A lifecycle- and sustainability-aware product configuration model for modular industrial systems

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Abstract
The incorporation of sustainability and lifecycle information is an important aspect of modern product configurators. In this paper, we describe how to enhance a classic component-based product configuration model by integrating sustainability and lifecycle data. We also identify the relevant external data sources—such as lifecycle assessment databases, product lifecycle management systems, and environmental product declarations—that provide the necessary input. Using a prototypical MiniZinc implementation, we demonstrate how to estimate lifecycle indicators when precise values are unavailable.

Keywords
Green configuration, Sustainability, Minizinc, Power supply

1. Introduction

Building on the Green Deal [1] and its sub-policy, the Circular Economy Action Plan (CEAP) [2], the EU's Clean Industrial Deal aims to address climate and environmental challenges while enhancing Europe's competitiveness and promoting a cleaner, more sustainable future. This also affects industry and industrial production, and from a product configuration point-of-view, the Ecodesign for Sustainable Products Regulation (ESPR) [3] needs to be considered in the product configuration phase. To comply with upcoming legal requirements established through delegated domain- and sector-specific acts complementing the ESPR, methods for measuring and documenting product sustainability indicators — such as ISO-certified, LCA-based Product Environmental Footprints (PEFs) or corresponding Environmental Product Declarations (EPDs)-will eventually become mandatory in the EU. According to the ESPR, sustainability-related product information must be provided through a Digital Product Passport (DPP), which aims to facilitate more circular product and material flows by promoting transparency, accountability, and environmental governance throughout a product's lifecycle.

Following this trend in the product configuration community, the term "green configuration" [4] has been established, referring to a product customization service which also considers sustainability aspects, e.g., in the form of carbon footprinting. In light of these regulatory trends, we argue that lifecycle-related product characteristics — such as total cost of ownership, environmental impact, repairability, reusability, and recyclability — should be considered during the configuration phase.

So far, the problem has been acknowledged and theoretically analyzed from various angles (e.g., [4, 5, 6]). In this paper, we discuss how a green configuration model differs from a traditional configuration model based on an example from the industry sector. We develop a conceptual product configuration model enriched with sustainability and circularity information, which helps us identify the challenges for getting the information from external sources like sustainability databases or product lifecycle

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management (PLM) systems. For this paper, we focus on the sustainability information at a level typically found in Environmental Product Declarations (EPDs). For a more thorough discussion of the dimensions of sustainability, especially in software engineering, see [7]. Furthermore, we show how to encode the conceptual model in MiniZinc [8]. Therefore, our contribution can be summarized as follows:

1. A conceptual model for sustainability-aware product configuration, which formally integrates component data with material compositions, lifecycle phases (from manufacturing to end-of-life), and key environmental performance indicators (KPIs).
2. A practical implementation of the model in MiniZinc, demonstrating how to encode complex sustainability constraints and objectives for a real-world industrial system, enabling both validation and optimization based on environmental criteria.
3. An analysis of the data-sourcing challenges and solutions for lifecycle-aware configuration, identifying key external data sources (PEF, EPDs, DPPs, LCA services) and outlining a tiered approach for acquiring and estimating the necessary data to populate the model.

The remainder of the paper is structured as follows: Section 2 summarizes the state of the art related to this paper and introduces the fundamental concepts and definitions used throughout the paper. The lifecycle- and sustainability-aware product model is described in Section 3 and followed by our Minizinc encoding in Section 4. Section 6 concludes the paper.

2. State of the art

In the following section, we summarize the state of the art and introduce the most important concepts.

2.1. Green Configuration

The combination of "green" and "configuration" usually describes an approach that combines configuration and sustainability. For example, in [9, 10] the term "Green Configurations" appears in an approach that leads to a greener design and implementation of cyber-physical systems. In [11], the term "Green Configuration" refers to a system to reduce the energy consumption of configurable software systems. In this paper, we use "Green Configuration" in the context of product configuration as it has been defined in [4].

Green Configuration represents an innovative approach that combines conventional product configuration systems with environmental impact assessments while incorporating circular economy principles such as recyclability, repairability, and reusability. By providing immediate feedback on environmental consequences of configuration choices, stakeholders are enabled to make informed decisions. This approach supports the transition toward more environmentally conscious product designs and circular business models, optimizing resource efficiency and minimizing waste throughout the product lifecycle.

One prominent example of environmental impact assessment used in Green Configuration is Life Cycle Assessment (LCA). LCA is an ISO-certified methodology [12, 13] that evaluates environmental impacts throughout a product's complete lifecycle - from raw material extraction ("cradle") through manufacturing, distribution, and use, to final disposal or recycling ("grave"). The process encompasses a detailed analysis of energy and material flows across supply and value chains, calculating associated environmental impacts and emissions. LCAs are fundamentally based on Bill of Materials (BOM) and Bill of Processes (BOP) throughout a product's lifecycle. For decades, LCA has served as the standard for environmental impact assessment according to ISO 14040, with results typically documented in Environmental Product Declarations (EPDs) following ISO 14025. Traditionally, LCA methodologies have operated independently from product configuration processes.

Recent research in green configuration has focused on describing requirements and architectures for integrating LCA into product configurators. Comploi-Taupe et al. [4] have identified four key architectural approaches for combining configurators, knowledge bases, and LCA tools:

1. Sequential Approach: LCA is performed manually after configuration.
2. Loosely Coupled Architecture: Automated but separate LCA calculations requiring synchronization between configurator and LCA tool.
3. Tightly Coupled Architecture: Configurator manages LCA data and directly interfaces with the LCA tool, providing a unified interface.
4. Integrated Architecture: LCA calculation is fully embedded within the configurator, enabling direct environmental data usage during reasoning and optimization.

While the integrated approach offers the most seamless user experience, it demands significant development resources and continuous maintenance to ensure compliance with standards.

Wiezorek and Christensen [5] follow a similar argumentation line that configurators and LCA tools must be integrated and propose extensions to existing product configurators to support green configuration. Jakobsen et al. [6] go one step further and argue that the sustainability aspect already needs to be considered in the product configurator design phase and provide a comprehensive overview of product configurator architectures and sustainable product configuration systems.

2.2. Legal

Although product configuration can be seen as a purely technical task of combining different components to fulfill technical and user requirements (constraints), it is also necessary to consider legal requirements in the configuration process, if they were not already addressed in the product design phase. Such legal requirements are not limited to isolated aspects of product configuration but cover different topics, such as information and documentation requirements, restrictions on the usage of hazardous materials or the disassembling and disposal of products. Additionally, there might be no single legal framework to be considered in a particular product configuration project but multiple national and international legal frameworks.

The rising importance of sustainability and related topics also triggered regulatory activities from the European Union. All of the regulatory acts are supporting overarching goals as laid out in the Clean Industrial Deal [14] and its sub-policies fostering climate-neutrality and the reduction of greenhouse gas emissions. Of special interest for industry is the Green Deal Industrial Plan [15], which aims to simplify the regulatory environment, get easier and faster access to funding, enable the improvement of skills and to foster fair and open trade. Another regulatory framework is the Ecodesign for Sustainable Products Regulation (ESPR) [3] focusing on improving circularity, durability and energy performance by defining ecodesign requirements to better meet the material and procedural demands of circular product design and end-of-life handling. Measures are laid out in the ESPR to achieve these requirements, such as the Digital Product Passport (DPP), which serves as a digital identity for products (including components).

In addition to the more general initiatives regarding sustainability and circular economy, prominent regulatory acts are the Waste from Electrical and Electronic Equipment (WEEE) [16] outlining the requirements on how waste has to be handled to protect humans and the environment. In particular, there are more specific regulations regarding different types of waste, for instance glass cullet [17] or metal scrap [18, 19]. Since there are more and more devices equipped with batteries, there is also a regulation laying out the requirements for the safe operation and disposal of batteries [20]. The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation [20] is another example to enhance safety by putting restrictions on the handling of chemicals. Similarly, the restriction of the use of certain hazardous substances in electrical and electronic equipment directive (EEE) [21] focuses on hazardous substances in electric equipment. Furthermore, the Green Claims Directive [22] will require companies to substantiate environmental claims which will also affect services such as product configurators.

In addition to regulatory acts from different legislative bodies, there are also activities from standardization organizations, for instance the International Standardization Organization (ISO) to be considered.

The standards ISO 14020 and 14025 are relevant for the generation of Environmental Product Declarations, ISO 59040 is dealing with circular economy and ISO 59014 with material sustainability.

2.3. Data Sources for Green Configuration

Product configuration typically relies on multiple interconnected data sources that provide the structural, commercial, and logical foundation required to define and validate a specific product variant. In configuration environments, especially those aligned with sustainability goals, these core data categories are increasingly complemented by sustainability and lifecycle data. The following sections outline the key data categories and their typical sources.

2.3.1. Configuration Rules & Constraints

These represent the logical and business dependencies that govern valid product configurations. Constraints define which combinations of components are allowed, required, or excluded. This information is usually maintained in knowledge bases, rule engines, or Product Lifecycle Management (PLM) systems and ensures that only technically valid and manufacturable configurations are generated.

2.3.2. Product Master Data

Sourced from Enterprise Resource Planning (ERP) or Product Information Management (PIM) systems, this includes product identifiers, descriptions, technical attributes, lifecycle status, and classification. It forms the foundation of the configurable product catalogue.

2.3.3. Bill of Materials (BOM)

Maintained in ERP or PLM systems, the BOM describes the hierarchical structure of a product, listing its components and subcomponents. It establishes the link between the configuration process and downstream manufacturing and procurement operations. For Product Configuration, a Maximum Bill of Materials (also known as 150% BOM) is required to encompass all possible product variations and options within a single structure. This comprehensive 150% BOM acts as the foundation for product configuration, enabling the definition of variants and options while managing dependencies between components. Through configuration rules and variant conditions, specific 100% BOMs can be derived for individual product variants, ensuring accurate representation of each product configuration.

2.3.4. Pricing Data

Originating from ERP systems or dedicated pricing engines, pricing data includes base prices, option surcharges, discount rules, regional pricing, and tax logic. This data supports real-time, customer-specific price calculation during the configuration process. Product configuration systems integrate sophisticated pricing mechanisms that dynamically adjust prices based on component combinations and their interactions. The systems process customer-specific pricing agreements and implement volume-based pricing tiers while supporting multi-currency calculations for global operations. For customized configurations, specific pricing models ensure appropriate pricing of unique product variants, while maintaining consistent margin calculations. The pricing engine adheres to established business rules and manages approval workflows for special configuration requests, ensuring accurate pricing across all possible product variants.

2.3.5. Inventory & Availability Data

Sourced from supply chain management or ERP systems, this includes real-time stock levels, lead times, and supplier availability. It enables feasibility checks and supports delivery date estimation for configured products. The system continuously monitors component dependencies to ensure that proposed configurations can be manufactured with available materials. Real-time inventory checks during the configuration process help prevent the creation of product variants that cannot be delivered within acceptable timeframes. Additionally, the system considers production capacity constraints and alternative sourcing options when determining component availability. This integration enables accurate promise dates for customized products while maintaining efficient inventory management across different configuration scenarios.

2.3.6. Sustainability and Lifecycle Data

In addition to data for traditional product configuration, Green Configuration requires sustainability and lifecycle data as a crucial data category that captures key environmental and circular economy-related information. This data category can include various environmental impact metrics such as carbon footprint, energy and water consumption, and material toxicity. It also might cover circular economy aspects like recyclability rates, material recovery potential, and product durability. Additionally, it encompasses regulatory compliance information, including supplier declarations and certifications. Such data can be sourced from various providers and is increasingly critical for aligning product configurations with sustainability goals and legal requirements. However, significant challenges remain in the practical implementation of these data sources. Many companies do not yet disclose environmental data for their products, partly because they do not know them themselves. This results in missing environmental data concerning the supply chain, usage, and end-of-life processing. Furthermore, the required data is often incomplete, with some components needing to be manually disassembled and weighed because suppliers do not provide corresponding data. The calculation of lifecycle assessments relies on comprehensive databases that contain environmental impact data for materials, processes, and energy flows. Key databases include Sphera (GaBi)[1], which provides detailed lifecycle inventory data for thousands of materials and processes across industries. The ecoinvent database[2] is another widely used source containing over 17,000 datasets with cradle-to-gate and cradle-to-grave environmental impacts. These databases include information on greenhouse gas emissions, resource depletion, water consumption, land use changes, and other environmental indicators. They follow standardised methodologies like ISO 14040/44 and are regularly updated to reflect technological advances and improved data quality. Regional databases like the European Life Cycle Database (ELCD) or the U.S. Life Cycle Inventory Database (USLCI) provide location-specific environmental impact factors. These databases are essential for conducting scientifically sound LCA calculations during product configuration and enable the comparison of different material choices based on their environmental impacts.

AAS-Based Data Provider The Asset Administration Shell (AAS)[3] is a standardized digital representation of a physical or logical asset, as promoted by the Industrial Digital Twin Association (IDTA) in Germany [23]. The AAS encapsulates all relevant data and services across the asset's Lifecycle providing a digital twin of a product. AAS supports a modular structure through submodels, which can represent specific sustainability aspects, such as carbon footprint or recyclability scores of a component. Thus, AAS-based services can be used to expose sustainability data as part of a product configuration.

Digital Product Passports from 3rd parties The Digital Product Passport (DPP) is a standardized, uniquely identifiable, digital record of a product introduced by the UN (as part of the UN Transparency Protocol [24] and currently adopted by the European Union as part of its ecodesign regulations [3]. It shall facilitate the sharing of product information among the stakeholders of a product's lifecycle by providing - among other things - highly granular, structured, machine-readable data on circularity-related product parameters such as material composition, substances of concern, environmental impacts, repairability, and end of life (EoL) treatment. Leveraging DPP data within the configuration process enables more informed, sustainable product choices, especially when selecting materials and components from 3rd party providers during the manufacturing phase.

[1]https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/
[2]https://ecoinvent.org/database/
[3]https://reference.opcfoundation.org/I4AAS/v100/docs/4.1

LCA Service A Life Cycle Assessment (LCA) service evaluates the environmental impact of products across their entire lifecycle — from raw material extraction to end-of-life. In product configuration, it enables the calculation of product-specific environmental impact indicators such as carbon footprint, energy use, and water consumption for different variants along pre-specified product category rules [25]. This allows for instant feedback on the sustainability impact of the user decisions and supports environmentally responsible choices. LCA services also provide verified data for integration into Digital Product Passports (DPPs), ensure compliance with regulations like the ESPR, and can generate standardized documentation such as ISO 14025 compliant Environmental Product Declarations (EPDs) or Product Environmental Footprints (PEFs) as mandated by the European Union [26]. Overall, they support informed decision-making for eco-design and sustainability optimization.

3. A sustainability enhanced configuration model

Stumptner et al. [27] define product configuration as the assembly of a complex system from simpler predefined components to satisfy some given user requirements. We add sustainability requirements to the basic product configuration model and describe the conceptual sustainability-aware product configuration model with UML [28].

The evolution of product configuration systems reflects a significant shift in focus over time. While early configurators primarily concentrated on ensuring technical feasibility – configurators were designed to validate whether a specific combination of components could function together effectively from a technical perspective – modern configuration approaches have expanded to address multiple optimization criteria. Today's configuration systems take a more comprehensive approach, considering various optimization goals beyond technical requirements. These include economic factors such as cost minimization, operational aspects like energy efficiency, and practical considerations such as ease of maintenance and serviceability. The optimization criteria have further evolved to include environmental impact, resource efficiency, and lifecycle considerations.

Green Configuration represents a holistic approach that integrates sustainability aspects into the configuration process. This approach considers not only the immediate technical and economic factors but also long-term environmental impacts, resource consumption, and end-of-life scenarios. By incorporating sustainability metrics into the configuration process, organizations can optimize their products for both performance and environmental responsibility. This includes considerations such as carbon footprint, material recyclability, energy efficiency during operation, and the overall environmental impact throughout the product's lifecycle. The goal is to find configurations that balance technical requirements, economic viability, and environmental sustainability in an integrated way.

In the following, we will make the information needed for sustainable product configuration more explicit. This way we can provide feedback, how the user decisions influence the sustainability of the configured product. We can not expect to assess the sustainability of a configured product in the same detail as it is done in a full lifecycle assessment process (LCA).

Still our main goals are:

- Compare configurations based on environmental KPIs across lifecycle phases
- Verify compliance with environmental regulations
- Allow specification of material constraints (e.g., hazardous substance restrictions)
- Identify key components and phases with highest sustainability impact
- Evaluate impact of various usage scenarios
- Represent end-of-life, recycling, and circular economy options

3.1. Example SITOP PSU8600 Power Supply System

As a running example, we use the task of configuring the industrial SITOP PSU8600 power supply system by Siemens.[4] This advanced modular and expandable system efficiently converts alternating current (AC) to stable direct current (DC) output, featuring high conversion efficiency and reliability for industrial applications.

An optimal SITOP PSU8600 system variant can be configured based on several critical technical requirements:

- **Input voltage specifications** – Supporting diverse power grid standards
- **Output parameters** – Precise current and voltage requirements for connected equipment
- **Environmental factors** – Operating temperature constraints and installation conditions
- **Power reliability** – Buffer load capabilities for system stability
- **Industrial networking** – Connectivity features including PROFINET or standard Ethernet integration

A SITOP PSU8600 variant comprises multiple components called modules that can be combined according to defined technical constraints. The UML class diagram in Figure 1 illustrates the components of the SITOP PSU8600 system considered in this paper and their interrelationships. Each SITOP PSU8600 system requires exactly one basic module. Up to four expansion modules can be added to the system. To safeguard the system against small power failures (up to several seconds) buffer modules can be added. For longer power outages, up to two Uninterruptible Power Supply (UPS) modules with max. five batteries are possible.

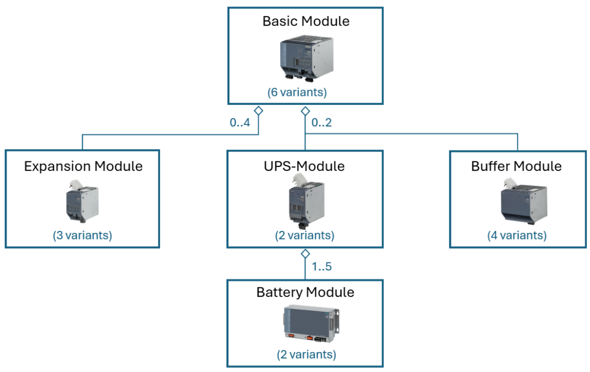

Figure 1: SITOP PSU8600 UML diagram

3.2. Materials

The material composition is an important part of the sustainability of a product. In the manufacturing phase the used materials impact the KPIs, e.g., CO_2 emission caused by providing the material. Problematic and hazardous substances impact the end-of-life phase. The materials of a component might either be fixed for supplied parts or variable for generic components, e.g., components whose dimensions can be configured. Figure 2 depicts a configuration model augmented with material information. To keep the model simple the class `Component` represents anything from products, assemblies to supplied (hardware) parts. Components can have materials and sub components.

`LCAScope` defines the lifecycle phases (`LCAPhase`) considered in the current `Configuration`. The class `Material` defines the amount of a Material used in a component or in a `MaterialAllocation`.

[4]See the SITOP PSU8600 product information at: https://mall.industry.siemens.com/mall/en/WW/Catalog/Products/10251281.

The class `MaterialAllocation` corresponds to additional material that cannot be assigned to a component, but is required only during one of the lifecycle phases, e.g., packaging material, consumable materials...

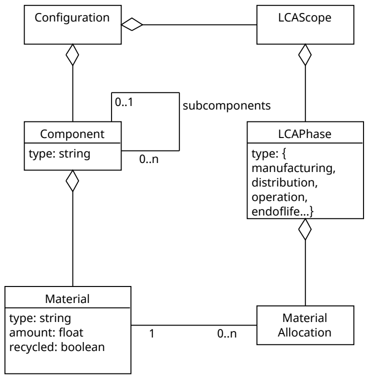

Figure 2: Configuration model with materials

Each component is composed of an arbitrary number of materials. The level of granularity regarding the used materials depends on the available information. In cases, where the material composition of sub-components is not known, the material information of a component just contains the aggregated values of the used materials in the sub-components. The aggregated materials of the whole configuration corresponds to the material composition that is reported in EPDs. For instance, in the PLM model (Siemens Teamcenter) the SITOP PSU8600 basic module of a given type is comprised of hundreds of sub-components, such as electronic parts, housing and so forth.

This detailed information is only relevant, if there are some constraints on the sub-components or the user wants to have insights on the material composition of the product. An simplified example for the material composition of a SITOP PSU8600 basic module is shown in Figure 3. The information about the materials is taken from the EPD of the basic module and lists the different types of materials and their weights.

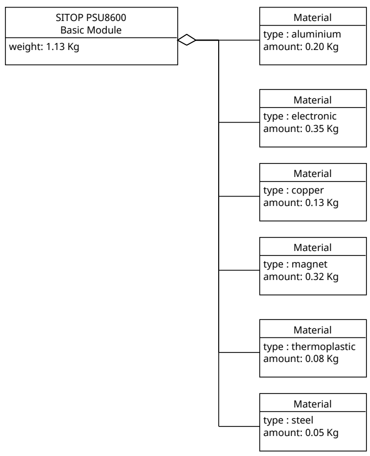

Figure 3: Basic module material example

3.3. KPIs and Lifecycle Phases

Another important aspect of LCAs and EPDs are key (environmental) performance indicators (KPI). They indicate the environmental impact and resource consumption of the configured product during specific lifecycle phases.

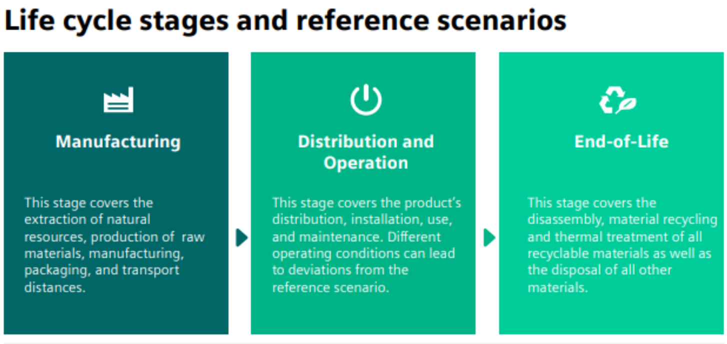

Figure 4: SITOP PSU8600 lifecycle phases (as defined in the EPD)

For the running example of this paper we use the lifecycle model of the EPDs of the SITOP PSU8600 system.[5] (Figure 4). In the EPD different phases are aggregated into one stage. For example raw material extraction, production of raw materials, manufacturing, packaging and transport are summarized in one manufacturing stage.

The LCA of a product typically covers the entire lifecycle, from cradle-to-grave. In a product configurator not every lifecycle phase will be considered depending on the configuration scenario.

For instance, in a sales configurator the manufacturing phase and the usage phase are the most important phases. Information about the detailed end-of-life options are very customer specific and may not be available to the sales configurator. However, at least information about the circularity and recyclability of the product can be provided. In contrast, in an in-house engineering configurator not only the usage but also circularity and end-of-life aspects are typically known as they are managed inside the organisation.

As can be seen in Figure 5, a KPI is assigned to a component and a LCA phase. On the configuration level these values are aggregated to KPIs per lifecycle phase and subsequently a total KPI can be computed. For our SITOP example, the estimation of the global warming potential (GWP) of the manufacturing phase of the configured SITOP PSU8600 system is the sum of the (manufacturing) GWPs of the components used in the configuration.

3.3.1. Manufacturing

For supplied components/products, we can expect to get data from existing EPDs or if available from a DPP (on the model level). In the case of the SITOP PSU8600 system the data can be taken from the published EPDs or from in-house tools like the green digital twin (GDT).

In the case of third-party components where this data is not available, we could still use approximate data for the type of product from environmental databases. The data is expected to be more accurate if a more specific type of product is considered. For example, when estimating values for a specific variant of a SITOP PSU8600 basic module, using data from another variant of the same basic module would be more accurate than using data from a SITOP CNX8600 expansion module. For the estimation of KPIs related to transportation, information about the shipping routes for the supplied parts and materials as well as the location where the configured product is assembled, is required. Data for common ways of transportation (air, container ship, rail) are standard in all environmental databases and LCA tools. Although one could define very sophisticated transport models, for the sake of the configuration scenario considering the distances and the mode of transport should be sufficient. Remember that accurate values are only required if it helps to find the most sustainable configuration among the possible configurations satisfying all the user requirements. If, for instance, in an engineering context there is only a single supplier with a single shipping site the exact values are not important. A sophisticated approach would be to analyze existing transport data and create a machine learning model for the most

[5] The EPD can be downloaded from https://support.industry.siemens.com/cs/ww/en/view/109824794.

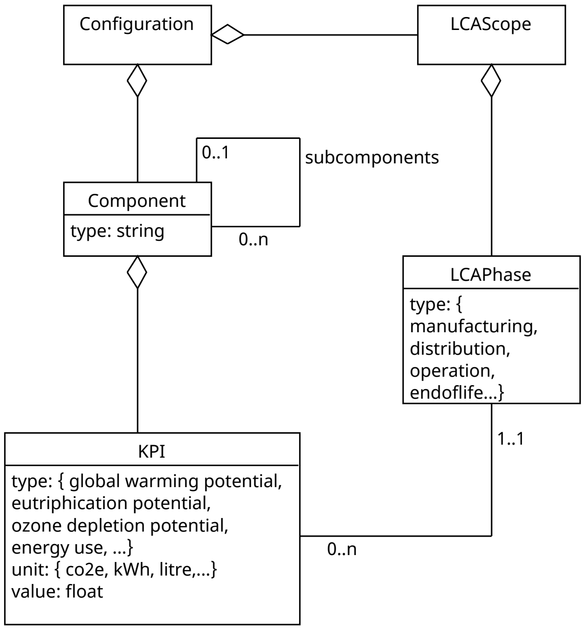

Figure 5: Configuration model with KPIs

likely mode of transport of products of type X from A to B.

The KPIs for production of raw materials and manufacturing the configured product can range from simple (consumer products) to highly complex, e.g., the production of a configured railway interlocking system. LCA of production and manufacturing must consider bill of processes (BOP), factory data (assembly lines). The LCA of complex systems, such as railway interlocking systems, involves additional factors like construction work, road work, and specialized equipment. Modeling this information within a product configuration scenario is unrealistic. Therefore, a product configurator must either access data from existing (parameterized) LCA calculations or rely on rough estimates.

3.3.2. Distribution and Operation

The transportation aspect of distribution is essentially the same as previously discussed in the manufacturing phases. An additional aspect is packaging as this requires additional (hopefully recyclable or reusable) material.

The impact of the usage phase is very specific to the configured product and the intended usage of the configured system. This is the phase where user requirements typically have the greatest impact. The KPIs for the usage phase are often specified for a defined time period (e.g., 10 years) and usage scenario (e.g., 24/7 operation). For electrical components the most basic calculation of the GWP is the energy demand of the component multiplied with the usage time multiplied by the GWP of the energy source. However, the situation is more complex in practice. Under a naive calculation a configuration with less components will have a better GWP KPI. But introducing components such as buffer modules increases the reliability of the entire system. Without buffer modules short drops in electricity (brown out) can lead to failures in industrial processes and negatively impact the sustainability of the production process as a whole. One way to communicate this to the user is through multi-objective optimization; specifically, showing the relationship between system reliability and sustainability in the case mentioned above.

For long-running systems, obsolescence considerations are a critical aspect of this phase, particularly in determining the number of components that will require replacement within the given time-frame based on their expected life expectancy. Repairability and spare parts availability significantly influence the usage phase. However, developing metrics to quantify these aspects remains challenging. Upcoming standards like the DPP will define some standard KPIs to measure these circularity aspects.

3.3.3. End of life

The minimum requirement for end-of-life treatment of products are landfills or thermal dissipation. The more sustainable option is to disassemble the product and recycle as much of the components as possible. Still better one of the R-strategies of the circular economy [29], i.e., reuse, remanufacture or refurbish should be applied to the product or its sub-components.

4. MiniZinc Encoding

In this section, we show the implementation of the running example in MiniZinc using our conceptual model.

4.1. Components and BOM generation

The MiniZinc encoding is simple and only serves the purpose of illustrating the sustainability enhanced aspects of the configuration model. In practice, a more generic and sophisticated encoding should be used, e.g., an encoding based on an object-oriented formalism.

Listing 1 shows how components and their quantities are encoded for the SITOP PSU8600 example. The cardinality constraints are taken from Figure 1.

Listing 1: MiniZinc Encoding of components

```
enum SITOPComponent = {
  % top level component
  BaseModule,
  ExpansionModule,
  BufferModule,
  UPSModule,
  % sub component
  BatteryModule
};

array[SITOPComponent] of var 0..10:
  component_quantity;

var 0..5: UPSModule1_nrofbatteries;
var 0..5: UPSModule2_nrofbatteries;

constraint
  component_quantity[BaseModule] = 1;

constraint
  component_quantity[ExpansionModule] <= 4;

constraint
  component_quantity[BufferModule] +
  component_quantity[UPSModule] <= 2;

constraint
  UPSModule1_nrofbatteries>0 <->
    component_quantity[UPSModule]=1;

constraint
  UPSModule2_nrofbatteries>0 <->
    component_quantity[UPSModule]=2;
```

```

constraint
  component_quantity[BatteryModule] =
    UPSModule1_nrofbatteries +
    UPSModule2_nrofbatteries;
```

4.2. Encoding of Materials

The materials of components are modelled with a table that contains the amount of material that is included in every component. This amount is considered fixed, i.e., for this simple example there is no variability. In a more realistic example the dimension of a component might be configurable, e.g., the length of a cable, and therefore the materials would also be dynamic. Based on the selected components and the material table the total amount is computed. This allows the easy formulation of constraints about the material content of the configuration, like the one in Listing 2 which states that the configuration should not contain any hazardous materials.

Listing 2: MiniZinc

```
enum Material = { aluminium,
  electronic,
  copper,
  lead };
enum Component_Material =
  { componentid, materialid, gram };

array[int,Component_Material] of int:
  material_table;

material_table =
     [| BaseModule, aluminium, 20,
      | BaseModule, electronic, 35,
      | BaseModule, copper, 13,
      %...
|];

int : material_table_rows =
  length(material_table) div 3;

array[Material] of var int: total_weight_material;

constraint
  (forall (m in Material)
  (total_weight_material[m] =
    sum([material_table[r, gram] *
         component_quantity[
         to_enum(
         SITOPComponent,
         material_table[r,
           componentid])] |
        r in 1..material_table_rows where
        material_table[r,
          materialid] = m])));

var set of Material:
  hazardous_materials = { lead };

% example:
% configuration should contain no
```

```
% no hazardous materials
constraint
  (forall (m in Material)
  (if total_weight_material[m]>0
  then not (m in hazardous_materials)
  else true endif));
```

4.3. Distribution

For the distribution phase, we can model the impact of transporting the final product from the assembly location to the customer. This involves defining different modes of transport, their respective environmental impact factors (e.g., kg CO_2-eq per ton-kilometer), and the total weight of the configured system. Listing 3 shows a simple implementation where the model can choose a transport mode based on user requirements or optimization goals.

Listing 3: MiniZinc

```
% available transport modes
enum TransportMode = {TRUCK, TRAIN, AIR};

% transport mode
var TransportMode: transport_mode;

% GWP in kg CO2-eq per ton-km for each transport mode
array[TransportMode] of float: transport_gwp_factor = [0.08, 0.02, 0.5];

% distance to customer in km (can be a user requirement)
float: distance_km = 1000.0;

% total weight of the configuration in kg (calculated from materials)
var float: total_weight_gram = sum(m in Material)(total_weight_material[m]);

% calculated GWP for the distribution phase
var float: distribution_gwp =
  transport_gwp_factor[transport_mode] * (total_weight_gram / 1000.0) * distance_km;

% example constraint: for urgent deliveries, air freight is required.
% constraint transport_mode = AIR;
```

4.4. Usage

The impact of the usage phase is highly dependent on the efficiency of the product and the operating scenario of the user. For the SITOP PSU8600, the primary environmental impact during usage stems from energy loss (heat dissipation), not the energy it delivers to other components. We can calculate this by taking the energy consumed by the power supply itself and multiplying it by an impact factor for the electricity grid. Listing 4 demonstrates this calculation.

Listing 4: MiniZinc

```
% efficiency of the basic module (can depend on the selected type)
param float: base_module_efficiency = 0.95;

% user requirements for usage profile
param float: avg_power_output_kw = 2.0; % Avg. power delivered
param float: lifetime_h = 43800; % e.g., 5 years of 24/7 operation

% environmental factor for the electricity grid (e.g., from EPD or database)
% kg CO2-eq per kWh
```

```
param float: grid_gwp_factor = 0.4;

% total energy delivered over the lifetime
var float: total_energy_delivered_kwh = avg_power_output_kw * lifetime_h;

% total energy consumed by the PSU
var float: total_energy_consumed_kwh = total_energy_delivered_kwh /
    base_module_efficiency;

% total energy lost as heat
var float: energy_loss_kwh = total_energy_consumed_kwh - total_energy_delivered_kwh;

% calculated GWP for the usage phase
var float: usage_gwp = energy_loss_kwh * grid_gwp_factor;
```

4.5. End of life

The end-of-life phase considers the environmental effects of disposing of, recycling, or reusing the product's materials. Different treatments yield different impacts; for instance, recycling metal often results in an environmental credit, avoiding emissions from virgin material production. Listing 5 models this by allowing a choice of end-of-life option for each material and calculating the resulting environmental impact. The effects of more sophisticated R-strategies like reuse, remanufacturing, refurbish on the GWP are too difficult to calculate in a configuration model. Regardless components to which these R-strategies can be applied should be preferred in the configuration either by modeling the options as boolean or giving them an "estimated" GWP value that is lower than the other EoL options.

Listing 5: MiniZinc

```
% End-of-Life options
enum EoL_Option = {LANDFILL, INCINERATION, RECYCLING};

% choose an EoL option for each material
array[Material] of var EoL_Option: eol_choice;

% GWP impact per kg of material for each EoL option (kg CO2-eq/kg).
% negative values represent credits from recycling.
% this data would come from LCA databases.
array[Material, EoL_Option] of float: eol_gwp_matrix =
  [| % Columns: LANDFILL, INCINERATION, RECYCLING
      0.02, 0.05, -1.5,   % for Aluminium
   |  0.05, 0.20, -0.8,   % for Electronics (simplified)
   |  0.02, 0.04, -2.8,   % for Copper
   |  0.04, 0.06, -3.5,   % for Steel
   |  0.5, 0.70, 0.70,    % for Lead
     %...
   |];

% calculated GWP for the end-of-life phase
var float: eol_gwp = sum(m in Material) (
    (total_weight_material[m] / 1000.0) * eol_gwp_matrix[m, eol_choice[m]]
);

% example constraint: Maximize recycling
constraint forall(m in {aluminium, copper, steel})(eol_choice[m] = RECYCLING);
```

5. Discussion

From a representational standpoint, constraints concerning sustainability are not different from constraints expressing technical restrictions or user requirements. The main difference is that exact values might not be available for the sustainability parameters. This is not a problem as long as the orders of magnitude are correct.

Since we cannot call external functions when solving a MiniZinc model, we have to gather the required sustainability data (material composition, carbon footprint, etc.) before we start the solving process. Then we can use multi-objective optimization to find the most sustainable (Pareto-optimal) configuration(s). In practice, there can always be contradictory objectives, e.g., avoiding hazardous substances vs. low carbon footprint. The final decision about which configuration to select is up to the user.

If the number of possible configurations for the given user inputs is relatively small (<=10) , we can alternatively ignore the sustainability aspects during solving and assess the sustainability of the found configurations with an external API afterwards.

6. Conclusions

The purpose of our sustainability-enhanced configuration model is to give the user an indication of how their requirements and selections affect the sustainability of the configured product.

While this approach does not replace a full LCA, carefully modeling sustainability parameters allows the configurator to suggest solutions that are likely to be sustainable both in the LCA and in real-world usage.

Currently the necessary sustainability data for the possible components of a configured product must be collected from various sources (EPD, LCA, sustainability databases, in-house tools). Sometimes this data is not even available in machine readable form, e.g., the documents of the EPDs.

Upcoming standards like the DPP ease this process as the necessary data will then be available in a digital form via standardized APIs. This should enable us to get most of the required sustainability information of the configuration model in an automated manner.

The DPP will also contain life data from the usage and end-of-life phase, which allows the comparison of the expected values for the KPIs with the actual KPIs measured in the product lifecycle.

The configuration model is not limited to first-time configuration. Once a sustainability-enhanced configuration model is established interesting reconfiguration scenarios are possible, e.g., replacing sub-components with more sustainable components that might not have been available at the time of the initial configuration. The changes in the configuration will then be reflected in an updated DPP.

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Declaration on Generative AI

During the preparation of this work, the author(s) used generative AI in order to: Grammar and spelling check. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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