieve the desire packing process or to reduce product parts without using more material to package.

The *DFSMC process guideline* constitutes a practical, understandable and useful guideline for those companies who want to explore the implications and opportunities of implementing the *DFSMC guidelines* in their product design and development process towards sustainable mass-customized products.

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