A Preparatory Approach to Environmental Assessment for Sustainable Mass Customization

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Abstract Mass customization (MC) is a growing trend in industry that fulfils the demand of customers for personalized products and services. Parallel to customization, more regulations and demand for sustainable products and environmental business practices have increased importance on the agenda of businesses today. However, the knowledge about the implementation of sustainable mass customization (SMC) models is still mainly theoretical. The SMC Excel project presents an approach for the development of an SMC environmental assessment based on life cycle assessment (LCA) methodology for a TV. The environmental assessment method denominated SMC Excel Sustainability Approach (SESA) presented in this study aims to provide reliable information of the environmental impacts of a product (TV) while serving as an efficient and applicable assessment methodology for MC. General requirements for the SESA are described and applied to a case study of a TV. Furthermore, the result of a full-scale LCA of a standard TV model is compared with those impacts obtained by SESA, which indicated that the variance between both results is nominal and, thus, SESA can represent a valid approach for environmental assessment methodologies. Additionally, with the test case scenario of a take-back service where both methods are compared, the impact disparity is similarly low. Nevertheless, further research and testing are required in order to improve accuracy and methodological procedures of the SESA method.

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1 Introduction

Today's businesses are faced with a growing demand from customers for more personalized products and services. Many companies have already incorporated mass customization (MC) either as an extension or as the main foundation of their business model [1]. MC, however, brings many challenges for the traditional mass production processes as well as the logistics and communication channels [2, 3]. Additionally, with the increasing demand from policymakers and customers for more sustainable business practices and products, MC business models have to include efficient structures not only at the business process level but also at the sustainability performance level.

In present industrial practices, sustainability performance is measured through indicators or assessment methods that are selected according to different criteria such as the sustainability focus (e.g. environment, health) or business type (e.g. chemical products) [4]. The best-known environmental assessment methodology is life cycle assessment (LCA), which is defined in ISO 14040 as the "compilation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle" [5]. However, LCA application can present several barriers for businesses due to its high complexity, demand for high-quality data and considerable requirements in terms of monetary and human resources [4]. According to a survey from the Finnish Environment Institute in 2010, LCA is mostly being adopted in companies that have developed customized and streamlined methods based on LCA [4]. Also in the framework of sustainable mass customization (SMC) business models, developing a new, adaptive environmental assessment method is essential to ensure the integration of environmental parameters on business processes and decisions, especially when these business processes are contrasting to the business-as-usual models that we know. The following sections describe the analysis of requirements and guidelines based on the results obtained from the SMC Excel project in order to contribute to future developments of an effective environmental assessment method for SMC business models.

2 Background

2.1 Environmental Assessment Methods

Numerous methodologies/indexes deal with sustainability measurements, which are assessing product, manufacturing process and supplying chain from an environmental (e.g. LCA, material flows), social (e.g. sustainable livelihoods, ecological footprint) and economic aspects (e.g. cost/benefit analysis, modelling). Singh et al. [6] provided an overview of sustainability assessment methodologies, categorized as indicators/indices, product-related assessment and integrated assessment. Despite having many assessment tools being used, only a few provided an integral approach that took into consideration environmental, economic and social aspects. They also concluded that while it may be possible to combine several different methodologies to ensure that all aspects are taken into consideration, it is not as effective when considering sustainability in its entirety as it is easy to miss the interlinkages and dynamics within a system.

Similarly, Boer et al. [7] conducted an extensive review of sustainability assessment methods and concluded that most indicators used were unbalanced and too qualitative to be applied effectively, as well as not always including the social aspects related to sustainability. Taking these points into consideration, Boer et al. [7] developed a sustainability assessment model (SAM), specifically devoted to the implementation of SMC, which involved developing environmental, social and economic indicators that are able to evaluate sustainability considering the solution space as a whole, i.e. considering the manufacturing system and supply network and looking at a single unit of product in order to foster an immediate perception of the burden set to the environment, society and economy connected to the final act of buying. As part of the assessment model, environmental, economic and social indicator calculation formulas, based on the LCA methodology, were also developed to calculate the impact potential, providing a concrete way to assess impacts and to be transparent.

Collado-Ruiz et al. [8] argued that the LCA method has limited usefulness during the early design stage of a product and can in fact limit designers' creativity and innovation potential; additionally when LCA results can be available, it tends to be either too late or too expensive to make major product changes. The LCA is a complex process requiring detailed information about a product that is not always available at the early design stage and therefore relies on previous products to estimate data required for the assessment (hence limiting a designers' potential) [8]. They suggest instead to infer common environmental behaviour based on similar products (with common functions, parts or properties) – defining the relevant life cycle stages based on past information from previous products' environmental performance, which can be performed at the early design stage.

2.2 Mass Customization

MC is a contemporary production strategy aiming to satisfy all individual customers' needs at the price of typical mass production. This strategy allows to push industries to survive against the global competitive pressure, developing new methods and technologies, mostly oriented towards high personalized products [7]. The emergence of MC is also due to the current manufacturing era [9]. Nowadays the product demand is simultaneously very high and strongly differentiated, which results into a fluctuating behaviour coupled with a high unpredictability since a considerable number of product variants are required for satisfying the specific needs of each customer.

The term MC has been firstly defined in 1987 by Davies [10] as a strategy for the provision of personalized product and services simultaneously treating individual customers. This definition has been refined several times adding new concepts and interpretations. Later on, MC gained popularity also due to process and technological innovations. In 1993, Pine et al. [11] defined MC as an industrial perspective able to provide a tremendous variety and individual customization at reasonable prices. This wave of popularity promoted a considerable number of academic articles and industrial experiments, which allowed a continuous evolution and refinement of the concept. For instance, according to Chen et al. [12], MC can be described as a production paradigm that tries to combine the benefits of craft production of pre-industrial economies and mass production of the industrial economies, aiming to deliver products and services that best meet individual customers' needs with near mass production efficiency.

Piller has provided a comprehensive definition, underlining some key drives of MC, in 2004: "Mass Customization refers to customer co-design process of products and services, which meet the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes. As a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment" [13].

This new production strategy, in order to be applied, needs specific conditions. In fact, not all type of industries can implement such strategy, in which success is strongly dependent on processes and product characteristics [14]. Walczac identified that assembly processes with low-medium production volume with many variants are the most suitable ones (e.g. clothing, computer manufacturing, mobile telephone, etc.). Fogliatto et al. in 2012 [15] while providing a wider review about MC success factors and enablers also highlighted the main steps required for generating and processing MC orders: building product catalogues, configuring customer orders, transferring orders to manufacturing, and manufacturing customized orders. In this context, Boer et al. [7] in alignment with Piller [13] specified four items needed to apply MC strategy: (i) customer codesign process, which meets (ii) the need of each individual customer, within (iii) a stable solution space representing the potential product configurations, the production system and the supply chain, and (iv) an adequate price based on cost and the premium price that customers are willing to pay for customized products.

In conclusion, one essential element that differentiates MC from mass production is the customers' active involvement in the value creation process in the former. In fact, in MC, customers are no longer passive recipients of products or services that are designed and produced for a nominal customer. Instead, each customer has his or her individual identity and provides key inputs in designing, producing and delivering the product or service based on his or her individual preferences [16].

2.3 Mass Customization and Sustainability

Nowadays, the most recognized definition of sustainability concept is that provided in 1987 by the Brundtland report [17]: "to meet the needs of the present generation without compromising the ability of future generations to meet their own needs". In 1994, Elkington further formalized the sustainability concept through the triple bottom line [18] framework where what is sustainable stays at the intersection among all the three dimensions:(i) environment, which encompasses the protection and conservation of the ecosphere; (ii) society, which includes the respect of the needs of individuals considering their well-being; and (iii) economy, which focuses on the importance of stable economic growth using resources in order to allow the business to continue over a certain number of years.

After the emergence of MC, some questions arose regarding how MC products can be sustainable and if MC could foster a more sustainable way to produce. The relation between MC and sustainability has been discussed conceptually in the research field, especially focusing on economic and environmental performances [19]. In order to evaluate how MC affects sustainability in a firm, several studies have been conducted in recent years also exploring how sustainability frameworks can be developed to evaluate MC sustainability performances as well as which business models can be implemented for the integration of both strategies [20, 21].

Can a MC product be sustainable? This is the question that Ditlev et al. in 2013 [22] tried to answer. They analysed the implication of using MC in three phases (production, use and end of life) concluding that there is not a causal relationship between MC and sustainability but there is the opportunity to integrate several factors that can enhance sustainability performance while developing MC products. Pourabdollahian et al. [21] evaluated the environmental performance of MC business models taking information from the literature. Depending on the company and the industrial sector analysed, the authors also identified challenges and problems of the potential impacts of MC enablers (postponement, modularity, suppliers' integration, etc.) on sustainability. Hankammer and Kleer [23] assessed the sustainability potential of MC as a particular example of collaborative value creation for the specific case of degrowth business models. They outline that, especially the build-to-order idea, the potential upgradability and the stronger involvement of customers constitute enablers for fostering sustainability through MC.

In order to take into account all possible sustainability implications while producing MC products, a dedicated sustainability framework has been developed by Bettoni et al. [24]. In this study, the attention is particularly paid to the design phase of a product, where the decisions taken by the designers are influencing most of the sustainability impacts. The framework includes guidelines about how to carry out each step of the design considering the product but also the manufacturing system and the supply chain needed to produce and distribute it; the framework has been conceived in a way that both mass customization level and sustainability are enhanced at the same time [25]. In addition, the study focuses on the development of suitable sustainability indicators that can guide the co-design of the MC solution space. Continuing this topic, Boer et al. [7] developed a MC assessment model that is meant to evaluate the sustainability of a MC product through a wide set of indicators that are covering all the three sustainability areas along the entire solution space life cycle. This assessment model allows to calculate the values of the selected environmental, economic and social indicators for the MC solution space; thus, all the potential variants of the personalized product will be weighted according to the relative frequency of choice of each customizable option. The authors present a real case belonging to furniture industry where the assessment model has been applied. The MC sustainability framework has been revised and used to map all useful features and to show how to build a viable business model and the skeleton of the solution space [24]. Moreover, Pourabdollahian et al. [26] described different impact factors along the life cycle of MC products on sustainability compared to mass production. Finally, a couple of studies shed light on the co-creation phase of MC and possibilities to foster sustainable consumption through MC [20, 27, 28].

Considering the literature analysed, it is not possible to state if MC could lead to a more sustainable manufacturing approach since many authors agreed that it is highly depending on the type of product or service [7, 29, 30]. What it has been recognized is that, given the great amount of possible product variants, methodologies and tools are needed to enable a reliable but also fast and simple assessment of the sustainability impacts generated by mass-customizable products [24].

2.4 Requirements for Environmental Assessment Methods in the Context of Mass Customization

As already presented in Sect. 2.3, the environmental assessment of a MC product requires further effort compared to a mass-produced product since a MC product is indeed constituted by all its possible variants; thus, a great amount of possible combinations of elements has to be managed. In order to estimate the environmental impacts of each of these elements, LCA and LCC methodologies can be applied. This requires collecting a considerable amount of data such as cost, weight, material characteristics, production processes, transportation means, etc.

Indeed, two possible approaches can be applied for the sustainability evaluation of MC products, depending on the assessment scope. On the one hand, the model proposed by Boer et al. [7] is meant to calculate the sustainability indicators for the mass-customizable product, thus including all its possible variants. This approach is suitable when the scope of the LCA is to evaluate how much the entire solution space is sustainable. On the other hand, it is possible to perform an LCA on every single product configuration (i.e. the MC product), when only a small number of product configurations have to be compared to promote the selection of the most sustainable one [31]. For configurators with greater variation, however, performing an LCA for each possible product combination is far too time-consuming and resource intensive [32]. In order to facilitate a combinatorial evaluation process at the same time providing environmental impacts for each product combination, the environmental assessment method requires to adopt the same modular nature of MC and segregate the product into its separate elements. Hence, as each element is added to form a product, similarly the impacts can be summed as well. The LCA-based methods require also to consider the life cycle stages of the product and how these interact with individual elements. At some stages, the product has to be assessed in its single parts (e.g. production of a frame or recycling of a copper cable), whereas in other stages the whole product is characterized by a single impact (e.g. energy consumption during the use phase). Furthermore, the MC business may choose to offer services that can influence the life cycle impact, such as a take-back service that can ensure the reuse or a more efficient recycling of a given physical product. Services behave differently when it comes to their environmental impact assessment as they rather act on one or more life cycle phases than on product parts. The environmental assessment approach selected for MC would need to consider these type of products or services as well.

According to Feitzinger and Lee, one of the benefits that brings modular product design to MC is the maximisation of standard components which also reduces the total number of components [33]. Similarly, such benefit can be applied to the assessment approach. By selecting and categorizing data on components that are standardized by either their application for different products or processes, the environmental assessment method can be applied more efficiently for MC than for businesses with higher end product variety.

3 SMC Excel Sustainability Approach (SESA) for the Environmental Assessment of Sustainable Mass Customization

We apply SESA in this work to the specific case of TV sets; for in this kind of products, the needs of each individual customer are satisfied through modularity; in fact, aesthetics, fit and comfort and functional features are addressed through the use of different modules that can be put together in order to satisfy the customer wishes. The TV modular system thus requires a flexible and combinatorial method, the SESA, that allows to assess the impact of independent components using a matrix structure and then calculate global impacts for each solution that can be generated by the customer during the codesign phase, using, for instance, a configurator. The cited matrix structure is known as the stable solution space [7] of the company and includes the description of all the possible components that constitute the mass-customizable product, defining also the required production processes and the supply chain-related data.

In order to allow the sustainability evaluation of the TV in a quantitative way, along its whole life cycle and to make available a fast but reliable assessment to the customer so that the environmental impact is introduced as an evaluation parameter, the SESA has been developed considering the following characteristics.

Life Cycle Oriented, Based on LCA Methodology The environmental impacts are evaluated along the whole life cycle of the components/product, starting from the production of raw materials, passing through manufacturing, use and maintenance phase and concluding with the end-of-life (EoL) phase. This approach is meant to avoid problem shifting and assure that environmental problems are not moved from one phase to another one or from an environmental compartment to another one. In order to address this requirement, life cycle assessment (LCA) method has been applied since it is considered as one of the most thorough and accurate methods among the environmental scientific community.

Screening LCA Approach The high complexity of the TV product combined with the fact that the solution space can produce several combinations of TV variants would make a full-scale LCA merely impossible within the SMC Excel project timeframe. It is thus important to clarify that the assessment proposed by the SESA is based on the LCA methodology but does not represent a full-scale LCA in the traditional sense. A full-scale LCA requires a considerable amount of time, data and resources, especially considering the aim of the SESA that is to compare product variants. The SESA thus has been based on screening LCA approach, allowing a preliminary evaluation of the product performances in order to understand the system hotspots but at the same time enabling the comparison between different product configurations. In screening LCA simplification and assumptions are made when specific life cycle inventory (LCI) data are not available; moreover, the life cycle impact assessment (LCIA) is estimated also relying upon generic data available in databases and the literature. The exploitation of screening LCA approach is also justified by the fact that the use phase of TVs is recognized as the most energy-intensive and environmental-impacting lifecycle phase, followed closely by the material production phase [34, 35]. Thus, in SESA a special attention is devoted to energy consumption data and material information, while the production/assembly and the transportation phase are those where most of the simplifications have been introduced.

Delta Evaluation Approach Since the scope of SESA is the comparison between similar products (they all belong to the same solution space), and considering the screening LCA perspective, a delta evaluation approach has been introduced in order to further ease the evaluation of the single product configuration. The idea behind this approach is showing only the impact variations. Therefore, it is not necessary to perform a complete LCA of the product but only focus on the analysis of the elements and features that both enable the TV personalization and generate environmental impacts (for instance, a software component is adding functionalities but is not introducing additional impacts if it does not require extra energy). The delta approach is a core concept of SESA and is described in detail in Sect. 3.1.

GWP Oriented but Extendible to Other Sustainability Areas LCA is commonly addressing the environmental area of sustainability covering different environmental compartments (air, soil, water, human being, etc.) and environmental problems such as global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), human toxicity potential (HTP), Ozone Depletion (OD) or Ecotoxicity Potential (ETP). In order to simplify the communication to the customer of environmental performances of the product variants, the assessment is restricted to the calculation of the GWP index, expressed in the unit kg CO_2 equivalent. This indicator is nowadays well recognized, and it has become of common use in environmental communication. Currently, only the environmental aspects of sustainability have been considered in SESA, but the approach, thanks to its structure presented in Sect. 3.1, can be expanded to also address the economic area, through LCC or the social one through S-LCA.

3.1 Scope and Methodology of the SMC Excel Sustainability Approach (SESA)

The main objective of the proposed assessment framework is to enable the customer to compare in terms of environmental impacts the configured product with a benchmark one that has been identified as a reference. This will be performed through a calculation engine directly connected to the configurator, so that the user can determine the impact of its choices, and to a LCIA database that contains the environmental impact information regarding the TV set components and features. During the configuration process, the configurator provides customers with the sustainability information in terms of the GWP characterization factor, which is expressed in kg CO_2 equivalent. As briefly stated in the previous section, this methodology is mainly based on the delta evaluation approach. A detailed description of the steps characterizing this approach is presented hereinafter.

Benchmark selection A baseline "standard" TV is chosen as a benchmark. The standard model has been chosen by the TV manufacturer VESTEL to serve as a reference point for a typical TV. The standard configuration features are reported in Table 1, where different aesthetics and functional characteristics are depicted. The reference use scenario has been defined as 6 years of lifetime, with a use time of 4 hours per day. A year is assumed to have all 365 use days without holidays. Concerning the transportation scenario, only the one bringing the assembled product from Manisa, Turkey (VESTEL production site), to München, Germany (customer), has been considered. All other transportation routes in the life cycle are neglected as specific data was not available.

Prioritization of the LCA analysis In order to select components to be included for the analysis using SESA, a structure that is meant to prioritize the interventions has been defined and depicted in Table 2.

Three different steps have been identified. In Phase I, the impact related to the components and features that are variable within the solution space and that are LCA relevant (in the sense they cause environmental burdens) is calculated individually.

Table 1 Standard configuration overview

Standard Configuration			
Screen size	49 inches	Smart TV	No
Resolution	UHD (3840 × 2160 px)	PVR-ready function	Yes
Energy label	A+	Wireless display	No
Colour of material	Black	Warranty	Standard warranty (2 years)
Frame	Plastic	Take-back service	No
Stand	Plastic	Production offsetting	No
Remote control	Yes	Packaging	Standard packaging
Satellite receiver	Yes	Delivery	Standard delivery
Lighting unit	No		
Charging unit	No		
Sound unit	No		

Table 2 Overview of components categorized in the scope of environmental assessment

Phase I	Phase II (Baseline)	Excluded from env. assessment
Variable LCA solution space: components that are variable and LCA relevant (e.g. frame material)	*Invariable LCA solution space:* components that are LCA relevant but not variable (e.g. motherboard, PCBs, etc.)	*Non-LCA solution space:* components that are variable but not LCA relevant (e.g. software that does not influence or, to a negligible way, the overall kg CO_2 eq. value
Screen size (energy) Screen resolution (energy) Energy label (energy) Frame (material) Stand (material) Remote control (material) Lighting unit (material) Wireless charging unit (material) Bluetooth speaker (material) PVR ready (energy) Warranty (material) Take-back service (material) Offsetting production (material) Packaging (material) Delivery (material)	Printed circuit boards Capacitors, resistors, etc. Electronic connectors Bolts and screws Cables Display module Backlight (LED)	Satellite receiver Smart TV Wireless display

Some of the features are provided by physical components, such as the TV frame or the support system; others are more intangible elements such as the energy class of the TV or the screen resolution. The ensemble of these components is called variable LCA solution space. In Phase II, the impacts related to the other elements belonging to the solution space that are LCA relevant but that do not change when passing from a configuration to another one are assessed. These components are thus the ones which constitute the baseline and are represented by a single value for each life cycle phase (e.g. baseline value for transport: 6.13 kg CO2 eq.). The baseline value is the average GWP impact obtained from three LCA studies on LED TVs [34, 36–38]. Some elements that have negligible LCA impact are excluded from the SESA approach but remain included in the configurator because they can influence the level of MC as well as customer satisfaction.

LCI of the Variable LCA Solution Space For each element included in the variable LCA solution space, the related LCI data has been collected in order to estimate the environmental indicators. For physical components, LCI information includes the material type and their quantity, the production processes and the EoL treatments undergone; for intangible elements, inventory data are, for instance, represented by the energy consumption of the TV function/characteristic. LCI data has been based on the ecoinvent database and literature, while product-specific data has been provided by VESTEL.

LCIA of the Single Components Starting from the LCI data collected in the previous phase, and exploiting LCIA database such as ecoinvent and PlasticsEurope, the calculation of the GWP indicator has been performed for each feature included in the SESA solution space. The GWP indicator, expressed in terms of kg CO2 equivalent, has been evaluated considering the CML2001 methodology.

For physical elements, the computation has been performed along the whole life-cycle of the item, thus considering all the related processes, from material extraction to end of life, passing through manufacturing, assembly and transportation. The calculation of the contributions to GWP indicator has been performed through the following formula:

$$\mathrm{Id}_{\mathrm{o,c}} \times \mathrm{CF}_{\mathrm{o}} = \mathrm{GWP}_{\mathrm{o,c}}$$

where:

- $\mathrm{Id}_{\mathrm{o,c}}$ is the inventory data of the o-th operation performed on the c-th component included in the variable LCA solution space
- CF_{o} is the characterization factor the o-th operation retrieved from the LCIA database cited
- $\mathrm{GWP}_{\mathrm{o,c}}$ is the contribution to the GWP indicator related to the o-th operation performed on the c-th component

For instance, the material extraction coefficient for the cardboard used for packaging is CFo = 0.65 kg CO2 eq./kg (where o is thus the extraction operation of cardboard), while the Ido,c of the packaging provided by VESTEL for the standard packaging for a 49” TV weights 1.19 kg, so the GWP related to the cardboard extraction is about 0.78 kg CO2 eq. The impact of most of the non-physical elements is calculated applying a similar formula, even if they are characterized in a different way specifying the consumed electrical energy expressed in kWh (Ide), and by the characterization factors for each electricity mix considered (CFe). The GWPo,c computed is stored in a repository that will be exploited by the configurator engine for the calculation of the total delta GWP.

Product variant delta GWP calculation Once the single elements have been characterized by the LCI, an assessment model has been developed in the configurator so that the impact in terms of GWP of each element is calculated. At the end of this process, the sustainability engine sums up all the variations so that a global delta GWP is estimated.

3.2 Data Collection and Assumptions

This section is meant to briefly present the data gathering activities that have been performed in order to complete the LCI and LCIA phases for the variable LCA solution space so that the related impact could be calculated through the formula mentioned above. Moreover, the paragraph also introduces the assumption applied to model the components and TV set life cycle. In the following, different subsections are reporting the information collected regarding raw materials (extraction and processing), manufacturing processes, delivery, use phase and end-of-life scenarios.

Material Extraction, Production and Processing LCI and LCIA Data

Two elements are needed for the computation of the GWP indicator: the inventory data, thus the type of the material constituting the element and its weight, and the related characterization factors. Table 3 reports an excerpt of the main components included in the variable LCA solution space with the inventory data cited.

As already stated, the variable LCA solution space contains both physical and non-physical elements that are relevant for LCA. Software elements that are not generating impacts have been thus excluded from this list.

Table 4 shows an excerpt of the LCIA data retrieved from available database (indicated in the table) and concerning the impact generated by the extraction of materials for the different elements constituting the variable LCA solution space. Table 4 moreover indicates if the considered dataset already includes transportations and the impact data of the electricity mix considered for the use phase. The same LCI collection process and electricity mix were applied to the manufacture and assembly processes.

Use Phase and Energy

The energy consumption is mainly influenced by screen size (49″ or 55″), energy label (A or A+) [39, 40] and resolution (full HD or UHD) [41]. The combination of these six variables gives eight possible combinations as shown in Table 5. The same table includes the power consumption and the energy consumed into the use scenario already cited (6 years, 365 days per year, with an assumed use of 4 hours per day) [42]. Moreover, the energy consumed has been translated into equivalent CO_2 emissions according to the electricity mix defined for the use phase as shown in Table 6.

Table 3 Excerpt of the variable LCA solution space

Variable	Variable	Solution space final		Weight
				kg
	Screen_0	Combination 0	49″, UHD, A+	9.7
	Screen_1	Combination 1	49″, Full HD, A+	9.7
	Screen_2	Combination 2	49″, Full HD, A	9.7
	Screen_3	Combination 3	49″, UHD, A	9.7
	Screen_4	Combination 4	55″, UHD, A+	11.7
	Screen_5	Combination 5	55″, UHD, A	11.7
	Screen_6	Combination 6	55″, Full HD, A+	11.7
	Screen_7	Combination 7	55″, Full HD, A	11.7
Material_49	Material_49_1	Casing (49″)	Plastic 30% recycled material	1.57
	Material_49_2		Bioplastic	1.13
	Material_49_3		Aluminium	2.17
Material_55	Material_55_1	Casing (55″)	Plastic 30% recycled material	1.74
	Material_55_2		Bioplastic	1.2
	Material_55_3		Aluminium	2.412
	Stand_1	Wall mount and stand options	Plastic stand	0.19
	Stand_2		Table top metal stand	1.5
	Stand_3		Wall-hanging apparatus	0.116
	Stand_4		Vdrop stand	3.25
Remote	Remote_yes	Remote control	Remote control	0.089
	Remote_no		Smart APP Remote Control	_

(continued)

Table 3 (continued)

Variable	Variable	Solution space final		Weight
Satellite	Satellite_yes	Satellite receiver	Yes	_
	Satellite_no		No	_
Lighting	Lighting_no	Lighting unit	No	_
	Lighting_yes		Yes	0.12
Charging	Charging_no	Wireless charging unit	No	_
	Charging_yes		Yes	0.35
Sound	Sound_no	Bluetooth sound speaker	No	_
	Sound_yes		Yes	0.45
Warranty	Warranty_1	Warranty	Standard warranty	_
	Warranty_2		Extended warranty	_
	Warranty_3		Premium warranty	_
Takeback	Takeback_no	Take-back service	No	_
	Takeback_yes		Yes	_
Offsetting	Offsetting_no	Offsetting	No	_
	Offsetting_yes		Yes	_
Packaging_49	Packaging_49_1	Packaging (49″)	Standard packaging	1.985
	Packaging_49_2		Packaging ECO	2.385
Packaging_55	Packaging_55_1	Packaging (55″)	Standard packaging	2.77
	Packaging_55_2		Packaging ECO	3.2
Delivery	Delivery_1	Delivery	Standard delivery	_
	Delivery_2		Express delivery	_
	Delivery_3		CO2 neutral delivery	_

Table 4 Excerpt of the LCIA data regarding material extraction

Material/component	Ref. unit	Dataset	Coefficient (eq. kg CO_2)	Includes transport?	Database
Aluminium	kg	Market for aluminium, primary, ingot, IAI area, EU27 and EFTA	9.3864	Yes	Ecoinvent
General-purpose polystyrene (GPPS)	kg	PlasticsEurope Eco-profile GPPS_HIPS 2013–04	2.2500	No	PlasticsEurope
Cardboard	kg	Corrugated board base paper, kraftliner, at plant	0.65838	Yes	Ecoinvent
EPS	kg	PlasticsEurope Eco-profile EPS 2015–02	2.37	No	PlasticsEurope
Case (PC/polycarbonate)	kg	Market for polycarbonate	7.8648	Yes	Ecoinvent
Rubber keypad (TPE, thermoplastic elastomer, e.g. Styroflex)	kg	Market for latex	2.7073	Yes	Ecoinvent
Speaker box (two units): PC (60%) + ABS (40%); Magnet (two units)	kg	60% PC + 40% ABS	6.529	Yes	PlasticsEurope + ecoinvent
PLA	kg	Market for polylactide, granulate	3.2561	No	Ecoinvent
ABS	kg	Market for acrylonitrile-butadiene-styrene copolymer	4.5253	Yes	Ecoinvent
Low-density PE (EPE)	kg	PlasticsEurope Eco-profile PE 2014–04	1.87	No	PlasticsEurope
PA 6	kg	Market for nylon 6, GLO	9.356	Yes	Ecoinvent
Frame	kg	Market for aluminium, primary, ingot, IAI area, EU27 and EFTA	9.3864	Yes	Ecoinvent

Table 5 Power consumption and GWP calculation of the possible TV combinations

	Power	Use for 1 year (365 days), 4 h per day	Use for 6 years (365 days), 4 h per day	Coefficient: electricity, low voltage, production, UCTE	Total (use for 6 years)
	(W)	(kWh)	(kWh)	(kg CO_2 eq.)	(kg CO_2 eq.)
49″, UHD, A+	78.87	115.15	690.89	0.51	349.34
49″, full HD, A+	60.67	88.58	531.45	0.51	268.72
49″, full HD, A	81.98	119.70	718.18	0.51	363.14
49″, UHD, A	106.58	155.61	933.63	0.51	472.08
55″, UHD, A+	97.51	142.37	854.23	0.51	431.93
55″, UHD, A	132.82	193.92	1163.52	0.51	588.32
55″, full HD, A+	75.01	109.52	657.10	0.51	332.26
55″, full HD, A	102.17	149.17	895.02	0.51	452.56

Table 6 Electricity mix for use phase

Material/component	Ref. unit	Dataset	Coefficient (eq. kg CO_2)	Includes transport?	Database
Electricity mix	kWh	Electricity, low voltage, production, UCTE	0.5056	No	Ecoinvent

End-of-Life (EoL) and Take-Back Service Scenario

Concerning the end-of-life scenario, in line with recent statistics at the European level, it is assumed that about 45% of the product returns into the recycling stream [43–45]. With dedicated take-back service, it is expected that up to75% percent of the product would be recycled. Table 7 presents an excerpt of the LCIA data considered to calculate the impacts generated by the different EoL scenarios.

In order to calculate the EoL coefficients, according to the end-of-life recycling approach suggested by the Declaration by the Metals Industry on Recycling Principles [46], the impacts of the recycling processes and the GWP credits gained thanks to recycling (since it avoids the extraction of raw material) are summed in proportion of the envisaged recycling rate.

The following comparative validation process will show the correlation between the SESA results with the results of a full-scale LCA based on the standard model configuration of the TV. Additionally, the take-back scenario is presented for both cases in order to analyse the difference on the overall system environmental impact with and without this service.

Table 7 Excerpt of the LCIA data for EoL scenarios

Material/component	Dataset (ecoinvent and PlasticsEurope)	Coefficients	Scenario 75% (eq. kg CO_2)	Scenario 45% (eq. kg CO_2)
Aluminium	Market for aluminium, primary, ingot, IAI area, EU27 and EFTA	9.39	−6.48	−3.87
	Treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter, RER	0.73		
	Market for waste aluminium	0.04		
Cardboard	Market for carton board box production, with gravure printing	0.66	−0.47	−0.26
	Market for waste plaster-cardboard sandwich	0.01		
	Treatment of waste packaging paper, municipal incineration	0.06		
Polycarbonate	PlasticsEurope Eco-profile EPS 2015–02	7.86	−5.44	−2.98
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Polystyrene (HIPS)	PlasticsEurope Eco-profile GPPS_HIPS 2013–03	2.43	−1.36	−0.54
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Polystyrene (GPPS)	PlasticsEurope Eco-profile GPPS_HIPS 2013–03	2.25	−1.23	−0.46
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Plastic (PC (60%) + ABS (40%))	PC (60%) + ABS (40%)	6.53	−4.43	−2.38
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
EPS	PlasticsEurope Eco-profile EPS 2015–02	2.37	−1.32	−0.51
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
PLA	Market for polylactide, granulate	3.26	−1.98	−0.91
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Rubber keypad	Market for latex	2.71	−1.57	−0.66
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Plastic (PC 30% + ABS 20% + PE 50%)	PC 30% + ABS 20% + PE 50%	4.16	−2.66	−1.32
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		

4 Comparative Validation of SESA with a Full-Scale LCA

Within the framework of the SMC Excel project, a full-scale LCA was performed focusing on the standard configuration of the TV presented in Sect. 3.1. The full-scale LCA study includes practically all the components and specifications that were applied for the SESA environmental assessment approach. As can be seen in (Fig. 1), the impacts per life cycle phase only differ minimally in both studies. Major discrepancies appear for the production stage which in the full-scale LCA is encompassing both extraction and production stages, while the SESA approach applied an independent environmental assessment for both phases, resulting in a higher value of GWP indicator. Looking at the graph and considering all life cycle phases, it can be noticed that the overall impact in kg CO_2 equivalent is not much different; with SESA the total GWP impact of the TV is 616.23 kg CO_2 eq., while the full-scale LCA displays a slightly lower impact of 572.39 kg CO_2 eq.

The impact of the take-back scenario presents a minor difference for both environmental assessment methods, acting in a proportional relation to the impact of the disposal phase. Nevertheless, in this study only a change in the recovery of materials is considered so that further effects on, for example, secondary impacts on recycling processes or disassembly are disregarded. We conclude that both methods present similar results, which indicate that the SESA approach performs with considerable accuracy and may be applicable for MC.

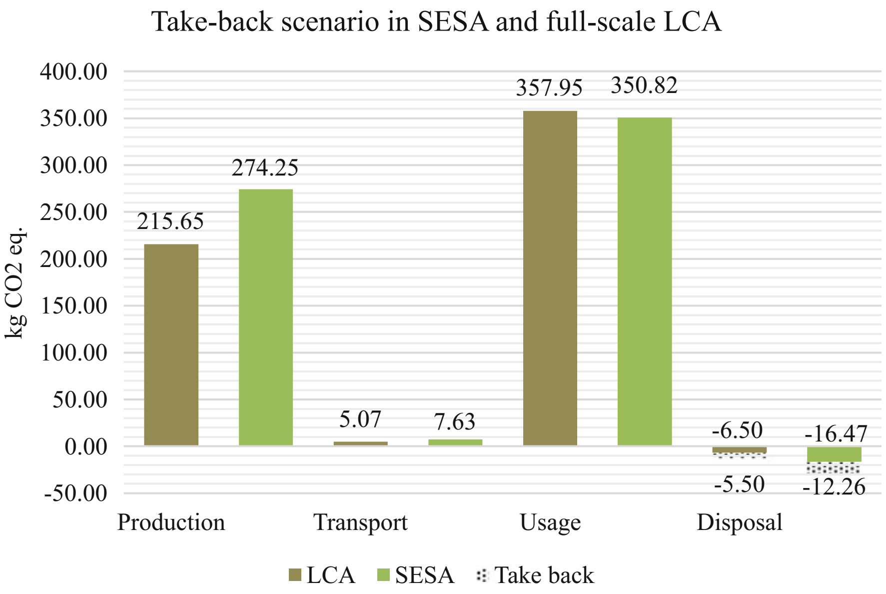

Fig. 1 Comparison between the SESA approach and the full-scale LCA on the standard configuration

5 Know-How and Communication

The proper communication through the configurator about the sustainability impact of the products or services offered is imperative for influencing customer behaviour. Customers need to be informed on the content and implications as well as the benefit of selecting a sustainable feature. Considering that information on environmental impacts is often difficult to associate with daily life experiences, it could be represented through a value-based approach. An example would be by comparing the impact with an amount of km driven by a car (gasoline value) as also applied by the Restart Project for their Fixometer [47]. Creating a value link between the effect of km driven and of TVs provides the user with an idea on the proportionalities of environmental impacts. Hendriks et al. also formulate such an approach in cost terms as proposed in their model of eco-cost/value ratio (EVR) [48]. Furthermore, through a survey performed during the SMC Excel project, it was found that providing a sustainable configuration as a starting point fosters more users to keep the sustainable features that are already preset by the system. Thus, the customers buying preferences can be as well influenced or "nudged" towards a more sustainable consumption on a more unconscious level.

One of the main traits of MC is the co-creation process [13]. This is basically the pivot at which business and customer interact and influence each other's practices, may it be in respect to production and design or consumers' lifestyle choices. But consumer and business are not isolated in this synergy as also other industries, and in a greater sense, the market of the MCs' sector can be influenced. The selection of materials has a repercussion on processes as well as suppliers and, therefore, also on the material extraction industry. Services may even influence post-production life cycle phases of the product, including the related industries to TVs during use phase (e.g. energy provider) and disposal processes (e.g. recycling of EEE). For these reasons, the co-creation process in SMC business models becomes a shared responsibility between the business and consumer for the inclusion of sustainable products in the market. The customer becomes less a subject but rather an actor in MC. Consequently, the customer may also be accountable for the success or failure of the sustainable development in that market, provided that the customer is also receiving in a suitable form the right information on the sustainable performance of the product [49]. As stated by the World Business Council for Sustainable Development (WBCSD) report, consumers are becoming more aware and increasingly concerned about environmental, social and economic issues and more willing to act on these concerns [50]. Hence, it is even more important that information on sustainable features is provided with reliable data and clear communication. Since customers become more aware, they also become more sceptical if information is not accurate, or conversely, they might receive the wrong information and think that it is sound science which leads to an erroneous state of awareness. The latter occurs in situations where companies massively underline only the product characteristics that improve sustainability, whether or not these improvements are significant looking at the overall product assessment, in order to advertise the product as truly sustainable; this phenomenon is also known as "greenwashing" [51]. The high problematic resulting from greenwashing is that it creates mistrust among consumers towards businesses and, consequently, reduces the effect of a productive co-creation mechanism that could lead to a sustainable development with the involvement of all stakeholders.

6 Conclusion

6.1 Key Findings and Major Contributions

This work proposes the adoption of SESA, an approximated sustainable approach based on delta LCA evaluation, developed for providing realistic information about product environmental sustainability to consumers involved into the codesign process of MC products. The approach allows focusing on the most significant impacts of the product and its life cycle phases as well as obtaining environmental data on all variable components and product combinations. The reliability of the provided sustainability information is evaluated confronting the results of SESA with those of a full LCA while evaluating an MC TV solution space. The analysis proved that SESA allows to obtain reliable results of environmental impacts and may be applicable for MC business models with a sustainable business approach.

SESA has been developed and kept simple in order to be continuously updated at reasonable costs while evaluating solution spaces that tend to become increasingly complex and to rapidly change, due to the continuous developments of new features and variants especially in sectors like the consumer electronics where the pace of innovation is quite high.

6.2 Limitations and Further Research

The approach has been partially validated considering a single use case and a unique sustainability indicator. Additional work is required for investigating the reliability of SESA in comparison with more expensive and complex full LCA on a broader sample of use cases and considering a greater variety of indicators. The effect of providing data about various indexes on consumer attitude towards sustainability must be further analysed in order to avoid customer confusion and effectively promote the adoption of sustainable consumption. The analysis of intangible product components and services also needs to be improved in order to identify how they can promote the adoption of circular economy business models [52]. Moreover, in order to decrease the risk of underestimating the impact of services, such as the product take-back analysed in the TV case, their LCA-based estimation has to be done taking a broader perspective and not just focusing on recovery of materials.

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