10th International Conference on Mass Customization and Personalization – Community of Europe (MCP - CE 2022)
Toward the Sustainable, User-Centric and Smart Industry 5.0
September 21-23, 2022, Novi Sad, Serbia

AUTOMATION OF LIFE CYCLE ASSESSMENT THROUGH CONFIGURATORS

Irene Campo-Gay[1], Lars Hvam[1], Anders Haug[2]
[1]Technical University of Denmark, Department of Mechanical Engineering, Kgs. Lyngby, Denmark
[2]University of Southern Denmark, Department of Entrepreneurship and Relationship Management, Kolding, Denmark

Abstract: *The manufacturing and construction industries face new sustainability regulations to reduce the environmental impact of products. Customers are also becoming increasingly interested in the sustainability evaluation of products. Thus, the use of environmental product declarations (EPDs) has steadily risen in companies as the preferred life cycle assessment (LCA) tool. These new demands for information transparency challenge companies that use configurators to support the further development of product specification activities to include such information. Given that the sustainability assessment of products is so new, guidance on how to integrate LCAs in general and EPDs in particular in configurators remains lacking. This study adds to this knowledge using an action research methodology. Specifically, this study uses literature to develop a framework for supporting the development of product configurators that include environmental assessment information for different life cycle stages. This proposed approach is tested through collaboration with a building construction company. The findings show that the proposed framework can support the development of a configurator that generates product design alternatives with information on their environmental impact.*

Key Words: ***Configurators, Environmental Product Declaration (EPD), Life Cycle Assessment (LCA), Product Variant Master (PVM), Sustainability Assessment***

1. INTRODUCTION

Product sustainability is an extensively discussed topic that is gaining even greater attention in research and for both customers and companies. Customers are calling for greater transparency and additional information on the sustainability of the products that they are willing to purchase. Moreover, new laws and recommendations are being enforced to induce companies to achieve better environmental, social, and governance (ESG) outcomes. To meet these new requirements, companies need new sustainability assessment tools that can encourage customers to select more sustainable solutions.

Manufacturing and construction industries generally use life cycle assessment (LCA), one of the most adopted methodologies for quantifying environmental product performance, to create environmental labels and declarations [1]. Environmental product declarations (EPDs) are verified, objective and transparent reports developed for communicating a product’s environmental impact at each stage of its life cycle in accordance with ISO 14025. One of the most significant advantages of EPDs is the comparability of its results across different companies. This is made possible by product category rules (PCRs) that determine the category-specific requirements for performing an LCA [2].

Although the issuance of EPDs has risen in various industries, the building construction industry pioneered them. This seems rightfully so, because, according to the United Nations (UN) Environment program, the building and construction sector is one of the most polluting sectors, accounting for 38% of all operational energy-related CO_2 emissions [3]. Therefore, governments are continuously implementing new laws and regulations, such as a statutory maximum average CO_2-eq emission per m^2 per year across the life cycle of new building construction [4].

One potentially relevant technology in this regard is configurators, which have been highly beneficial in supporting the customization of products. Specifically, companies have been using configurators since the late 1970s to enhance specification processes such as design and engineering, production, and sales. The use of configurators has led to substantial benefits such as shorter lead times, improved specification quality, fewer errors, resource reduction, and improved product design [5]–[8]. However, research on configurators as sustainability assessment tools is limited, and in particular, research that argued for the feasibility of configurators for sustainability assessment is non-existent.

To address this literature gap, this paper presents the framework we designed for developing and implementing configurators that assess and report LCAs. This paper also discusses the test we conducted to determine the usefulness of the proposed framework through action research [9].

This paper is structured as follows. In Section 2, we review the literature on which we based the framework. In Section 3, we describe our methodology for designing and testing the framework. In Section 4, we present our findings from the case study that we conducted as part of our action research methodology. In Section 4, we discuss the findings. Finally, in Section 5, we conclude this paper.

2. LITERATURE REVIEW

2.1. Life cycle assessments

Sustainability is often described as the confluence of three distinct dimensions (environmental, social, and economic), disregarding the fact that these dimensions are not equal in significance. The environmental dimension should be regarded as the central dimension, as socioeconomic elements are directly dependent on it [10]. The sustainability assessment of products, particularly customized products, is an emerging topic that is steadily gaining attention from academics and industry practitioners. Studies [11], [12] have been conducted on the assessment and quantification of the sustainability aspects of the mass customization of products using LCA methods.

However, digital tools for sustainability assessment, particularly configurators, have been scarcely developed. Within this context, attention has been focused on offering sustainable options through the user interface, which very few configurators currently have [13]. Based on a case study, Bakås et al. discussed how sustainability information could be integrated into the customer's decision-making process [14]. Likewise, Medini et al. proposed a mathematical model for integrating sustainability considerations into configurators that can be presented on the configurators' interface [15], [16]. Wang et al. proposed a graphical approach to mapping simple customized products on an ontology model for the same purpose [17]. However, these approaches are outside the ISO standards for LCA methods. Consequently, Wiezorek et al. proposed a new configurator architecture for sustainability integration guided by LCA ISO standards, which include a complementary sustainability assessment interface fed by additional life cycle databases [17].

This paper differs from past studies in its use of a certified and standard ISO approach based on the automation of EPDs. Moreover, this study adopts the existing structure of configurators to integrate case-specific sustainability information.

2.2 The Product Variant Master technique

The product variant master (PVM) technique is often applied when developing configurators to capture and discuss knowledge from domain experts [6]. There are different definitions of the PVM notation, one of which is by Haug [19]. Based on this definition, Fig. 1 shows an example of this technique for a "toy car." The figure shows that the left side describes the aggregation (part-of) structure, whereas the right side describes the specialization (kind-of) structure. Under the parts, attribute values and rules, as well as constraints, are described.

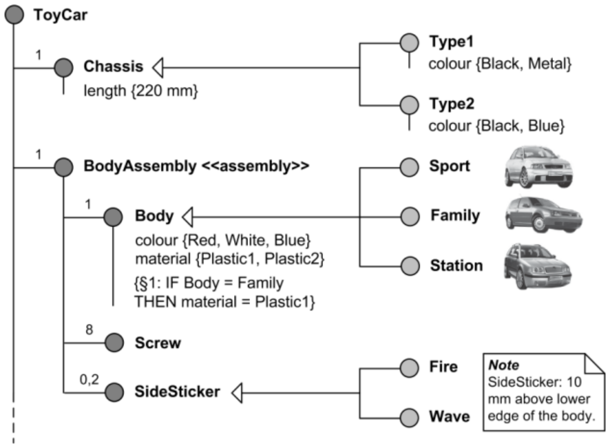

Fig. 1. *Example of the PVM technique [19]*

PVM can be used as a data collection and communication tool that structures product knowledge to enable discussions on the model. Such formalized knowledge can later be integrated into the configurator. This is illustrated in Fig. 2.

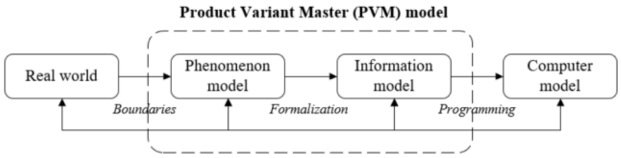

Fig. 2. *Translation of knowledge from the real world to the configurator model. Adapted from [20].*

3. AN LCA CONFIGURATION FRAMEWORK

Dealing with LCA knowledge can be a complex task, and as mentioned previously, it is hardly known how such knowledge can be automatically applied using a configurator. To address this gap, we propose the use of an information model to converge traditional product knowledge and the new environmental parameters. More specifically, we suggest the use of the PVM technique that maps the knowledge from domain experts in an ontology model.

As illustrated in Fig. 3, to consolidate environmental information, some requirements must be met. Specifically, it is essential to determine the objectives for integrating environmental aspects into configurators. This process requires defining the environmental configurator goals, choosing an environmental assessment methodology, and defining the system boundaries. We argue that there can be two main drivers of the integration of environmental aspects into configurators: (i) the increased product value perception of customers and (ii) the automation of environmental quantification. If the main objective is to guide the customer towards more sustainable choices, an arbitrary sustainability score methodology can be selected, as Wang et al. proposed [17]. On the other hand, if the objective is to provide reliable environmental measurements, an LCA approach is necessary according to the standard ISO 14044 [21].

Finally, the quantification of environmental measurements must be defined through the environmental unit. Each EPD standard includes a list of environmental units associated with a particular PCR. Two factors strongly influence the choice of an environmental unit: (i) legislative considerations and (ii) information accessibility. With regard to legislative considerations, new laws and recommendations are progressively coming into play that enforce the computation of environmental indicators and directly define the required unit of the environmental impact indicator. Concerning information accessibility, sustainability information on manufactured products, which is often limited and disconnected, is expected to expand and thus, give customers more choices on account of the new environmental approach, as has already happened in the building construction industry.

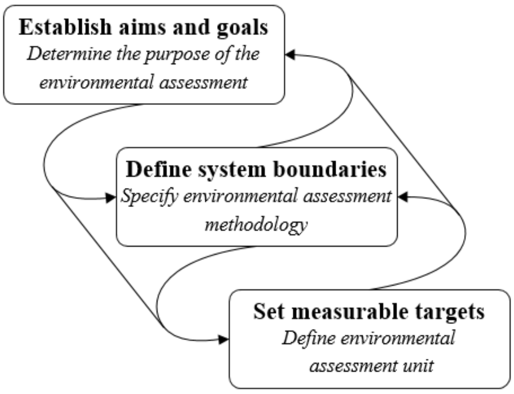

Fig. 3. *Framework for integrating environmental knowledge in configurators*

LCA knowledge can be described in the PVM technique according to three data types: (1) parts data, (2) engineering data, and (3) customer data.

The first type of LCA knowledge, parts data, refers to the sustainability information on components and modules of the product. Such information is mainly stored in the knowledge base. It is usually depicted as *other product attributes*. An example of an environmental part attribute is the global warming potential (GWP) per kg of CO_2 eq emissions of a product part. Another attribute is the characterization of bioproducts (i.e., materials available on a renewable basis) with their Boolean domain.

The second type of LCA knowledge, the engineering view, describes product-associated processes concerning the LCA methodology, which are mainly user inputs. This concerns, for instance, the transport distance attribute measured in kilometers, which characterizes the material transportation process. Another example of a process-description attribute is the construction season (warm season or cold season).

The third type of LCA knowledge, the customer view, concerns LCA quantifications for the customer. LCA knowledge is quantified according to the pre-established environmental unit for each life cycle stage. Each life cycle stage impact is computed individually according to the functions detailed in the EPD. An example is the computation of the total CO_2 eq emissions during EPD stage A4 (Transportation from the gate to the site).

Fig. 4 shows an example of a PVM, including the aforementioned data.

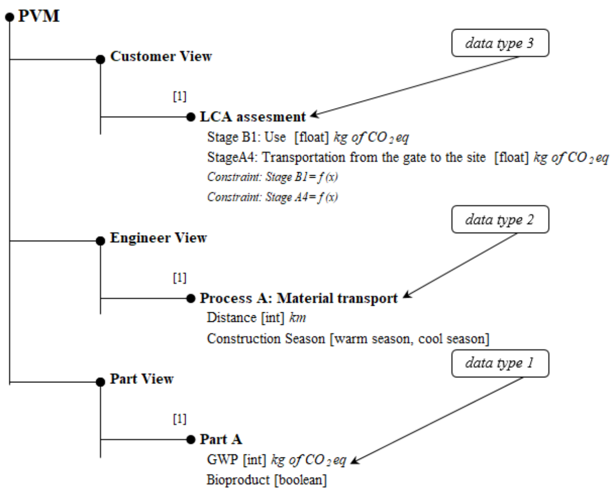

Fig. 4. *PVM model with LCA data*

4. RESEARCH METHOD

This paper aims to contribute to the literature on configurators and LCA by developing a framework for integrating LCA in configurators while understanding the practical implications of configurators as environmental assessment tools. An action research approach was chosen since it allows for experimentation in improving a condition within an existing organization and the adoption of methods in practical contexts [22] while contributing to science [23]. Besides, action research is among the preferred methodologies in studies of organizations [9], [24].

In this study, we collaborated with a building construction company to meet our stated research objectives.

4.1. Case context

Our case company is a medium-sized Nordic company that is part of a large international construction group with more than 20,000 employees and whose revenue in 2021 exceeded 10 billion euros. The company develops, manufactures, and markets materials for the building construction industry. We chose it because of its relevance to our research focus (a large building construction company) and because it was open to participating in this study.

4.2. Data collection and analysis

To enable us to construct the PVM, we collected the product data (hereinafter, LCA data) through modeling sessions with domain experts. Table 1 shows the information on the main session participants. The sessions were conducted regularly once a week throughout the study duration. Each session lasted approximately one hour and was held with individual informants, except for coordination meetings. Open-ended questions were formulated to require the respondents to elaborate their explanations. Moreover, the questions for each session were prepared based on the previous encounter and its subsequent development. The formulated questions can be categorized as *product-specific*, that is, aiming to gather conventional product data, and *LCA-based*, that is, pertaining to the computation of EPDs. All the interviews were supported by the exchange of documents and reports.

Table 1. *Main modeling sessions*

Expertise	Role	No. of sessions	Interviewee job position
Product	Project leader	28	Head of R&D (case company)
EPDs and LCA methodology	Environmental assessor	24	Construction environmental expert (external consultant)
Product	Domain expert	3	Development project manager (case company)

Fig. 5 presents an overview of the information workflow across the persons involved in the project.

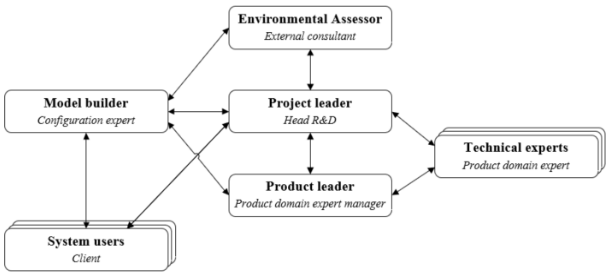

Fig. 5. *Information workflow across stakeholders*

Besides the modeling sessions, feedback on the PVMs and the configurator was acquired through monthly meetings with an external project committee composed of the client's marketing manager, regional manager, building construction expert, product manager, and the sales manager of the building construction company. During these meetings, videos of the configurator interface and additional informative slides were shown. The final configurator version was tested in April 2022 through a three-hour workshop with the external project committee.

5. FINDINGS

5.1. Project background

The marketing strategy of the case company is to position itself as having sustainable practices that include customer support and support for new and imminent environmental regulations. For this reason, the company aims to make environmental decision tools available to its customers and to automate its generation of environmental assessment reports, which are both complex and time-consuming processes. Therefore, the primary goals of the study project are (i) to recommend more sustainable product choices to the customers, (ii) to provide alternative options and compare them with standard choices, and (iii) to automatically quantify specific case EPDs (i.e., not generic EPDs).

An LCA configurator project was launched in June 2020 to support the aforementioned strategy. For the first phase, approximately seven person-months were allocated from June 2020 to April 2022. The project was developed part-time, allocating 3 hours per day. This first phase included a subset of the company's product portfolio. The subsequent phases were planned for the further development of the configurator and to cover the company's entire product portfolio.

5.2. Development of the configurator

Initially, it was decided that the system boundaries regarding the LCA methodology would be set by the corresponding construction EPD standard, EN 15804 [25]. According to such standard, the selected environmental impact indicator unit was kg CO_2 eq. Besides, the unit could be correlated to the available information and the expected new laws and requirements.

Then, a PVM model was created based on the information provided by the product and environmental experts. The data were acquired through a set of interviews, and consequently, the PVM evolved under a series of iterations. The model was built as described in section 3. Fig. 6 shows an extract of the *Customer View*, *Engineer View*, and *Part View* sections on the PVM describing the product's LCA. As seen in the model, the information is presented according to the different life cycle stages (A to D) and substages.

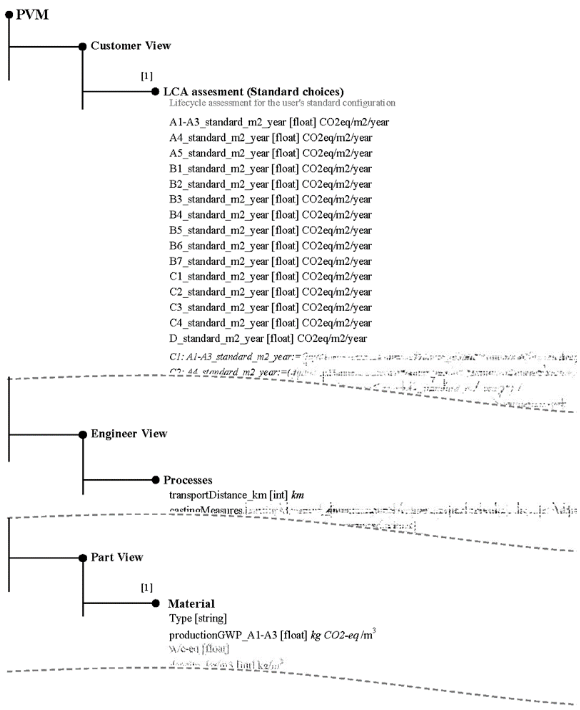

Fig. 6. *Extract from each PVM's views showing the computation of the LCA as explained in section 3*

The configurator was developed simultaneously with the PVM model over the same period. Thus, each PVM iteration enhanced the configurator outcome until the final version was achieved in April 2022. The final configurator contains seven relational table rules and 49 constraints. The sustainability features of the configurator are summarized in Table 2.

Table 2. *Environmental features of the new configurator*

Feature	Description
Decision support	The configurator could provide more sustainable choices to the user during the configuration process (e.g., users can select any building construction material, but that with the highest performance and lowest GWP value is recommended.
Comparison	An automatic comparative report is generated once the configuration has been completed according to the user requirements and the configurator guidance. The report presents a numerical and graphical presentation of different alternatives in kg CO_2 eq per m^2 per year (e.g., users can contrast their choices with one with a lower maintenance level; see Fig. 8).
LCA report documentation	The LCA assessment is documented through an automatically generated EPD. This EPD document is developed for the user's configuration, and each alternative provides the customer with an additional evaluation material (see Fig. 9).

In the weekly modeling sessions with the three persons involved in the project, time was allocated for presenting and discussing the status of the PVM model and the configurator. Fig. 7 shows an example of a configurator user interface and how the standard product features and the LCA features come together and influence each other.

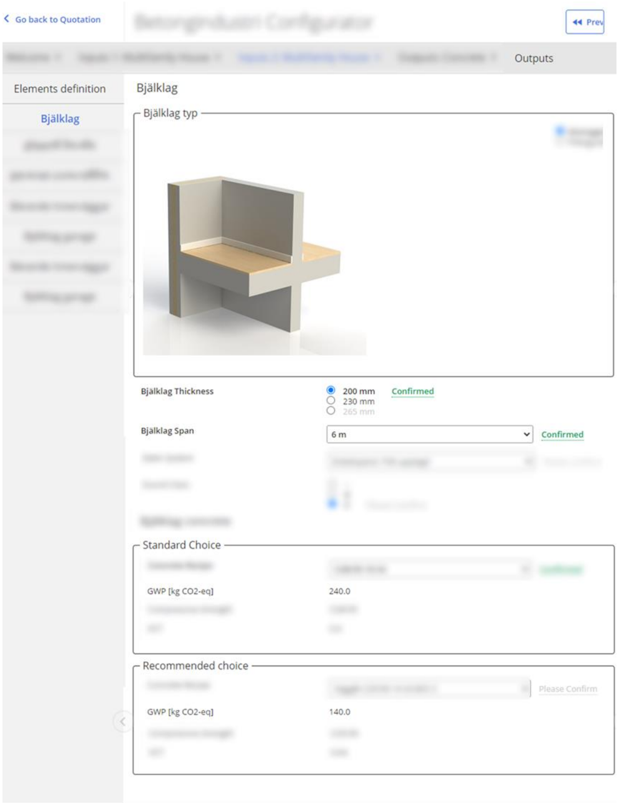

Fig. 7. *Screenshot of the configurator*

After a product is configured, reports can be generated. Fig. 8 shows an environmental impact comparative report generated by the configurator, including numerical and graphical representations of the alternatives.

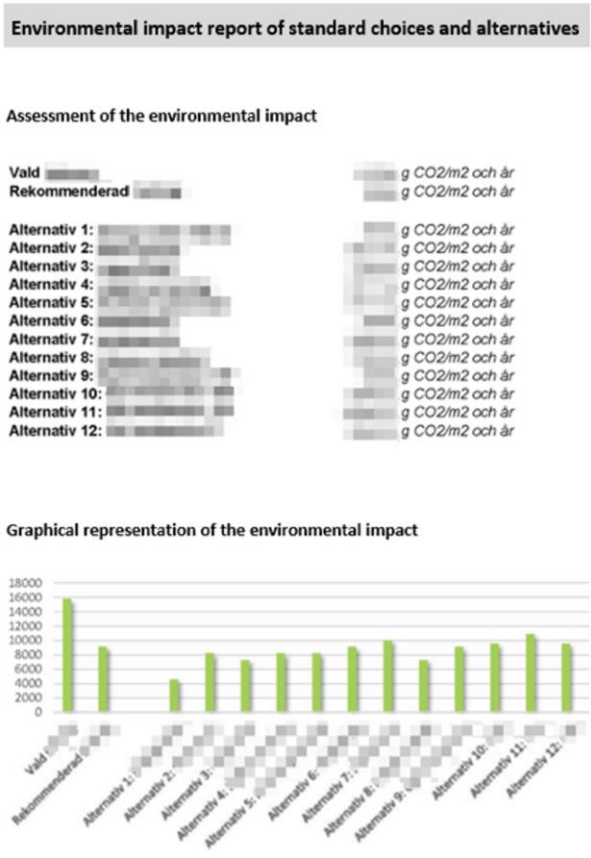

Fig. 8. *Environmental impact comparative report*

The configurator can also generate EPD reports. An example of these reports is shown in Fig. 9. The document details the total environmental impact in the predefined unit (CO_2 per m^2 per year) for each cycle stage (from A to D).

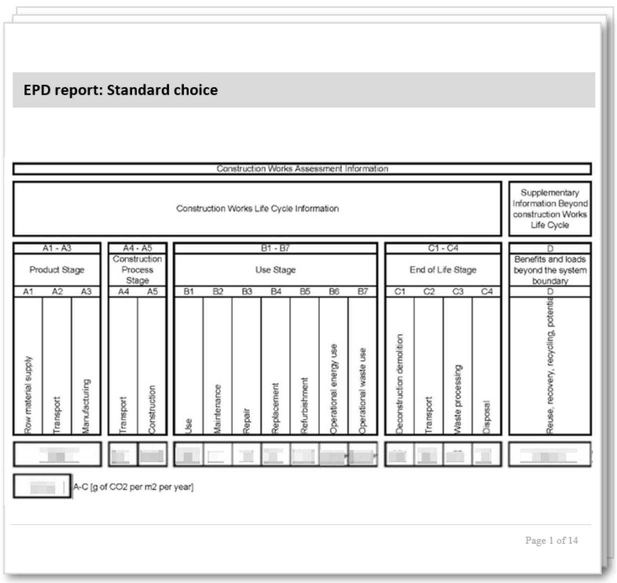

Fig. 9. *The automatically generated EPD report*

5.3. Evaluation of the adapted PVM technique

This study showed that the LCA-oriented PVM technique provided the necessary information basis for developing a configurator. Table 3 presents a compilation of observations of the project participants on the usefulness of the LCA-oriented PVM technique.

Table 3. *Evaluation of the LCA-PVM framework*

Inquiry	**Observation**
Usefulness of the PVM in reporting environmental attributes	The PVM model successfully accommodated all the required features for mapping the LCA attributes of a product.
Effort required to use this new approach	According to the conversations with and the observations of the involved domain experts, the modeling of the LCA features in the PVM model did not present significant challenges, unlike the modeling of the regular product features. However, it must be noted that the development of an information model is strongly dependent on expertise and the particular case.
Need for training of domain experts	Only a simple introduction to the PVM technique was needed to enable the domain experts to understand the models developed.

6. DISCUSSION AND CONCLUSIONS

The building construction sector has traditionally centered its sustainability efforts on improving energy consumption during building use. Currently, the attention is on the materials' climate impact. However, a new strategy is needed to address environmental aspects from a more holistic perspective that includes all life cycle stages to avoid suboptimization when deciding on the design of a building. The adoption of this strategy has become urgent due to new environmental law that has set a maximum amount of CO_2 emissions in new buildings, which is expected to become even more restrictive in the coming years.

To address such challenges, we proposed the use of configurators to automate the computation of the LCA. Specifically, we developed a framework that uses the PVM technique to organize sustainability knowledge, including product features and additional sustainability parameters. The proposed approach utilizes the quality-based and certified system of EPDs to develop case-specific reports (i.e., including computations and not solely based on databases).

The proposed approach is novel due to its EPD data-driven approach, which provides reliable and robust information to avoid greenwashing. The most significant benefits that were observed concern automated EPD report generation, support for influencing customers to choose more sustainable products, a higher customer-perceived product value, and improved customer communication.

While other researchers have developed configurators that can assess the environmental impact of customizable products, the methodologies that they used are not standardized or certified, and hence, they are user-subjective. It should also be noted that existing cases of LCA computation are not comparable. Current literature proposes some methodologies for automating LCAs within configurators. However, such LCAs are generic (i.e., their information is based on databases) and not product-specific (i.e., based on certified calculations such as specific-case EPDs). Thus, to the authors' knowledge, this paper is the first to present a framework for implementing LCA properties in configurators.

As this study was limited to one product line, future studies need to investigate the use of our proposed framework for other types of products.

7. REFERENCES

[1] J. Fava, "Life cycle knowledge informs greener products," in *Life Cycle Assessment Handbook: a Guide for Environmentally Sustainable Products*. New Jersey, USA: John Wiley and Sons, 2012, pp. 585–596.

[2] A. del Borghi, "LCA and communication: Environmental product declaration," *International Journal of Life Cycle Assessment*, vol. 18, no. 2, pp. 293–295, 2013.

[3] UNEP - UN Environment Programme (n.d.). https://www.unep.org/ (accessed April 14, 2021)

[4] Denmark, *National Strategy for Sustainable Construction*. 2021.

[5] A. Felfernig, L. Hotz, C. Bagley, and J. Tiihonen, *Knowledge-based configuration: From research to business cases*. Waltham, USA: Elsevier Inc., 2014.

[6] L. Hvam, N. H. Mortensen, and J. Riis, *Product customization*. Berlin, Germany: Springer Berlin Heidelberg, 2008.

[7] C. Forza and F. Salvador, "Managing for variety in the order acquisition and fulfilment process: The contribution of product configuration systems," *International Journal of Production Economics*, vol. 76, no. 1, pp. 87–98, 2002.

[8] C. Forza and F. Salvador, Product information management for mass customization: Connecting customer, front-office and back-office for fast and efficient customization. Houndmills, UK: Palgrave Macmillan, 2006.

[9] P. Coughlan and D. Coghlan, "Action research," in *Research Methods for Operations Management*. New York, USA: Routledge, 2016, pp. 249–283.

[10] D. Griggs, M. Stafford-Smith, O. Gaffney, J. Rockström, M. C. Öhman, P. Shyamsundar, W. Steffen, G. Glaser, N. Kanie, and I. Noble, "Policy: Sustainable development goals for people and planet," *Nature*, vol. 495, no. 7441, pp. 305–307.

[11] A. K. Briem, T. Betten, M. Held, D. Wehner, and M. Baumann, "Environmental sustainability in the context of mass personalisation: Quantification of the carbon footprint with life cycle assessment," *Int. J. Ind. Eng. Manag.*, vol. 10, no. 2, pp. 171–180.

[12] T. D. Brunø, K. Nielsen, S. B. Taps, and K. A. Jørgensen, "Sustainability evaluation of mass customization," in *Ifip Advances in Information and Communication Technology*, 2013, pp. 175–182.

[13] S. Hankammer, M. Hora, L. Canetta, and S. K. Sel, "User-interface design for individualization services to enhance sustainable consumption and production," in *Procedia CIRP*, 2016, pp. 448–453.

[14] O. Bakås, B. Sjøbakk, L. Skjelstad, and M. Thomassen "Integrating sustainability knowledge in choice navigation" in *Proceedings of the 8th International Conference on Mass Customization and Personalization*, 2018, pp.8-15.

[15] K. Medini, T. Wuest, E. Jelodari, D. Romero, and V. Laforest, "A decision support system to operationalize customer-centric sustainability," in *Procedia CIRP*, 2021, pp. 122–127.
[16] K. Medini, T. Wuest, D. Romero, and V. Laforest, "Integrating sustainability considerations into product variety and portfolio management," in *Procedia CIRP*, 2020, pp. 605–609.
[17] W. M. Wang, L. Wolter, K. Lindow, and R. Stark, "Graphical visualization of sustainable manufacturing aspects for knowledge transfer to public audience," in *Procedia CIRP*, 2015, pp. 58–63.
[18] R. Wiezorek and N. Christensen, "Integrating sustainability information in configurators," in Ceur Workshop Proceedings, 2021, pp. 65-72.
[19] A. Haug, "Managing diagrammatic models with different perspectives on product information," *Journal of Intelligent Manufacturing*, vol. 21, no. 6, pp. 811–822, 2010.
[20] A. H. B. Duffy and M. M. Andreasen, "Enhancing the evolution of design science," in *International Conference on Engineering Design*, 1995, pp. 29–35.
[21] Environmental management – Life cycle assessment – Requirements and guidelines – Amendment 2 (ISO 14044:2006/Amd 2:2020). (2020).
[22] E. Gummesson, "Taking off and landing: The route from preunderstanding to understanding," in *Qualitative methods in management research*, London, UK, 2000, pp. 57–82.
[23] A. B. Shani and W. A. Pasmore, "Towards a new model of the action research process," in *Academy of Management Proceedings*, 1982, pp. 208–212.
[24] M. Easterby-Smith, R. Thorpe, P. Jackson, *Management research*. Los Angeles, USA: SAGE Publications Ltd, 1991.
[25] Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products (DS/EN 15804:2012+A2:2019) (2019).

CORRESPONDENCE

Irene Campo-Gay, Ph.D.
Technical University of Denmark
Department of Mechanical Engineering,
Nils Koppels Allé, B404
2800 Kgs. Lyngby, Denmark
ircag@dtu.dk

Lars Hvam, Prof.
Technical University of Denmark
Department of Mechanical Engineering,
Nils Koppels Allé, B404
2800 Kgs. Lyngby, Denmark
lahv@dtu.dk

Anders Haug, Assoc Prof.
University of Southern Denmark
Department of Entrepreneurship and Relationship Management,
Universitetsparken 1
6000 Kolding, Denmark
adg@sam.sdu.dk