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3-S BOM: Pioneering Sustainability-Scoring-System for Multi-Functional Product Configurations Based on ESG and Circularity

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Abstract

The Bill of Materials (BOM) is the primary place where product configurations are formulated and designed. Despite its critical role, the BOM falls short in addressing sustainability concerns. The current state of the art does not capture data on the sustainability performance of suppliers of listed components. Furthermore, the BOM neglects synthetic information on reusability and circularity of components. To overcome these limitations, this study proposes the introduction of a Sustainability-Scoring-System (3-S BOM). The aim is to upscale the traditional BOM to the new sustainability market demand. The 3-S BOM has two purposes: to integrate synthetic data on sustainability and to allow further configurations of products based on diversified sustainability profiles. Specifically, each component, sub-assembly and assembly within the BOM is assigned an Overall Sustainability Score (OSS), which covers three key sustainability areas On the supplier side, an ESG score will be representative of the supplier's level of sustainability, while on the component side, a Hazardous Substances and Virgin Materials (HV) indicator and a Hazardous Substances and Virgin Materials Circularity (HVci) indicator will assess the sustainability of the components, taking into account their composition and circularity. The customer is actively involved in defining the sustainability profile of the purchased product by defining how the ESG, HV and HVci must influence the final assembly of the purchased product, choosing between different levels of specificity.

Keywords: sustainability, Bill of Materials, ESG, circularity

1. Introduction

Sustainable development, defined as the pursuit of meeting present needs while safeguarding the ability of future generations to meet their own (WCDE, 1987), encompasses three vital dimensions: the environment, economy, and society (Elkington, 2004). While the economic and environmental aspects can be quantitatively measured, social measurements must go beyond the conventional biophysical measures, requiring a semiquantitative and qualitative approach (Fricker, 1998). As concerns of sustainability increased over the past decades, businesses, governments, and academia have become steadily more interested in developing methods to measure sustainability, considering its three-dimensional nature (Ameta et al., 2010). Specifically, in evaluating the sustainability of companies, the rise of environmental, social, and social (ESG) challenges has captured the attention of various stakeholders (Atkins, 2020) since its introduction in a United Nations study in 2006 (UN PRI, 2006). Recognizing the significance of ESG factors, in 2018 the European Commission revealed a comprehensive action plan, encompassing the integration of ESG factors into financial guidance, research, and market analysis (EU, 2018). Additionally, on a global scale, the market is witnessing a shift driven by well-informed and discerning customers who demand sustainability (Koren, 2010). It is recognized that evaluating a company's sustainability practices has become an increasingly prominent matter (Shao & Ünal, 2019; Di Bella, et al., 2023)., attracting attention and scrutiny, making it imperative for businesses not only to align with new sustainability regulations but also to meet the evolving expectations of the market (Atkins, 2020). The evaluation of a company's sustainability performance currently relies on the widely accepted framework of environmental, social, and governance (ESG) criteria, and governments recommend that publicly traded firms disclose material ESG (Savastano et al., 2022). Although the framework of ESG is widely accepted, when considering separately it the three pillars and the accepted measures, there is no commonly agreed-upon stance (Lee & Tang, 2018). Indeed, of the three ESG, the "E" and "G" pillars have widely accepted measures, as quantitatively defined, whereas the "S" pillar does not, given its ambiguity in terms of definition and measurement (Dai & Tang, 2022). Notably, ESG impacts, which play a crucial role in product development and green innovation (Long, 2023; Li, 2023), are particularly significant in the case of consumer electronic products, given the complex supply chain and the entire life cycle of these products (Babbitt et al., 2020; Kaur et al., 2020). ESG impacts and benefits are indeed associated with their manufacturing, use, and disposal (Trappey, 1996). In this context, a crucial role is played by the Bill of Materials (BOM), which is considered the central hub of a general product data management system, as it provides essential data for running a manufacturing process (Favi et al., 2018). Despite of the fact that the BOM is where component configuration processes into assemblies and final products take place (Olsen, 1997), the sustainability performance of the suppliers responsible for manufacturing the components, using the ESG framework, is not extensively and comprehensively reported (Baud-Lavigne, 2014; Liotta, 2015). This limitation results in subsequent configurations that cannot be established based on specific sustainability criteria, leading to a misalliance of the offer towards the demand, therefore, a lost opportunity to increase the perceived value of the final product. By the way, it becomes critically important to define an evaluation model not focused solely on the supplier's ability to work to certain standards, but able to assess whether the individual product is made according to a best practices framework and matches requirements in terms of ESG. Indeed, assuming that an effective supply chain management plays a crucial role in the success and profitability of manufacturing companies in almost every industry (Fan & Stevenson, 2018) and recognizing the importance of sustainability at every level, from suppliers to end consumers, it becomes imperative to expand the scope of sustainability analysis beyond individual products. A comprehensive evaluation that encompasses also the supply chain associated with those components (Wilson, 2013) by considering the environmental, social and governance (ESG) factors of the suppliers, is considered to be crucial in the definition of the sustainability of the parts within the BOM, which serves as a central repository of data for product manufacturing (Trappey et al., 1996). According to the purposes of this study, the existing methods and frameworks used to assess the sustainability along the supply chain and the extent to which this information is registered in the BOM have been analyzed. The conducted analysis reveals that several studies propose methods and models to address sustainability along the supply chain (Ali, 2022; Calzolari et al., 2022; Confessore et al., 2013) by considering sustainability parameters with the aim is of optimizing the production and the distribution in a global supply chain (Stecca et al., 2013). However, the limit expressed by these studies is the incorporation of the integrated sustainability dimensions (Baid & Jayaraman, 2022), which include not only economic and environmental aspects of sustainability, but also social ones (Sullivan et al., 2021). Furthermore, none of the analyzed studies propose methods to systematically integrate ESG factors associated with each component within the BOM. Concluding, several methods exist to evaluate the sustainability within BOM, but most of them focus on the integration of environmental parameters of sustainability (Liotta, 2016), using an LCA approach (De Benedetto & Klemeš, 2010) and are characterized by a high degree of specificity (Mahmood, 2017; Ouhimmou, 2021; Sadiq, 2021). Several models have also been developed in order to track sustainability within the supply chain underlying products, but are mostly focused on the integration of environmental and economic aspects of sustainability (Oltra et al., 2019). None of the analyzed studies proposes an integrated method, based on the introduction of ESG factors within the BOM in a standardized and straightforward manner. To overcome this limitation, this paper proposes a new method called Sustainability Scoring System for Bill of Materials (3-S BOM), which combining the economic and managerial aspects of sustainability with the BOM concept (Kurniadi & Ryu, 2021). The proposed method integrates ESG factors systematically into the BOM to evaluate the sustainability of the main suppliers. Additionally, two indicators, HV and HVci, are used to assess the sustainability of the components in terms of composition and circularity (Pereira & Fredriksson, 2015). In the configuration process, the customer has the option to define how the three sustainability dimensions of the 3-S BOM should influence the final assembly's configuration. The objective of this study is therefore to outline a shift from the classic BOM towards the 3-S BOM, which incorporates sustainability data at all levels of product structure, from basic components up to final assemblies in form of scores, allowing further customer-defined configurations based on the new availability of data. The reminder of the paper is organized as follows. The section 2 presents a theoretical background where the environmental sustainability concepts and ESG applications within the Bill of Materials (BOM) are explored. In Section 3 the Sustainability-Scoring-System for Bill of Materials (3-S BOM) is presented and validated through a case study, based on a BOM of a cooling system, which serves as a practical application of the proposed approach and provides insights into its theoretical and practical implications for enhancing sustainability within the BOM. In the concluding section (Section 4), the key findings of the study are summarized, and their implications are discussed.

2. Theoretical Background

2.1. Bill of Materials (BOM)

The Bill of Materials (BOM) refers to a document that outlines the fundamental materials, components, parts, and their respective quantities required for the production or provision of a specific product or service. (Confessore et al., 2013). BOM can be defined as the set of raw materials and components that characterize a product, through which the relevant quantities are defined (Liu et al, 2013). The structure of the product is represented hierarchically where components and their configuration into assemblies are listed at different levels (Marques et al, 2017). All the individual parts or assemblies that comprise a superordinate assembly are represented at a higher level than the parent assembly (Eigner & Stelzer, 2009).

Equation 1: Composition of an assembly

$$\boldsymbol{A} = \sum_{i=1}^{n} \boldsymbol{SA_i} + \sum_{i=1}^{m} \boldsymbol{K_i} \tag{1}$$

In which:

A: assembly

SA: subassembly

K: component

The number of BOM list items$\boldsymbol{A}$in a BOM is the sum of all sub-assemblies$\boldsymbol{SA}$and all components $\boldsymbol{K}$, as shown in equation 1.

To this study's purposes two main types of BOMs were distinguished, namely the Engineering Bill of Materials (EBOM) and the Manufacturing Bill of Materials (MBOM) (Babbit et al., 2020). The EBOM provides a design-focused description of the product and includes all potential configurations of components and sub-assemblies, including variants (Leidich et al., 2021). On the other hand, the MBOM pertains to the physical arrangement of components within the product and is based on the selected components and sub-assemblies of the EBOM (Leidich et al., 2021). Since the MBOM, concerns the technical design of the chosen configuration of the product within the EBOM, it does not include variants. With an increasing need to adjust the BOM to meet actual sustainability requirements and objectives, the transparency of the sustainability of manufacturing processes has become a crucial issue (Osorio et al., 2013). Such transparency could prove useful in configuring and developing products in accordance with various sustainability criteria. According to this need, it is essential to recognize that sustainability, similar to quality, is subjective and can vary across sectors, categories, and regions, the intrbomretation can differ therefore among individuals (Mani et al., 2014). In the context of measuring the sustainability performance in manufacturing processes, it can be considered as a means to represent a specific aspect of quality.

2.2 Sustainability in the BOM

After having examined the existing literature on sustainability within the Bill of Materials (BOM), employing targeted keywords such as "Bill of Materials" and "Sustainability," we have detected that most of the analyzed studies are focused on the integration of the environmental aspect of sustainability in the BOM, proposing new ecodesign methodologies based on a Life Cycle Assessment (LCA) approach (Samant & Prakash, 2021; Milaj et al., 2017). Assuming the need of environmental awareness into product and process development, one study (Devanathan et al., 2010), proposes a systematic approach for reconfiguration planning in Reconfigurable Manufacturing Systems (RMS). The approach involved incorporating sustainability considerations using a Green-BOM, which improves the traditional BOM by considering additional sustainability factors such as energy use, toxicity, recycled materials, VOC density, and reusability (Anderson et al., 2023).

Another study (Kuo et al., 2006), proposes a method to integrate disassembly and recycling planning (Pehlken & Baumann, 2020) into the product design process using LCA analysis (De Benedetto & Klemes, 2010). By considering dissolvability and recyclability early on, designers can utilize the analytical results from the LCA analysis to evaluate the ease of disassembly and the recyclability of the products during the early design stage (Samant & Prakash, 2021). This evaluation enables them to proactively identify areas where improvements can be made to optimize the disassemblability and recyclability of the products, by gaining insights early on. Furthermore, another study (Vanegas et al., 2018) proposes a method to assess the ease of disassembly of products, offering sustainability insights for material efficiency, product lifetime extension, and recycling. However, the subjectivity involved in the assessment process limited the generalizability of the findings. Overall, the examined studies agree on the importance of enhancing environmental sustainability within the BOM, recognizing that standardized methodologies and improved data availability are essential for integrating sustainability aspects into the BOM (Babbit et al., 2020). However, the high degree of specificity associated with each component within a product, addresses a significant challenge, making the development of such standardized methodologies, able to manage multi-disciplinary data, difficult (Kurniadi & Ryu, 2021).

2.3 Integrating ESG and Sustainability Concepts Within BOM: State of the Art and Challenges

The ESG principle was put forth in 2004 as an emerging field of research when Kofi Annan and other 18 financial institutions drafted a report that called for the integration of ESG factors into financial analysis, asset management, and security brokerage (Li et al., 2021). Since then, ESG has been actively implemented, as an extension of the traditional Corporate Social Responsibility (CSR) approach (Sampong et al., 2018). ESG reporting has a positive effect on promoting the transparency of financial information, as it involves the evaluation and ranking of how well companies manage environmental, social, and governance risks and opportunities (Cimprich et al., 2018). Based on stakeholder theory, the ESG research suggested a positive correlation between the performance of “good” ESG performance and the overall performance of the company (Li et al., 2021). However, the registration of ESG performance of suppliers within the Bill of Materials (BOM) faces significant challenges, due to several reasons. Firstly, manufacturers seldom disclose such information, and it is only found scattered in case studies within the open literature. Secondly, the lack of a standardized approach to characterizing sustainability in manufacturing makes it difficult to establish uniform ESG metrics for all the suppliers. In addition, obtaining comprehensive and structured information about the ESG practices of suppliers can be challenging, leading to incomplete or unreliable data (Babbit et al., 2020). To the purposes of this study, despite the growing global emphasis on ESG criteria, our literature rewiev reveal consistent finding: currently no standardized method exists for integrating ESG data related to the suppliers of components within the BOM. Indeed, none of the listed components provide information about the sustainability performance of the suppliers responsible for their manufacturing. Consequently, products can’t be configured according to these criteria, hampering not only the transparency in the supply chain during the manufacturing phase of the parts, but also the customer’s purchasing experience. Customers are left unaware of how the parts have been produced in terms of ESG, and can’t buy products which are manufactured according to a certain ESG performance of the suppliers.

3. Methods

After having identified the gaps in the state of the art and given the research question on which the method proposed in this study relies on, which include the investigation on qualitative factors of sustainability (Li et al., 2021), the proposed method is designed to assess sustainability categories that can be standardized across all components in the EBOM (Finkbeiner et al., 2010). Regardless of type or composition and their operational structure, the proposed method enables customers to choose their own sustainability configuration of the product, even if they are not familiar with the complex core sustainability areas and their analytical assessment. Indeed, assuming a medium-skilled customer in terms of sustainability, transversality and quick-understandability[] are the two main key-principles on which the proposed method relies on (Mani et al., 2014). The proposed Sustainability Scoring System for Bill of Materials (3-S BOM) is based on a systematic integration of ESG data within the BOM and information about the components sustainability, to which purposes two indicators are used: the Hazardous Substances and Virgin Materials Indicator (HV) and the Hazardous Substances and Virgin Materials Circularity Indicator (HVci)). The 3-S BOM aims to provide comprehensive sustainability information in form of scores about the components listed in the BOM. The assessment areas focus on the sustainability performance of component suppliers and the compositional features of the components themselves (Finkbeiner et al., 2010). Specifically, the aim is to integrate in the EBOM an Overall Sustainability Score (OSS) for each of the listed components, sub-assemblies and assemblies, as reported in Figure 2.

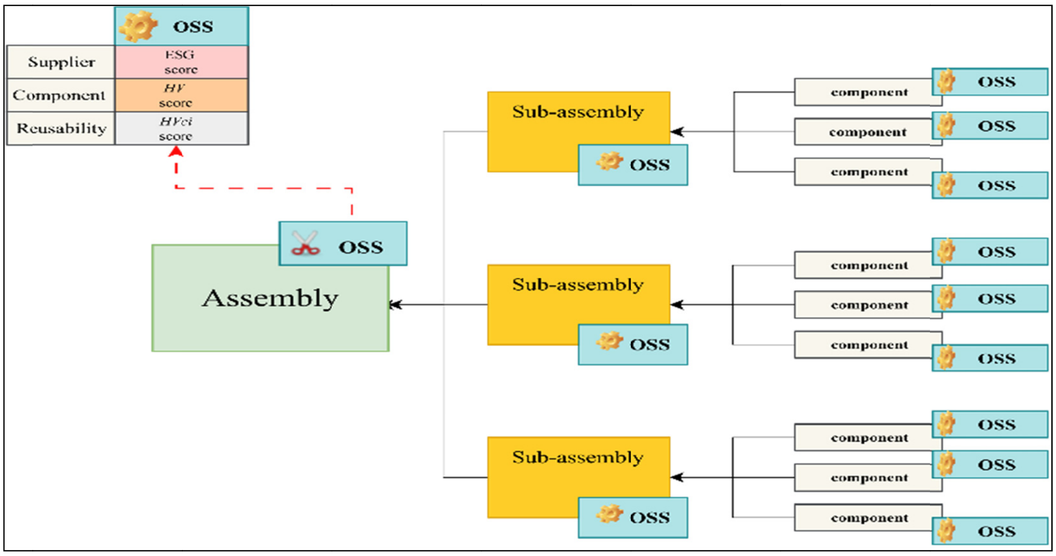

Figure 1. Structure of the 3-S BOM method

The Overall Sustainability Score (OSS) encompasses three different sustainability areas and sustainability scores: ESG, HV, and HVci. Starting from the lowest layer of the BOM, each component is assigned an OSS which is then progressively condensed into a higher-level OSS score. Based on the OSS score, the 3-S BOM aims to allow multiple customer-defined configuration processes of components into assemblies, according to different and specific sustainability needs. The 3-S BOM relies on a transversality and quick understandability principle. Indeed, the method is designed to be implemented on each component within the EBOM, regardless of its type and composition. The aim is to provide a straightforward method, able to simplify the complex multidimensional sustainability assessments, in form of scores, enabling customers to define their own sustainability configuration event if not familiar with core sustainability areas. The 3-S BOM encompasses the evaluation of the company's and the components sustainability. These evaluations will be incorporated within the BOM in form of scores. The three core areas on which the OSS is based are reported in Figure 3:

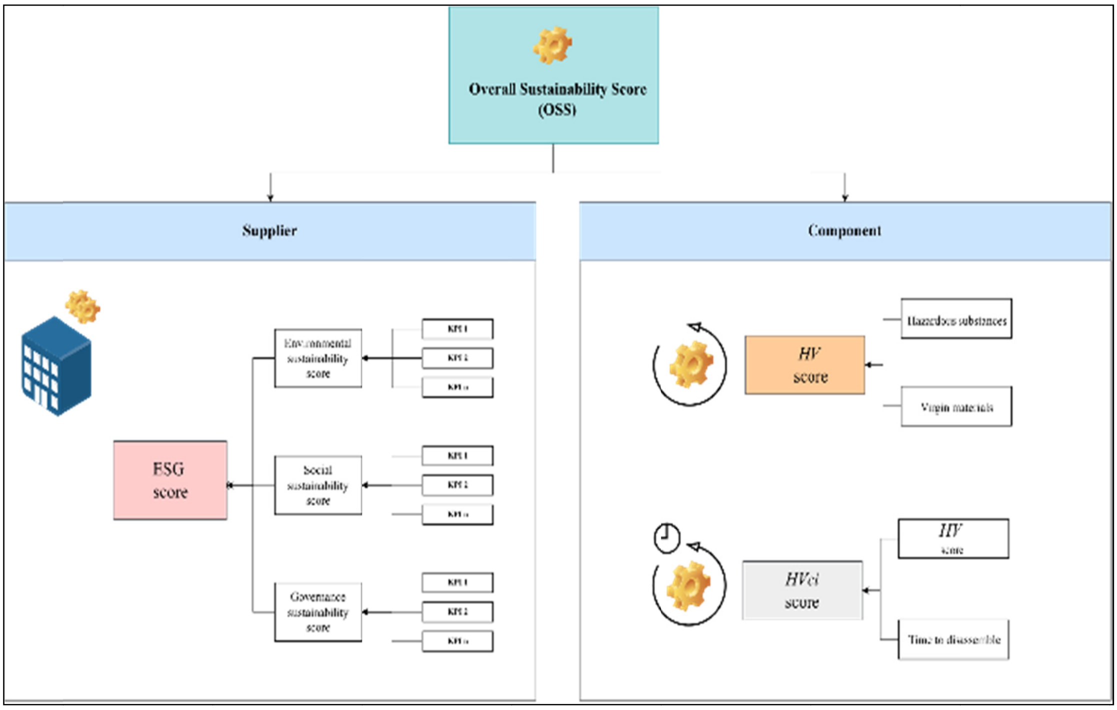

Figure 2. Areas of assessment of the 3-S BOM

The sustainability performance of the main supplier is assessed using the ESG framework. Specifically, Key Performance Indicators (KPIs) are utilized to measure the company's sustainability across various disclosure topics. By employing these indicators, the supplier's sustainability level can be determined. Considering the specific sustainability needs of the customer, two alternative configuration processes can be activated based on either a generic ESG level or an analytical KPI level, according to which the components will be configured into assemblies. The component sustainability is assessed by two indicators based on categories identified as crucial in dismantling plans of customers (Cusenza et al., 2019). The HV is introduced to evaluate the sustainability of the component, considering its composition materials. Elements such as the presence of hazardous substances and virgin materials are evaluated. The result of this assessment, condensed into an HV score, becomes an integral part of the 3-S BOM. Similar to the ESG score, a customer-defined configuration process can be activated based on the HV score, ensuring alignment with specific sustainability requirements. The second indicator assesses the sustainability of the component's composition in relation to the time required for disassembly. The HV result obtained from the previous evaluation is then related to the disassembly time of the components within an assembly, measuring the HV circularity (HVci). As with the ESG and HV scores, a customer-defined configuration process can be activated based on specific sustainability requirements.

3.1 ESG Score

The ESG score of suppliers is focused on material disclosure topics and accounting metrics, comprehensively covering all ESG dimensions with appropriate KPIs (Stecca et al., 2013). This assessment will culminate in the definition of an ESG score (Savastano et al., 2022). To ensure a thorough evaluation of the supplier's sustainability performance, it is essential to establish system boundaries as narrowly as possible. In the development of the 3-S BOM, only the primary supplier of the component is evaluated, precluding the possibility of an assessment that extends to the entire value chain. By shortening the system boundaries, the 3-S BOM can handle any supplier more effectively, and the data obtained is considered more valuable since it is directly disclosed. The identified system boundaries of the 3-S BOM follow the Polluter-Pays-Principle (PPP), which is linked to the Precautionary and Prevention Principles. Under these principles, the supplier's manufacturing locations, if more than one, are consolidated into a single location (if available), and sustainability evaluations are performed uniquely and comprehensively across all locations of one supplier. In accordance with the method's goals, two primary standards have been recognized as the most appropriate to identify the KPIs for the ESG evaluation of the company: SASB and GRI. The KPIs have been designed also in accordance with the 17 SDGs of Agenda 2030. For the Environment (E) dimension five ESG material disclosure topics have been identified (ESG 1, ESG 2, ESG 3, ESG 4, ESG 5), for each of which KPIs assess specifically the sustainability level:

ESG/KPI	**DEFINITION**
ESG 1	**Energy efficiency**
KPI 1-1	Total energy consumption
KPI 1-2	Specific energy consumption, per unit of production volume
KPI 1-3	Deployment of renewable energy related to the medium composition of the energy mix
KPI 1-4	Deployment of non-renewable energy
KPI 1-5	Energy use improvement compared to the previous year: energy efficiency per value added
ESG 2	**GHG Emissions**
KPI 2-1	Total GHG emissions, per unit of production volume
KPI 2-2	Direct GHG emissions (Scope 1)
KPI 2-3	Indirect GHG emissions (Scope 2)
KPI-2-4	Other indirect GHG emissions (Scope 3)
KPI-2-5	Initiatives to reduce greenhouse gas emissions and reductions achieved
KPI 2-6	Total environmental fines (in USD)
ESG 3	**Waste management**
KPI 3-1	Formal programs of waste disposal and waste reduction goals
KPI 3-2	Waste covered by Extended Producer Responsibility (EPR)

KPI 3-3	Production of hazardous waste, per unit of output
KPI 3-4	Waste recycled
ESG 4	**Water management**
KPI 4-1	Water consumption (total water withdrawal- total water discharge)
KPI 4-2	Internally developed quality standards or guidelines for water management
KPI 4-3	Water stress of the area where the company is located
KPI 4-4	Change in water consumption in areas with high and very high-water stress
KPI 4-5	Total water discharge in all areas
KPI 4-6	Total water discharge in areas with medium and very high-water stress
KPI 4-7	% of the total water discharge released into a receiving waterbody
KPI 4-8	% of the total water discharge released into a point-source discharge
KPI 4-9	% of the total water discharge in a non-point-source discharge
KPI 4-10	Internal water treatment plant for water recycling
ESG 5	**Biodiversity**
KPI 5-1	Operational sites of the company located in areas of high biodiversity or adjacent
KPI 5-2	Impacts of activities on biodiversity
KPI 5-3	Habitats protected or restored

For the Social (S) dimension, three ESG material disclosure topics have been identified (ESG 6, ESG 7, ESG 8), for each of which KPIs assess specifically the sustainability level:

ESG/KPI	DEFINITION
ESG 6	Gender equality and equal opportunities
KPI 6-1	Percentage of women/diverse in management position
KPI 6-2	Parental leave
KPI 6-3	Remuneration of women to men
KPI 6-4	Gender pay gap
KPI 6-5	Diversity of governance bodies and employees
ESG 7	Economic inclusion
KPI 7-1	Inclusion of vulnerable groups
KPI 7-2	Supplier diversity program
KPI 7-3	Local community engagement
ESG 8	Salary and employees' rights
KPI 8-1	Alignment to minimum wage, if available
KPI 8-2	Employees covered by collective bargaining agreements
KPI 8-3	Children's rights
KPI 8-4	Training and education
KPI 8-5	Recordable work-related injuries
KPI 8-6	Occupational health and safety management systems

Finally, in the G dimension three ESG material disclosure topics have been identified (ESG 9, ESG 10, ESG 11), for each of which KPIs assess specifically the sustainability level:

ESG/KPI	DEFINITION
ESG 9	**Sustainable supplier selection**
KPI 9-1	KPI 9-1 Suppliers screened using social criteria
KPI 9-2	KPI 9-2 Suppliers screened using environmental criteria
KPI 9-3	KPI 9-3 Suppliers screen using transportation criteria
KPI 9-4	KPI 9-4 Proportion of spending on local suppliers
KPI 9-5	KPI 9-5 Supplier diversity programs
ESG 10	**Corruption and anti-competitive behavior**
KPI 10-1	KPI 10-1 Confirmed incidents of corruption and actions taken
KPI 10-2	KPI 10-2 Legal actions for anti-competitive behavior, anti-trust, and monopoly practices
ESG 11	**Innovation and security of products**
KPI 11-1	KPI 11-1 R&D expenses or funding of research on ESG to external agents
KPI 11-2	KPI 11-2 Spendings on product safety

To this point, multiple KPIs have been identified for each category of E, S, and G to assess the sustainability performance of the supplier. After the assessment of each KPI, the results will be internally benchmarked, based on the average value defined and the score will be determined for each KPI and ESG according to the following scorecard:

Table 1. Scorecard for the KPIs of the ESG

Score	Degree of fulfillment	Distance from the average value	Percentage of fulfillment
1	Very poor	<50%	0–19%
2	Poor	50–25%	20–39%
3	Average	Average Value	40–59%
4	Good	25–50%	60–79%
5	Very good	>50%	80–100%

Each supplier company will be assigned scores ranging from 1 to 5 for every KPI, based on the degree of fulfillment, benchmarked to the internally defined medium value. A score of 1 point will be automatically assigned to the undisclosed KPIs. The single KPI results will then be ranked according to their respective category. All KPIs will receive equal weightage. The company's score for all KPIs will be evaluated based on the scorecard (Table 1). Moreover, the individual KPI scores can be combined to produce an overall evaluation of a particular ESG category (e.g., energy management) or dimension (E). An example of the calculation is provided in Table 2.

Table 2. Example of calculation of ESG

Dimension E					
ESG	**ESG 1** **Energy efficiency**				
KPIs	**KPI 1-1**	**KPI 1-2**	**KPI 1-3**	**KPI 1-4**	**KPI 1-5**
Maximum score obtainable for each KPI	5	5	5	5	5
Maximum score obtainable for ESG 1	25				
Score obtained by company x	20				
Score for ESG1	$degree\ of\ fulfillment = \frac{\sum points\ obtained}{\sum \max points\ obtainable\ in\ that\ category\ or\ dimension}$				
Percentage of fulfillment	$\frac{20}{25} = 0{,}8 = 80\%$				
Score attributed to the company for ESG1	5				

Assuming that the E dimension consists of 5 KPIs, each of which can score a maximum of 5 points, the maximum number of points achievable in the energy efficiency category of the E dimension is 25. With reference to Table 6, if a company achieves a score of 20 points in the energy efficiency category, the degree of fulfillment of dimension E in the energy efficiency category is calculated by dividing the total points obtained by the maximum points obtainable in that category (or dimension).

3.2 The Customers Involvement in the Definition of the ESG Score: Analytical and Generic ESG Configuration

After the assessment and the score assignment, the EBOM should contain all the needed data to assess the sustainability level of all the suppliers of components within the BOM. Based on this information, on the ESG side of the 3-S BOM, the customer is given the opportunity to choose between two possible configurations of components into assemblies, which can be more or less analytically defined, e.g., on a generic ESG level or on an analytical KPIs level. Assuming an analytical configuration of components based on a weighting factor applied at the KPI level, the individual scores for the Environmental (E), Social (S), and Governance (G) dimensions are calculated according to the customer's needs. In each Equation (2, 3, 4), the KPI indicator (KPI_i) and its corresponding customer-defined weighting factor (χ_{KPI_i}) are used to determine the contribution of that KPI to the overall ESG score for the dimension. Specifically:

Equation 2: Calculation of the E score, given weighting factors for the (E) KPIs

$$ESG(E) = \frac{1}{\sum_{i=1-1}^{5-3} \chi_{KPI_i(E)}} \cdot \sum_{i=1-1}^{5-3} KPI_i(E) \cdot \chi_{KPI_i(E)} \tag{2}$$

Equation 3: Calculation of the S score, given weighting factors for the (S) KPIs

$$ESG(S) = \frac{1}{\sum_{i=6-1}^{8-6} \chi_{KPI_i(S)}} \cdot \sum_{i=6-1}^{8-6} KPI_i(S) \cdot \chi_{KPI_i(S)} \tag{3}$$

Equation 4: Calculation of the G score, given weighting factors for the (G) KPIs

$$ESG(G) = \frac{1}{\sum_{i=9-1}^{11-2} \chi_{KPI_i(G)}} \cdot \sum_{i=9-1}^{11-2} KPI_i(G) \cdot \chi_{KPI_i(G)} \tag{4}$$

In which:

$\chi_{KPI_i(E)}: Weightingfactorforthei - thKPIintheEDimension$

$\chi_{KPI_i(S)}: Weightingfactorforthei - thKPIintheSDimension$

$\chi_{KPI_i(G)}: Weightingfactorforthei - thKPIintheGDimension$

These equations are incorporated into the 3-S BOM to allow customers to define the importance of each KPI in the sustainability of the assembly based on the customers' specific needs. By setting a weighting factor $\chi_{KPI_i}$for each KPI, customers can prioritize sustainability factors (KPIS) that are most important to them, therefore relevant in the sustainability of the final assembly. On the other hand, if the customers demand corresponds to a generic need in terms of sustainability performance of the suppliers, the configuration process will be based on the values of weighting factors assigned to the three E, S and G dimensions, as follows:

Equation 5: Calculation of the ESG score, given weighting factors for the E, S and G dimensions

$$ESG = \frac{\chi_{ESG(E)} \cdot ESG(E) + \chi_{ESG(S)} \cdot ESG(S) + \chi_{ESG(G)} \cdot ESG(G)}{\chi_{ESG(E)} + \chi_{ESG(S)} + \chi_{ESG(G)}} \tag{5}$$

In which:

$\chi_{ESG_{(E)}}: weightingfactorfortheEdimension$

$\chi_{ESG_{(S)}}: weightingfactorfortheSdimension$

$\chi_{ESG_{(G)}}: weightingfactorfortheGdimension$

Summarizing, on the ESG side, the 3-S BOM method allows customers to choose between two possible configurations of components into. Customers can choose to apply a weighting factor at the KPI level, where they assign a weighting factor to each KPI within the three E, S, and G dimensions. Alternatively, customers can choose a generic sustainability configuration process by choosing a weighting factor for each of the E, S, and G dimensions.

3.3 The HV and HVci Score

Based on the gaps in the literature review, a new indicator to assess the sustainability of the components listed in the BOM is presented, based on the characteristics identified as crucial for customers in dismantling plans. Specifically, the Hazardous Substances and Virgin Materials Indicator and the Hazardous Substances and Virgin Materials Circularity Indicator (HVci) concern the second and the third level of the three scores included within the 3-S BOM. The categories and units of measure needed for the calculation of the HV and HVci are listed in the following Table.

Table 3. Categories and units of measure for the definition of the HV and HVci

Characterization of the component	**Unit of measure**
Quantity of different materials	Qty
Weight	Kg
Quantity of hazardous substances	Qty
Hazardous substances, % of all materials	%
Virgin materials, % of the total weight	%
Circular materials, % of the total weight	%
Time to disassemble	Min

For each component following characteristics must be revealed: the total weight of the component, the quantity of different materials used, distinguishing between the circular and virgin proportion, and the quantity of hazardous substances. Once the data is gathered, the HV can be assessed. The result of the HV is then furtherly related to the time needed to disassemble the component or the product, leading to the definition of the HVci. However, calculating the HVci including the variable "time to disassemble" is considered only relevant at a component level, if the component contains multiple parts that can be further reused. If a component consists of a single piece that cannot be disassembled, calculating the HVci at the component level is not practical. Therefore, in this study it is recommended that the HVci be calculated at the higher level of assemblies of BOM in which that component is used. The calculation process begins by evaluating the circularity of the component. This is done by determining the proportion of circular materials (i.e., recycled or reused materials) in the component, divided by the total amount of materials (circular and linear) used in the component. The circularity of the component is calculated using Equation 6:

Equation 6: Calculation of the circularity of the component

$$Circularityofthecomponent[\%] = \frac{circularmaterialsinthecomponent[kg]}{circular[kg]+virginmaterialsofthecomponent[kg]} * 100 \tag{6}$$

Following, the linearity of the component, which represents the percentage of virgin materials used in the component, is calculated using Equation 7:

Equation 7: Calculation of the virgin proportion of the component

$$Virg\% = 1 - \ circularityofthecomponent \tag{7}$$

After having assessed the circularity and the virgin proportion of the component, the HV score can be determined, based on the quantity of hazardous substances and virgin materials in the component. The HV score is calculated using Equation 8:

Equation 8: Calculation of the HV

$$HV = 1 - \left[\frac{1}{(1+\mathcal{X}_{HV})}\right]\left[\mathcal{X}_{HV}\left(\frac{QtyHaz}{QtyTot}\right) + Virg\%\right] \tag{8}$$

In which:

$QtyHaz$ = quantity of hazardous substances

$QtyTot$ = quantity of different materials in the component

$Virg\%$ = % of virgin materials in the total weight of the component

$\mathcal{X}_{HV} =$ weighting factor for hazardous substances (≥ 0)

The result of the HV ranges from 0 to 1, hence from the lowest to the highest level of sustainability. If the HV = 0, all materials in the component are hazardous substances and virgin materials. If HV = 1, no hazardous substances and no virgin materials are present in the component. A weighting factor $\mathcal{X}_{HV}$represents the value of hazardous substances towards the virgin materials proportion of the component. As in the ESG configuration process and can be decided by the customer. For instance:

$\mathcal{X}_{HV} = 1$ hazardous substances are as important as the virgin materials.

$\mathcal{X}_{HV} = 5$ hazardous substances are 5 times more important than virgin materials.

The result of the$HV$is then related to the time to disassemble needed for the component or the product, and the $HVci$ is calculated:

Equation 9: Calculation of the HVci

$$HVci = \left[\frac{1}{(1+\mathcal{X}_{HVci})}\right]\left[\mathcal{X}_{HVci}\left(1-\frac{Timetodisassemble}{Maxtimetodisassemble}\right)+HV\right] \tag{9}$$

In which:

$Timetodisassemble$ = time needed to disassemble the product [seconds]

$Maxtimetodisassemble$ = maximal time needed to disassemble that category of products [seconds]

$\mathcal{X}_{HVci}$ = weighting factor of the time to disassemble, e.g., how much the time to disassemble is more important than HV (≥0).

As in the case of the HV, also the value of the $HVci$ ranges from 0 to 1, hence from the lowest to the highest level of sustainability. The result of the HVci is comprehended within a range between 0 and 1, if the HVci= 0, the time to disassemble is maximal and the HV= 0; whereas if the HVci=1, the time to disassemble is equal 0 and the HV= 1.A weighting factor $\mathcal{X}_{HVci}$ represents the value of the time to disassemble towards the HV and can be decided by the customer. For instance:

$\mathcal{X}_{HVci} = 1$ the time to disassemble is as important as the HV.

$\mathcal{X}_{HVci} = 5$ the time to disassemble is 5 times more important than the HV.

4. Discussion

The 3-S BOM method, introduced in this study, represents a significant stride towards integrating sustainability into the engineering concept of Bill of Materials (BOM). The primary aim is to provide a comprehensive and user-friendly tool catering to individuals with varying expertise levels and sustainability concerns. A crucial aspect of this method is its focus on improving the product configuration process by actively engaging customers in shaping the sustainability profile of the product they intend to purchase.

Revisiting the initial research objective, which centers on the customer involvement in defining the sustainability profile of the product of purchase, it is evident that the 3-S BOM method achieves this by incorporating three key metrics: ESG, HV, and HVci. The ESG score evaluates the sustainability performance of the supplier, ranging from 1 to 5. The HV score assesses the sustainability of the component based on circularity, virgin materials, and hazardous substances, with values ranging from 0 to 1.

The HVci score builds upon the HV results, integrating disassembly time into the sustainability evaluation. These metrics collectively empower customers to opt for specific grades that align with their sustainability preferences during the final assembly of purchase.

To enhance clarity, conceptual affinity and operational affiliation among these terms are illustrated in Figures 1 and 2. Figure 1 depicts the interplay between Sustainability, ESG, HV, and HVci, illustrating their interconnectedness in the BOM. Figure 2 aims to represent the the relationship between Circularity, BOM, and KPIs, providing a visual representation of their operational affiliation.

5. Conclusion

In conclusion, the 3-S BOM method emerges as a robust and accessible approach for seamlessly integrating sustainability into the engineering concept of BOM. It successfully addresses the initial research objective by actively involving customers in shaping the sustainability profile of the product they intend to purchase, utilizing the interconnected metrics of ESG, HV, and HVci. As future directions, this study suggests a continued focus on key areas of improvement. Supply Chain Transparency and Traceability, expanded metric scope, stakeholder involvement, and continuous improvement are highlighted as crucial for further enhancements of the 3-S BOM, in order to enhance sustainable engineering, promote informed decision-making and contribute to a more environmentally conscious and socially responsible approach to product development, taking into account different customer's needs.

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