Requirements and architectures for green configuration

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Abstract

Green Configuration combines product configuration technologies with environmental impact calculations and enables customers to balance cost drivers and environmental impact drivers (such as CO_2 footprint) for their preferred product variants. We analyse requirements for configurable products that go beyond the state of the art of classical Life Cycle Assessment (LCA), and we list corresponding challenges for configurators, such as missing environmental impact data, total costs over the product life cycle, confidence in data accuracy, performance of the calculation, multi-objective optimisation, comparability of the results, and efficient explanations. To address those challenges, we discuss three architecture variants which go beyond sequentially calling separate tools for configuration and LCA: loosely coupled (where the configurator communicates via parameters with the LCA tool), tightly coupled (where the configurator also manages the basic environmental data and lets the LCA tool calculate the impact values for assemblies), and integrated (where the LCA calculation is implemented as part of the configurator). We find that all architectures rely on complete and reliable input data (which might be synthesised offline by data-driven AI methods) and have different advantages and disadvantages concerning efforts for tool vendors, product modellers, and customers.

Keywords

product configuration, sustainability, green configuration

1. Introduction

With the European Green Deal [1, 2], the European Union drives the EU society to a more sustainable future. The EU Agenda 2050 defines environmental, economic, and social goals to be achieved by production systems [3]. Requests for Proposal (RFPs) and other B2B offers of all manufacturing companies will soon require proof of highly sustainable production and operations – due to higher awareness of customers and national authorities, and stricter laws such as the forthcoming Ecodesign for Sustainable Products Regulation (ESPR) [4] or Sustainable Products Initiative (SPI) of the EU.

To persist, companies need to document the Product Carbon Footprint (PCF) or even Product Environmental Footprint (PEF) of all their products transparently and reliably, according to valid or forthcoming regulations like the Digital Product Passport (DPP) [5]. For mass production, processes to assess the environmental impact have already been defined and standardised, e.g., Life Cycle Assessment (LCA) is standardised by ISO 14040 [6].

Product configuration [7] and Industry 4.0 architectures [8] go beyond mass production, and mass customisation allows to manufacture individualised (i.e., lot-size 1) products. The transition towards a circular economy, as required by ESPR, puts challenges to mass customisation and configuration systems, such as the promotion of circularity-based business models, integration of eco-design principles to serve sustainable business demands (i.e., green procurement), and documentation and understanding of the product's material characteristics, manufacturing processes, energy usage, and environmental impacts over the complete life cycle. Only by integrating pre-manufacturing data with data from usage and end-of-life phases can genuine circularity and optimised sustainability (e.g., maximising the product's utility while minimising waste) be reached for configurable products.

The term "Green Configuration" was established a few years ago[1] for this enhancement of configuration tools with environmental impact calculations. This gives the user comprehensive information about the specific effects of their decisions. Small changes in configuration can have a significant impact on the ecological footprint. Multi-objective optimisation strategies make it possible to optimise the product configuration according to desired dimensions (financial and sustainable) depending on specific requirements. Furthermore, provisions must be made so that the final product remains in accordance with the increasingly complex legal framework. This affects not only sales configurators (where customers shall see the expected environmental impact and corresponding costs at the point-of-sale, i.e., before they order a product) but is also vital for engineering configurators (which need to prove that the finally manufactured and deployed product keeps the promises of the sales phase to avoid penalties or non-compliance costs).

Wiezorek and Christensen [11] have given a good overview of the topic, and we will extend their work based on the current developments, e.g., by considering various types of environmental impact (not only CO_2 equivalents) and by integrating the total cost of ownership (TCO) over the complete life cycle (not only the production phase). Our goal is to find alternative architectures for combining configuration and environmental impact calculation and evaluate them w.r.t. user requirements and challenges of their application in practice.

In the next section, we will analyse the state of the art of environmental data and impact calculation. In section 3, we discuss which challenges arise when this is to be applied to configurable products. In section 4, we present the main architectures for green configuration and describe how they deal with those challenges. Finally, we conclude what this can mean for configurator vendors.

[1]The term "Green Configuration" has been used more by CPQ solution providers than in academia, e.g., by encoway [9] and CAS [10].

2. Environmental impact assessment: The state of the art

Life Cycle Assessment according to ISO 14040 [6] has been the means of choice for environmental impact assessment for products, processes, and solutions for decades. More and more LCA tools and databases are available, and LCA results are used for Environmental Product Declarations (EPDs) according to ISO 14025 [12]. Examples for commercial providers are SimaPro[2], iPoint[3], and sphera[4]. Ecoinvent[5] is an extensive database used by providers such as SimaPro. Some tools and databases target single environmental indicators only – e.g., SiGREEN [13]. ESTAINIUM[6] is an open network to exchange PCF-related data in a non-profit-oriented way.

The LCAs are based on the product's Bill of Materials (BOM) and Bill of Processes (BOP) along its life cycle. Most LCAs are done after the final product design when the materials and processes are identified. LCA can also be applied earlier in the design process of configurators to improve design decisions before finalisation.

In customer communication, EPDs are often used to show the results of the LCA. However, the EPDs are based on a specific, fully specified product or – less individually and less precisely – on a representative product, an average (fictive) product, or the worst-case product of a homogenous product family. Thus, they cannot help customers decide on product details or with customer-specific optimisation. In the best case, they can give a rough orientation based on existing LCAs for product representatives or typicals.

As EPDs are used for customer communication, Product Category Rules (PCR) and Product Specific Rules (PSR) are defined to provide comparable results [12]. PCRs and PSRs harmonise the system boundaries and provide default parameters for EPDs. However, the usage scenario to be applied in EPD refers to a fictive reference service time. This reference service defines the years of service, load, and operating hours for calculation purposes only. It does not consider the customer-specific usage conditions. Although PCR and PSR aim to provide comparable EPD results within a product category, customers still have to make an effort to relate these results to the individual life cycle conditions and make the right purchase decisions.

Besides the insufficient consideration of the customer-specific usage scenario, the broad range of existing background data sets makes it hard to figure out the product-specific environmental performance, as this is influenced by applied LCA data sets as well. The LCA data sets often provide a market average or a representative example process and do not reflect a specific supplier's product and production-specific environmental impacts. There is still a gap in using primary data along the supplier chain.

Recent initiatives[7] target the PCF accounting and management to improve the primary PCF data share in product accounting and to provide trusted and reliable data along the supply chain. However, even for PCF, several standards and guidelines are in place [14, 15] – and sufficient methods are not yet available to make the data comparable. Large-scale products may require data on millions of materials and components from thousands of suppliers across multiple industrial sectors, which poses considerable challenges to data management and performance.

As PCRs and PSRs try to harmonise the environmental impact assessment within one product category, large-scale systems such as rolling stock, production lines, or process technology are composed of products or assemblies with multiple PCRs and PSRs to be applied, which are not necessarily comparable. Inline environmental assessments are required independently of PCRs and PSRs, especially in large-scale system configuration or turnkey projects. Focusing on customer-specific usage conditions will provide tailored results. However, small changes in the conditions may significantly impact the product's LCA results.

There is little related work concerning combining LCAs with a dynamic modelling approach to consider customer-specific usage or to adapt the background database to future scenarios (cf. Udriot et al. [16] for one example). Such a scenario analyser often applies the same product configuration to multiple usage scenarios. Changes in the product configuration could be made iteratively and sequentially.

Other research reports about work on guidance to integrate LCAs in general and EPDs in particular into configurators and its evaluation in the construction sector [17]. Wiezorek and Christensen [11] suggest an architecture for integrating LCA into a configurator based on a profound analysis of sustainability assessments according to the Ecological Scarcity Method (ESM) and data from the ecoinvent database – focusing on the supply chain and manufacturing phase and mapping all impact to PCF values. A qualitative study [18] lists several advantages that sustainability-focused configurators can potentially provide.

3. Challenges of impact assessment for configurable products

Manufacturing companies need to document not only the PCF but also the PEF (i.e. more environmentally critical substances than just CO_2) of all their products transparently and reliably, according to valid or forthcoming regulations like DPP. This must be based on information from suppliers and knowledge about production processes and operations (i.e., usage and end-of-life phases) and includes the selection of suppliers and processes which minimise the overall environmental impact. In addition, economic key performance indicators (KPIs), such as costs for production, transport, usage, disposal, etc. need to be considered and require multi-objective optimisation with good user guidance (including understandable explanations).

The configuration of such an environmentally conscious system is difficult, especially for complex products, because:

- Many suppliers are involved, among them many small and medium-sized enterprises (SMEs), which often cannot provide sufficiently good documentation on materials and PEF (e.g., several thousand suppliers for parts of metro trains).
- Parts have entirely different properties as they come from different industries such as electrical, engineering, or building technology and may interpret environmental KPIs differently.
- Different countries have a wide variety of regulations and certificates (which may even change over

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[2]https://simapro.com/
[3]https://www.ipoint-systems.com/
[4]https://sphera.com/
[5]https://ecoinvent.org/
[6]https://www.estainium.eco
[7]Initiatives such as the aforementioned SiGREEN and ESTAINIUM.

time), so different solutions (i.e., combinations of components) are necessary.

- The environmental impact (e.g., concrete PEF values) depends on the production technologies and locations of the suppliers and the location of deployment and conditions at customer sites.
- Sustainability data for many components is missing or questionable, and improvement is difficult as it is out of the control of the system integrator.
- The system configuration is often not yet defined in sufficient detail at the offering time, and therefore, the environmental impacts can only be estimated but not precisely calculated.
- Adaptations during contract negotiations or after deployment can affect compliance and/or performance and require efficient re-calculation and updating of documentation.

To handle those requirements, we need algorithms and techniques for:

- Calculation of all relevant sustainability metrics at point-of-sale: This is not possible in advance (as currently done) because it depends on user decisions, which can lead to billions of potential variants. It must be fast enough to ensure a good user experience and, therefore, requires high performance.
- Reliable aggregation of the values of all sub-parts: This includes highly accurate approximations for missing values specific to the current customer selections. For the usage phase, this cannot be based on sub-parts alone (as is currently done) but on the functionality of the whole product or sub-systems.
- Guided optimisation of several objectives: It is not sufficient to calculate only one (combined, weighted) optimum (as in current tools). The user must be supported in evaluating the Pareto front efficiently and finding the best compromise for conflicting goals.
- Concise visualisation of the results: This helps the user to easily understand the impacts of their decisions. It shall explain the system's confidence in its calculations and where to change a decision to achieve a better result (which goes beyond the capabilities of current systems).

In the remainder of the text, we will focus on the following concrete challenges of Green Configuration:

1. Missing environmental data from suppliers: Many, especially smaller companies, do not yet disclose environmental data for their products (partly because they do not know them themselves). This not only concerns the supply chain, i.e., the impact of the production of those sub-parts, but also their usage and end-of-life processing. To ensure proper LCA calculation, missing data must be synthesised as accurately as possible, i.e., by specific approximations based on machine learning from similar suppliers and/or components, simulation of production and/or operation, using intelligent extrapolation which takes trends into account (e.g., new versions of components typically get better).

2. Unclear impact data for the usage phase: The environmental impact is customer- and even application-specific. It depends on the context, such as operating hours (e.g., whether an engine runs 8 or 24 hours

a day) and energy mix (e.g., how much fossil, how much wind power or photovoltaic) [19].

3. Complexity of PEF calculation: The calculation of the complete product's environmental impact (e.g., CO_2 emissions) is more complicated than just adding the corresponding values of all the parts [20]. LCA tools such as Green Digital Twin™ (GDT) [21] or SimaPro implement such details and are certified to comply with the standards.

4. Confidence in calculated data: As the input data come with a certain uncertainty, we must hand over that uncertainty to the intermediate and total values (e.g., with a confidence level or a value range). Plausibility checks (e.g., assembly cannot have less impact than the sum of parts) would be helpful.

5. Multi-objective optimisation: For the customer, it is helpful to know about the impact distribution over the phases (supply chain, production, deployment, usage, end-of-life) and separately for different impact types (energy consumption, pollution, etc.). The corresponding costs (especially TCO) over different expected lifetime periods (e.g., 10 years vs. 20 years) are vital for good decisions. This means the values for all those metrics must be tracked individually.

6. Effective explanations and user guidance: It is insufficient to simply show the user the resulting LCA and TCO values. The user must also understand the causes for those values, i.e., which of their decisions contributed most. Transparency must be established to support users in understanding the impact of a specific configuration on economic and PEF KPIs.

7. Comparability of data: Data often depends on assumptions (such as those mentioned in challenge 2), and players may use different assumptions. To make offers from different vendors comparable, those assumptions and the algorithms used must be disclosed or harmonised, e.g., according to standards such as ISO 14040 [6].

4. Comparison of architectures for green configuration

This section presents architectures with increasing degrees of integration, starting with simply using an existing configurator and feeding its results into an existing or newly customised LCA calculator. In subsections, we will discuss how each deals with the challenges from the previous section and summarise the whole section in a table at the end.

4.1. Status quo: Separate tools

A naïve approach to Green Configuration is sequential – based upon the availability of two separate tools: configurator and LCA calculator. For the configurator (i.e., the left lane in Figure 1), a modeller defines the product model (i.e., variety and dependencies) in a knowledge base (KB) by using the integrated development environment (IDE) for the configurator. A customer or salesperson uses the configurator user interface (UI) to set values to configuration parameters to fulfil their requirements. Continuously, the solver checks compliance with the KB and sets other parameters accordingly. Only when the configuration is finished, the solver hands over the resulting BOM to the LCA tool
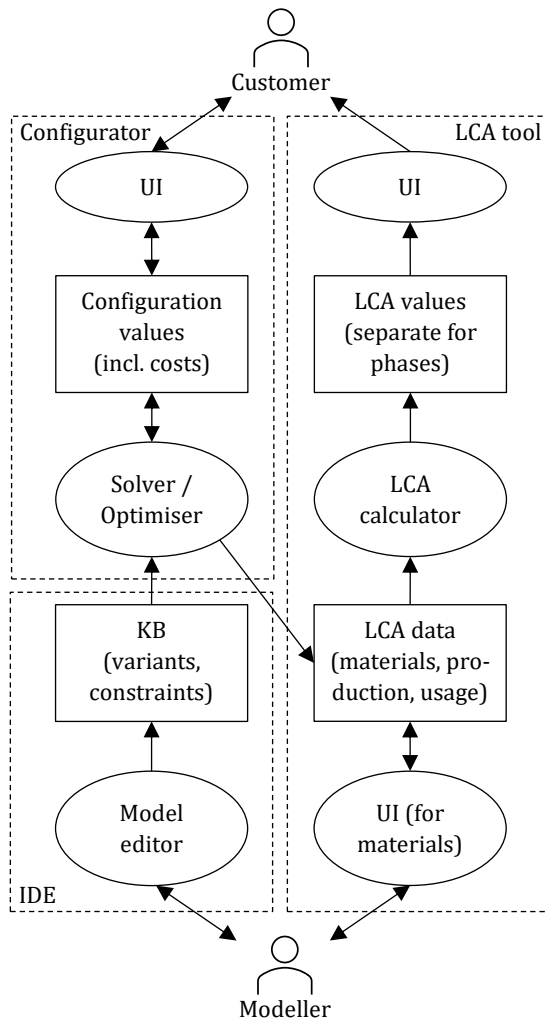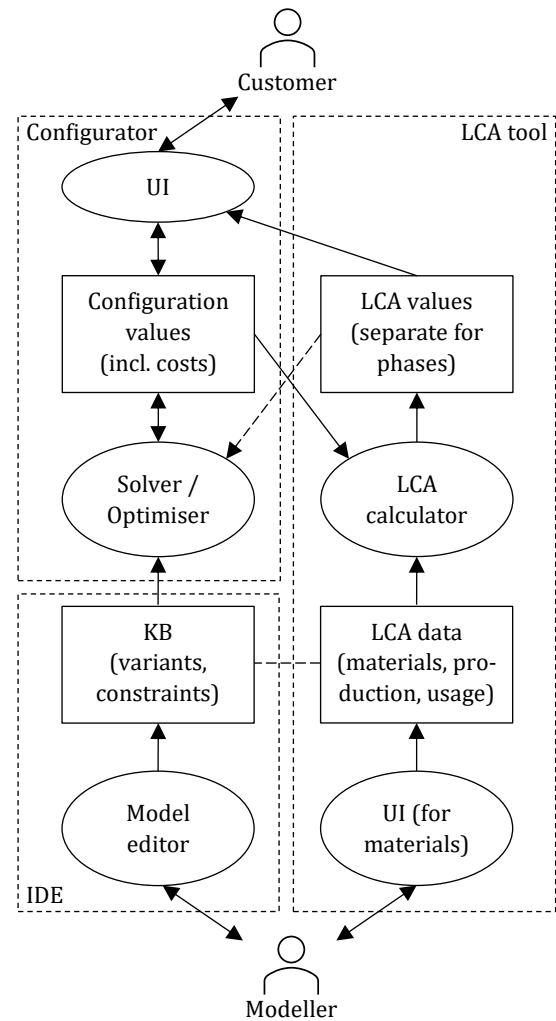
Figure 1: Sequential architecture

Figure 2: Loosely coupled architecture

(right lane). A (typically other) modeller now collects all necessary LCA data for the materials for all relevant phases (supply chain, production, usage, end-of-life) and calculates the environmental impact values for the product.

We will not go into more detail because this approach does not really combine the two tools and is impractical due to the typically long duration of the manual LCA assessment.

4.2. Loosely coupled architecture

To achieve faster results for the user, one can automate the process. Such a loosely coupled approach was taken by, e.g., Tacton [22]. It is based upon modelling the environmental impact in an LCA tool (such as SimaPro) and synchronising it with the configurator by mapping configuration features with parameters for the LCA (as sketched by the dashed line between KB and LCA data in Figure 2). After each user action in the configurator UI, the LCA calculator is called and returns the adjusted sustainability values to be shown in the configurator UI. The final LCA values may be used for optimisation, i.e., minimisation of environmental impact, in the configurator (indicated by the dashed arrow from the LCA values to the solver).

The main challenge for the configurator vendor is to define a clean generic mapping between configuration and

LCA concepts and continuously maintain this interface to comply with the evolving versions of both the configurator and the LCA tool and API. Modellers need much expertise and additional effort because they must specify the LCA model separately from the configurator model and make sure that both are in sync (i.e., define the core structure and the dynamic parameters, include all relevant materials and components, map those included components to configuration features, i.e., parameters). They may even need to involve a tool specialist, at least for the first setup of the system. The configurator users benefit from the proven LCA processes and the typically up-to-date data in the corresponding databases (e.g., ecoinvent). On the other hand, user experience may still be weak because of possibly long response times in interactive use (due to the overhead of calling an external tool and – especially for the first calls – the comparably long time to calculate the resulting value). Optimisation is challenging as the configurator cannot easily access intermediate values for sub-assemblies, thereby steering optimisation in the right direction. This loosely coupled architecture covers the challenges from section 3 in the following way:

1. Missing environmental data from suppliers: Available LCA data for the sub-parts (from suppliers), for the manufacturing tasks (in the own production

process), for various time periods in the operations phase (depending on details of usage and surroundings), and for end-of-life (e.g., recycling efforts) can be reviewed and – if necessary – extended by the modeller in the LCA tool's UI before the configuration process starts. Additionally, an external tool based on machine learning could help to synthesise data offline (this needs to be implemented by other experts).

2. Unclear impact data for usage phase: Information about expected usage can be collected as configuration data and handed over as parameters to the LCA calculator to achieve customer-specific values.

3. Complexity of PEF calculation: The LCA calculator can be trusted to comply with the rules for proper calculation (PCR, PSR).

4. Confidence in calculated data: Current LCA tools do not (yet) sufficiently inform about (missing) accuracy of values.

5. Multi-objective optimisation: LCA values of sub-parts and sub-assemblies are not available to the optimiser, which can lead to weak (sub-optimal) performance.

6. Effective explanations and user guidance: The configurator UI cannot access the internals of LCA calculation and thus cannot assist the user with explanations and recommendations.

7. Comparability of data: The LCA tool is typically certified. Therefore, the resulting LCA values are comparable to other calculations based on the same standards.

4.3. Tightly coupled architecture

Some LCA tools, e.g., Green Digital Twin™ (GDT) from Siemens, are generic and expect that the LCA data for the LCA calculation is handed over at the call. This can be used for a tightly coupled architecture, where the configurator manages the LCA data and just calls the LCA tool (see Figure 3).

Again, the advantage for the customer is that they are facing just one UI (for configuration and LCA values). But now, the same is true for the modeller (a single UI for configuration and LCA models). This means that the configurator vendor must supply such a modelling UI, which allows the binding of configuration variants to their LCA data (typically extracted from LCA data sets), and a solver which hands the LCA data for the selected variants over to the LCA calculator. The LCA calculator can even be called for parts of the product (not only for the whole product). The tightly coupled approach covers the challenges from section 3 in the following way:

1. Missing environmental data from suppliers: Similarly to the loosely coupled approach, LCA data for the relevant sub-parts can be prepared or synthesised offline.

2. Unclear impact data for usage phase: The configurator hands those LCA data over to the LCA calculator, corresponding to the customer's expected usage.

3. Complexity of PEF calculation: The LCA calculator can be trusted to comply with the rules for proper calculation (PCR, PSR).

4. Confidence in calculated data: Current LCA tools do not (yet) sufficiently inform about (missing) accuracy
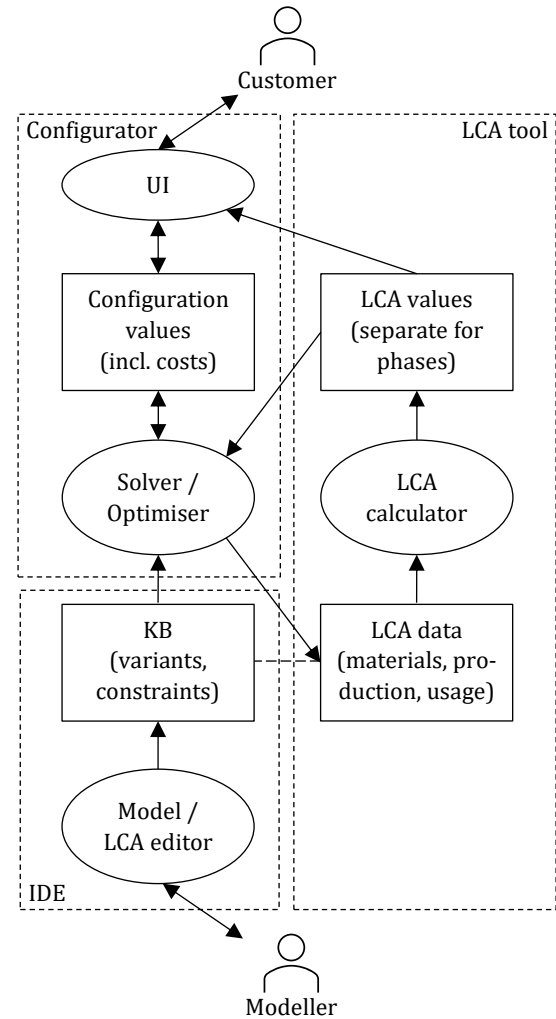

Figure 3: Tightly coupled architecture

of values, but as the solver has access to the LCA values of sub-assemblies, it can partly validate them.

5. Multi-objective optimisation: The optimiser can use the LCA values of sub-assemblies for informed heuristics.

6. Effective explanations and user guidance: The configurator UI cannot access the internals of LCA calculation but can use the LCA values of sub-assemblies for some recommendations.

7. Comparability of data: Similar to the loosely coupled approach, the LCA values are comparable to other calculations based on the same standards.

4.4. Integrated architecture

One can go one step further and directly integrate LCA calculation into the configurator by extending the modelling environment (IDE) with a component for LCA and calculating sustainability values directly in the configurator (see Figure 4). Such an approach was taken by, e.g., CAS Merlin [11, 23].

The integrated approach has the advantage that it does not need an explicit mapping to an LCA tool during modelling and can use environmental data during reasoning and optimisation to come up with a more preferred solution. On the other hand, it needs considerable effort for the
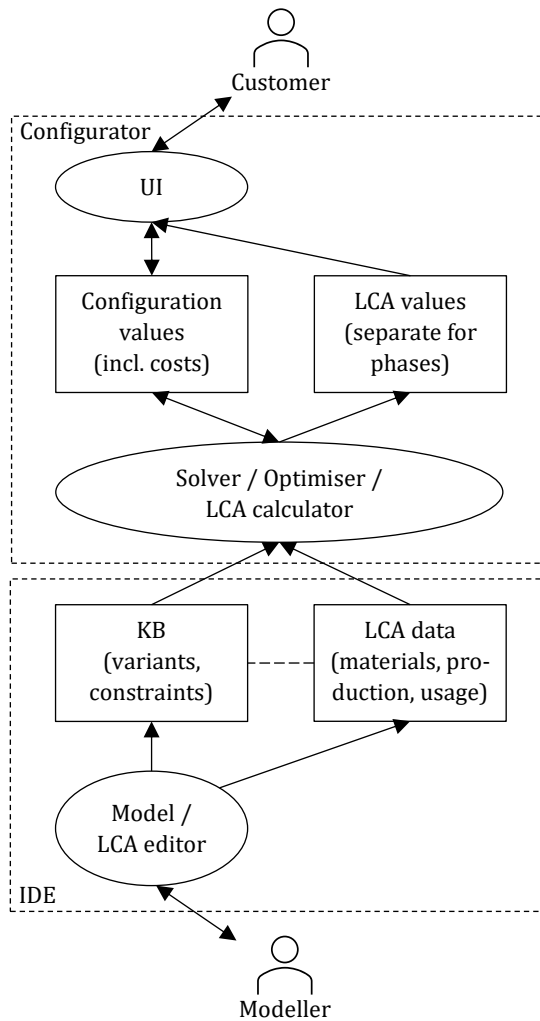
Figure 4: Integrated architecture

configurator vendor to implement the calculation, care for certification (for LCA calculation according to ISO 14040, for EPD generation according to ISO 14025), and continuously maintain it to keep compliance with standards up to date. Development efforts can be reduced if certification is unnecessary, e.g., because customers need not compare their products with competitors but only with their internal variants. The integrated approach covers the challenges from section 3 in the following way:

1. Missing environmental data from suppliers: Similarly to the coupled approaches, LCA data for the relevant sub-parts can be prepared or synthesised offline.

2. Unclear impact data for usage phase: The combined solver and calculator can directly access the expected usage information as specified by the customer to compute the LCA values.

3. Complexity of PEF calculation: Simple impact calculations (e.g., the addition of upstream) can be easily integrated into the solver. Covering the same functionality as an LCA tool and achieving certification requires much more effort by the configurator vendor.

4. Confidence in calculated data: The combined solver and calculator can keep track of the accuracy of the

calculated LCA values for assemblies if the accuracy of the input data is known or can be estimated.

5. Multi-objective optimisation: As the optimiser and LCA calculator are fully integrated, intermediate LCA values can efficiently control optimisation.

6. Effective explanations and user guidance: The complete integration of the solver and LCA calculator and full access to all their intermediate data allows for detailed explanations and recommendations.

7. Comparability of data: The extension of the solver with LCA calculation leads to highly individualised LCA values. If the configurator vendor does not achieve certification (e.g., due to high costs and/or efforts), the LCA values may not be comparable to commercial LCA tools.

4.5. Summary

Summing up, all three approaches have strengths and weaknesses when dealing with the challenges. Challenge 1 (missing data) is not discriminating, and the best way to cover it is by extending and/or improving input data offline, e.g. with the help of data-driven AI. Therefore, we rate only challenges 2 to 7 in Table 1 and use a three-valued scale – the approach has strengths, is neutral, or has weaknesses – to condense the arguments from the preceding subsections.

Table 1
Concerning the challenges, the architectures have strengths (+), are neutral (o), or have weaknesses (-)

Challenge	Loosely coupled	Tightly coupled	Integrated
2 - usage phase	o	+	+
3 - calculation	+	+	o
4 - confidence	-	o	+
5 - optimisation	-	o	+
6 - explanations	-	o	+
7 - comparability	+	+	o

The integrated approach offers more value to the customers, e.g. more optimisation possibilities and better explanations. On the other hand, this requires more effort for the configurator developer because they must implement LCA calculations (not just call existing tools or libraries) and care for the necessary certification to make the calculations transparent and comparable.

The coupled approaches take advantage of re-using off-the-shelf LCA calculators and can even hand over configuration information as parameters, but neither (especially the loosely coupled architecture) can easily integrate the calculation results into their reasoning (e.g. for optimisation and explanations). The tightly coupled architecture can access values from sub-assemblies to achieve better usability.

A product modeller may prefer the tightly coupled approach and especially the integrated approach because data management can be done with only one tool: the configurator.

5. Conclusions

Green Configuration, the combination of product configuration technologies with environmental impact calculations, is a vital approach to address sustainability challenges. We

have analysed requirements and challenges and discussed several architectures for configurators implementing a green configuration approach.

We have seen that the different architectures have different strengths and weaknesses, advantages and disadvantages. All of them are feasible and require different efforts from stakeholders, i.e., tool vendors, product modellers, and customers. From the viewpoint of a product owner, the selection of their individually preferred architecture depends on the product's complexity, the level of product customisation, the number of offers per year, the LCA impact of the usage phase, and the need to enhance customer experience and operational efficiency.

There is much room for future research on efficiently merging sustainability management with configuration lifecycle management, e.g., reference architectures, reliable data exchange, individualised impact calculation, multi-objective optimisation, elaborate standards, etc.

As one of the most important, we see the monetary assessment of PEF as a means of providing an estimate of the TCO. Visualising the monetary impact of configuration decisions over the whole lifecycle of the product will create a real incentive for the customer to choose the more sustainable product configuration (e.g., less energy costs during the operation phase). Green Configuration extended with TCO minimisation can lead to a triple-win situation: minimised total cost of ownership for the customer, increased demand for high-quality products for the industry, and less environmental damage.

Green Configuration enables the creation and scale of application-specific EPDs and DPPs based on more precise information and assumptions on the concrete product properties and usage. To make such specifically customised values comparable between tools, existing standards like ISO 14040 and the ISO 14020 series [24] need to be adapted or extended. Transparency of the individual impact values per phase and/or criterion is necessary for well-founded decisions.

Disclaimer: Much of the presented work is "thought work". Currently, we are working on prototypes to confirm the ideas and results in practice.

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