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Abstract

Global temperature rise, and growing consumption of limited resources are global threats. Therefore, industry and consumers will need to reduce their environmental impacts. For this Product Environmental Declarations (EPD) are used for eco design and product impact comparison. As EPDs are likely to become mandatory the total number of products to be assessed will increase tremendously. Therefore, the entire EPD workflow will need to be automatized to allow large-scale application of EPDs. The goal of this thesis is to develop an automated workflow for EPDs (aEPD) by combining Model-Based-Systems Engineering (MBSE), Digital Twin and Life Cycle Assessment concepts. While MBSE is used for the multilevel requirements analysis the focus was set on automating data collection along the supply and value chain using the AAS 4.0 Implementation of the Digital Twin concept. The applicability of the aEPD workflow is shown in the prototypical implementation of an aEPD for an electric motor. Even though progress has been made research should be continued in the development of further AAS Submodel templates and PCRs to allow standardized data collection and communication on a global scale.

Keywords: Digital Twin, Asset Administration Shell, Model-Based Systems Engineering, Life Cycle Assessment, Environmental Product Declaration

Originality Statement

‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at TUKL or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at TUKL or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation, and linguistic expression is acknowledged.’

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List of Abbreviations

AAS	Asset Administration Shell
AASX	Asset Administration Shell Explorer
aEPD	Automated Environmental Product Declaration
BOM	Bill of Material
CF	Carbon Footprint
CEAP	Circular Economy Action Plan
DM	Digital Master
DS	Digital Shadow
DT	Digital Twin
EPD	Environmental Product Declaration
ERP	Enterprise Resource Planning
EU	European Union
GHG	Green House Gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCF	Product Carbon Footprint
PCR	Product Category Rule
PEF	Product Environmental Footprint
PEP	Product Environmental Profile
PSR	Product Specific Rule
MBSE	Model-Based Systems Engineering

1 Introduction

The first chapter discusses the need for automated environmental product declarations to improve the overall environmental performance by enabling large-scale environmental product assessments. The general background and correlated problems are highlighted with a set of research questions. Promising concepts such as Model-Based-Systems-Engineering, Digital Twin and Life Cycle Assessment are introduced as basis for the development of a holistic workflow for an automated Environmental Product Declaration. Finally, the scope of this master's thesis is elucidated, and its structure is outlined.

1.1 Motivation and Problem Description

Some of the biggest planetary challenges for today are the fight against the global temperature rise, increasing environmental pollution and ever-growing consumption of limited resources [EU, 2022]. Even worse, the overall population and world economy is growing at the same time. In combination, global resources are reduced faster on average then they can be recreated by natural processes. Gradually but steadily, humans destroy their own living environment.

This fact is largely recognised by science and politics which increase their efforts to transform the global linear economy to become more circular and more sustainable overall. [EU, 2022]

The European Green Deal including the EU's Circular Economy Action Plan (CEAP) sets many initiatives to foster this economic transformation on several ways e.g., Product Environmental Footprints and Digital Product Passports. [EU, 2022]

Regulations, policies and environmental targets as well as an increased public awareness in matters relating to sustainability have increased the pressure on companies to make sustainability a prime parameter in production and other company activities [Hermann, 2010]

As a consequence, industry will need to reduce the environmental impact of their production and products but also consumers will need to adapt their consumption and use behaviour. [Chen et al., 2021; Eigner et al., 2011].

In order to enable consumers and industry to manage this transformation, metrics and indicators must be determined and reported to allow all stakeholders controlling their impacts along the product life cycles. [Chen et al., 2021]

For this reason, Product Environmental Declarations were developed and are already applied in several industries. On the one hand EPDs are an important tool for companies to evaluate their products environmental performance and thereby the support of eco design. On the other hand, the declaration scheme allows comparability of different products. EPD's therefore, deliver customers a supportive tool for taking sustainable purchase decisions based on defined sustainability metrics. [Del Borghi, 2013]

The use of EPDs will significantly increase as more and more countries change from voluntary to mandatory EPD assessments. In addition, the European Commission is likely to announce some kind of obligation for the application of the PEF in the near future [Schenck, 2009; iPoint, 2022a]. While EPDs are generally well established they are currently only performed for a small number of products due to the immense costs that occur for data collection and EPD creation. [Schenck, 2009]

The high costs currently come from the large amount of manual data collection across all life cycle stages but especially from raw material creation and manufacturing due to complex and multi-level global supply chains. Currently the information is often distributed across a global network of data handling and Enterprise Resource Planning Systems with different set ups and naming conventions. Both hinder automated data collection and exchange across several value chain partners and require case specific data collection procedures. In other cases, information is not available at all and has to be derived by literature research or estimations. [Eigner et al., 2011; 2021]

As mandatory environmental declarations become real for all kind of products the total number of products to be assessed as well as the associated costs for companies will increase tremendously. [Schenck, 2009]

Therefore, the entire EPD workflow will need to be automatized to allow large-scale application of product environmental assessments. Only this will bring down the costs and personal resources to a level that creating EPDs becomes possible for almost all new products at all. [Sundaravaradan et al., 2011]

Automation of workflows and certain activities is already a focal point of interest but currently limited to individual concepts or interfaces [Riedelsheimer et al., 2021] and mostly looked at from only one perspective. For instance, EPD automation in the building sector can already be done with a specialised building tool. [Chen et al., 2021]

However, the full workflow has not yet been considered by looking for concepts and solutions that support generic automation of the EPD process.

Here the integration of digital twin concepts with LCA and Modelling-Based-Systems Engineering concepts are promising to enable automation across the entire value chain for a wide range of different products. [Riedelsheimer et al., 2021; Eigner et al., 2011]

1.2 Goal and Approach

Proceeding from this background, the goal of this master's thesis is to develop an automated workflow for Environmental Product Declaration by combining Model-Based-Systems Engineering, Digital Twin and Life Cycle Assessment concepts.

The general problems to be researched are related to the product specific data collection to allow a sufficiently complete product specific life cycle inventory. Currently data collection is in most cases a manual activity. Unfortunately, product specific data collection in a global manufacturing network of increasingly complex products require extensive personnel resources. Consequently, automation is needed to enable the large-scale application of EPDs.

Three main areas are distinguished within the data collection that need increased levels of automation:

- Primary data collection along all life cycle stages and along the entire value chain of the product
- LCI dataset mapping for connection of intermediate materials with its specific supply chain impacts
- Harmonization and standardization regarding EPD methodological requirements for comparable and standardized assessments

Therefore, the primary research question to be answered in this thesis is "How can the full workflow of an Environmental Product Declaration be automated to decrease the need for manual work?"

Related to this question further secondary questions arise "What does the full workflow of an EPD look like?", "Which methodologies and concepts are currently being worked on that support automation?", "How can these concepts and methodologies be used for automation if available?" and if not yet readily available "What is still needed to allow their application to enable automation?"

To reach this goal, and to answer the above stated research questions different approaches are used.

A review of MBSE, DT and LCA concepts is performed to identify the aspects that are currently being worked on for digitalisation and handling of large and complex systems.

The MBSE is then used for system model engineering of the proposed EPD workflow. Based on requirements engineering the different perspectives, disciplines, and stakeholders along all product life cycles and the entire value chain are considered to depict the entire workflow for an EPD creation.

In alignment to the system model a corresponding data engineering model is outlined containing the toolchain information for accessing, handling and evaluating product data. The toolchain additionally shows the different tools involved as well as their field of application and interconnection.

The system model in combination with the corresponding toolchain is used to close the gap for automation of EPDs. Along the visualised EPD workflow system model and the toolchain the most important activities that need automation are highlighted and elaborated before their application is used on an electric motor example.

At the end the outlined aEPD workflow will provide clear guidance to stakeholders from different domains how generic EPDs can be performed as well as provide an overview on the work that is still to be done for ready to use a EPDs.

1.3 Structure of the Thesis

The first chapter introduced the need for automated EPDs to decrease the manual input needed for the creation of an EPD. This is the foremost requirement to allow the creation of large-scale EPDs that are needed to meet the global environmental impact reduction targets. Therefore, several approaches such as MBSE, DT and LCA are introduced together with the main research questions regarding automation that shall be addressed within this thesis.

The second chapter introduces the main concepts of Model-Based-Systems Engineering, Digital Twin including Asset Administration Shells and Environmental Product Declarations with underlying Life Cycle Assessment. In the first instance the concept MBSE is described giving details about the development, methodology and its application possibilities in the industry as well as similar methods. The same procedure is chosen to introduce Digital Twin concepts with the focal point on Asset Administration Shells as well as for the introduction of the EPD methodology. Further, software tools that find application within the development of the aEPD are explained to give an understanding of the main functionalities as well as the reason for their deployment. Afterwards, a review of existing integrative methods combining multiple concepts or tools is given regarding industrial best practices.

The third chapter introduces the conceptual model for a holistic EPD workflow combining the introduced methods in a way that has not yet been done and that is an important preparation for the identification of automation potentials. The methods are combined by introducing relevant multi-level requirements and views along the entire product life cycle. The Live Cycle Inventory, Product Lifecycle Management as extension to MBSE and DT, Supply Chain and Method level requirements are therefore distinguished and elaborated. The goal to develop a generic aEPD workflow with a holistic view and applicability for different products and companies makes it important to consider company, domain and discipline specific aspects as well as aspects regarding data availability and accessibility.

In chapter 4 the solution design for automated EPDs is elaborated by assessing available approaches and providing concepts for its realization. Therefore, the three following aspects for automation of the input data are outlined in more detail. The consistent and automated data collection, the automated Life Cycle Inventory dataset mapping and the creation of harmonized Product Category Rules. The aspect of consistent data collection is then considered in further detail regarding the use of Asset Administration shells and corresponding submodel templates. Finally, the actual design of the aEPD workflow using AAS is described in detail and current limitations and challenges are derived.

In Chapter 5 the application of the aEPD workflow is performed on an electric motor EPD. The objective of the prototypical implementation is to proof the concept and applicability on a real case and to provide guidance and further support for other interested stakeholders on the aEPD application. Therefore, general information about the product is given and subdivided into product BOM and product specific data. In addition, method related standard values and LCI data set mapping is given for the final EPD creation. Afterwards, the implementation is evaluated in relation to weaknesses and its key contributions.

In Chapter 6 the content and results of the thesis are summarized. Furthermore, the developed aEPD workflow and the prototypical solution are evaluated against the initial research goal and research questions. Based on this, the aEPDs feasibility to meet the needs for large scale EPDs and data input automation is discussed. Finally, recommendations for future application and further research and development are given.

2 Foundations for automated Environmental Product Declaration

This chapter introduces the main concepts of Environmental Product Declaration, Digital Twin and Model Based Systems Engineering in order to prepare the conceptual approach combining these methods in an automated EPD workflow. First of all, the concept of MBSE is described, detailing development, methodology and possible application in industry as well as similar methods. The same approach is chosen to introduce life cycle thinking approaches while focussing on EPD and LCA as well as the industry 4.0 implementation for DT using Asset Administration Shells. Thereafter, a review of existing integrative approaches combining multiple concepts or tools is given before a summarising evaluation of existing methods is done to provide a scientific based decision rationale for the development of the aEPD workflow.

2.1 Conceptual Overview of Model-Based Systems Engineering

The Model-Based-Systems Engineering concept, its background, development, field of application are described. Within the literature many different concepts, languages and notations exist. In this thesis, mostly the basic concepts and definitions that are elaborated by INCOSE [INCOSE, 2020] are used. In addition to this, further developments and challenges regarding MBSE are outlined.

2.1.1 Background and Development of MBSE

MBSE is an approach used within Systems Engineering which is itself a holistic approach to realizing systems successfully. The system can be nearly anything from different products, services or software as well as a combination of these or anything in between. The central aspect of systems engineering is to not only focus if the system is build right but also ensuring to build the right system. [INCOSE, 2020a]

As a holistic approach Software Engineering (SE) covers all life cycles stages from cradle-to-grave during the systems development. Specific life cycle stages cover everything from conception, development, production, utilisation, support and retirement. [INCOSE, 2020a]

The V lifecycle model in Figure 1 depicts the logical relationship between the different Systems engineering Activities or Processes.

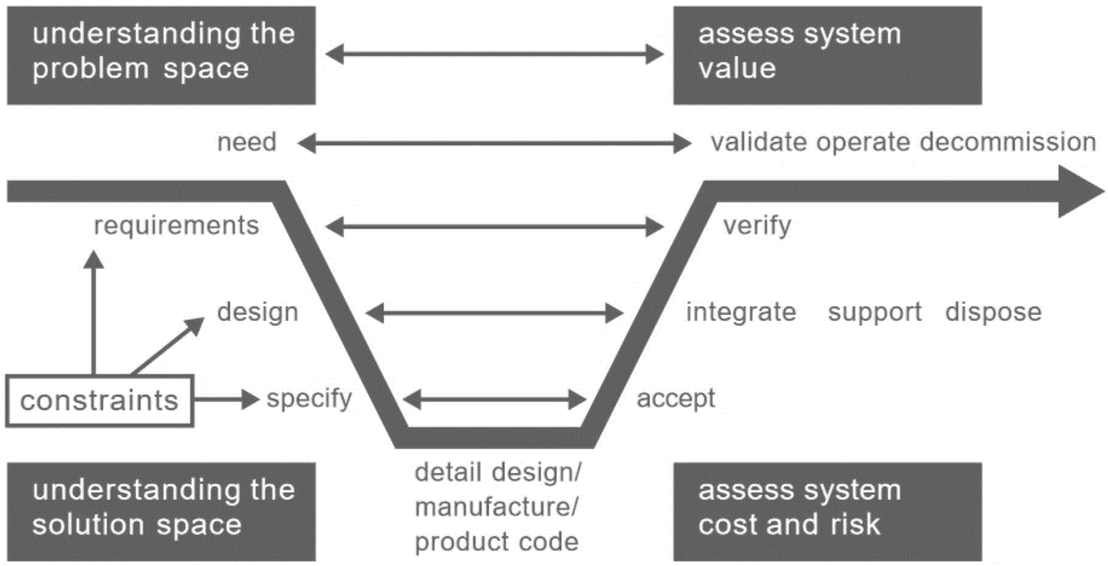

Figure 1: V lifecycle model overview for Systems Engineering activities [INCOSE, 2020b]

As such 6 main steps are called out to develop a system successfully:

- Understanding the problem
- Investigate alternative solutions
- Prepare the test and support systems
- Agree and manage requirements
- Agree and manage interfaces
- Track progress against a plan

[INCOSE, 2020b].

Model-Based Systems Engineering is an approach to SE and represents a formalised application of modelling across all life cycle stages to support system requirements, Analysis, Design, Verification & Validation [INCOSE, 2020 c].

According to [Holt & Perry, 2008] MBSE is: "An approach to realising successful systems that is driven by a model that comprises a coherent and consistent set of representations that reflect multiple viewpoints of the system".

The traditional Systems Engineering results in a set of stand-alone documents which are only loosely connected and make it difficult to iteratively check and validate potentially overlapping content against defined quality criteria. MBSE in contrast uses the model as a single point of reference. The model is an abstraction of the system of interest and can be constructed from one or more representations and viewpoints on different stakeholder concerns. The connected nature facilitates the application of quality criteria and allows automatic queries or verification. [INCOSE 2020 c]

In total this results in an abstraction of the system that has higher quality and is more insightful with further benefits such as: [INCOSE 2020 c]

- **Reduced risks** concerning cost estimates, requirements validation & verification and error occurrence
- **Improved communication** with stakeholders, between engineering disciplines and across language barriers
- **Improved quality** due to improved requirements specification, issue identification, traceability, integrity and consistency
- **Increased productivity** by better impact analysis of requirements and design changes, better interaction between teams, reuse of existing models, automated documentation

Model-Based Systems Engineering

MBSE is based on several concepts which allow the holistic and interconnected nature of this approach. The general concepts (Model, System of Interest, Representation, Viewpoint, and Quality Criterion were shortly mentioned above and shall be explained in more detail below according to [INCOSE 2020 c]:

Model

The model is an abstraction of the system of interest and contains as a single point of reference the total knowledge of the project.

System of Interest

The System of Interest is the subject/reason of the Systems Engineering activity. It covers the problem (environment), project (people and processes) and solutions.

Representation

The Representation is a partial description of the system of interest and reflects a particular viewpoint. As such a representation should use the most appropriate notation. This can be a text, table or diagram in a given language as well as graphical langue (e.g., SysML) or other notations.

Viewpoints

The viewpoints specify the purpose of a representation and allow decomposition of complex problems to only those aspects relevant to associated concerns.

Quality Criterion

The Quality Criterion are measures selected to ensure that specific aspects of the model fit its planned purpose (e.g., correctness, completeness, and consistency)

Concern

The Concern is something a stakeholder wants to know or ensure about the system of interest. Each concern is addresses by one or several viewpoints.

Stakeholder

Any person or group that has touchpoints and related concerns with the system of interest

MBSE is an integrated approach to systems engineering in which all activities should ideally reference the model for maximum benefits. Model-Based Systems Engineering represents therefore a paradigm shift from document-based development to model-based development. The difference between both forms is in the approach how primary artifacts in the life cycle are created. Artifacts represent elements of the model. [INCOSE, 2015]

In document-based development, subclasses of model elements are generated manually in the form of independent text documents, tables, diagrams, and presentations. Meanwhile, the management of independent documents, especially with regard to the consistency, is extremely laborious. Therefore, when changes are made, knowledge is needed about which records are affected, but also where they can be found and what other dependencies exist. [INCOSE, 2015]

Using MBSE, every detail can be represented in the system model as required. The system model thus serves as the central source for design decisions. Each design decision is recorded in the model as an element or a relationship between elements. The MBSE approach means that all excerpts, such as diagrams or texts, are only views of the underlying system model, not the model itself [INCOSE, 2015]

Modelling Languages form a standardized medium for communication. A modelling language is a semiformal language and defines model elements. The rules defined in each modelling language give uniqueness to the elements and relations present in the model. [INCOSE, 2015]

SysML is a modelling language for systems engineering. Through it, it is possible to visualize and communicate the crucial aspects of system design (structure, behaviour, requirements and parameters).

The grammar and vocabulary consist of graphical notations. These are defined in a standard specification and managed by the Object Management Group (OMG). SysML uses a subset of the Unified Modelling Language (UML) and provides additional extensions to meet systems engineering requirements. [INCOSE, 2015]

Figure 2 provides an overview of the categories and relations between the different SysML diagrams.

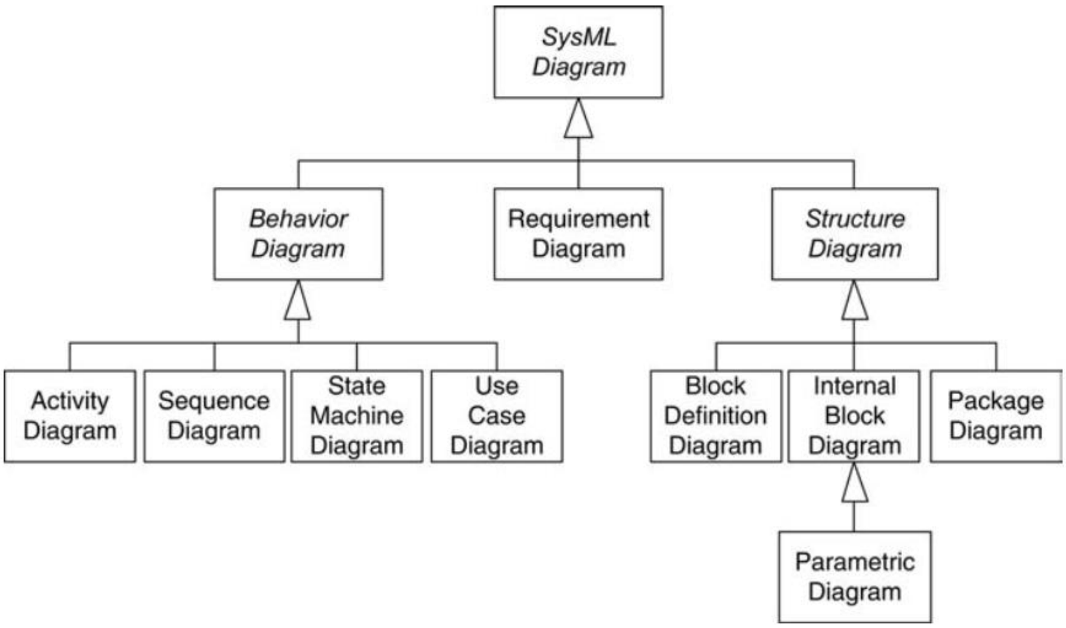

Figure 2 SysML diagram taxonomy [Delligatti, 2014]

For understanding it is important to know that the hollow, triangular arrowheads can be read as “is a type of” in the direction of the arrowhead. [Delligatti, 2014]

Apart from the strengths and opportunities of MBSE some major challenges remain regarding the use of MBSE concepts and modelling languages. Especially, the use of modelling languages among different stakeholders and experts can create difficulties. For instance, due to different terminologies and competences the use of modelling languages is more troubling for non-it-related engineers. Also, there are huge differences of the level of abstraction between concrete discipline-specific models to abstract multidisciplinary system models. [Albers et al., 2013]

2.1.2 Current State regarding MBSE Methods

In model-based systems engineering (MBSE), models are used for description and specification to facilitate structuring of complex technical problems. This involves capturing the relationships between properties for analysis at a higher structural level. Stakeholders from different disciplines are involved in the design and development of a complex system. Each stakeholder has a different view of the specification. The methods of model-based systems engineering can help to describe a multidisciplinary product in an abstract way. VDI 2206 defines a systematic approach for the development of mechatronic systems. The focus is on the left wing of the "V" and extends it with the use of methods from model-based systems engineering (see Figure 3). [Eigner et al. 2012]

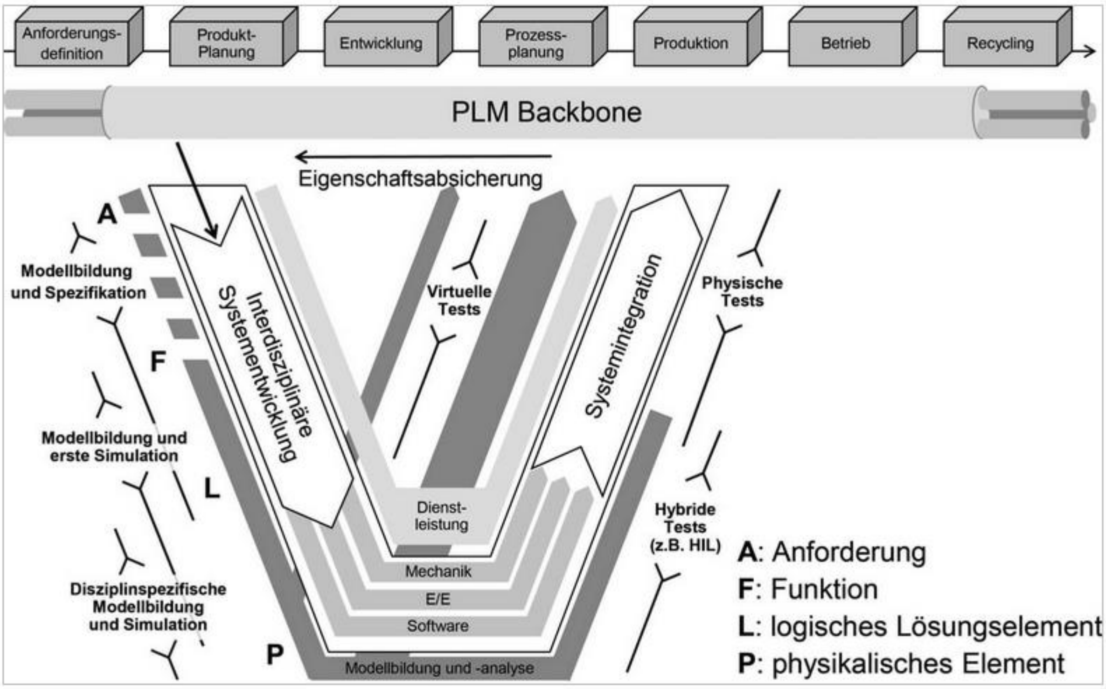

Figure 3 Extended V-Modell for Model Based Systems Engineering [Eigner et al., 2012]

The concept of system lifecycle management can integrate information upstream of PLM, such as the early phase of interdisciplinary system development. The information downstream of PLM, which arises during the product use and support phase, can also be used. This allows information from different sources and stakeholders to be integrated throughout the lifecycle of the systems. In the use phase of smart products, system lifecycle management supports the management of instance-specific data, aggregations, analysis, and visualization, allowing information from the use phase to be accessed in the development phase. [Eigner et al., 2012]

Eigner not only considers PLM as a key concept to combine with MBSE but also for the establishment of sustainable product development. In "Sustainable Product Life Cycle Management: A lifecycle-based Conception of Monitoring Sustainable Product Development" an integrated Sustainability Triangle is introduced (see Figure 4).

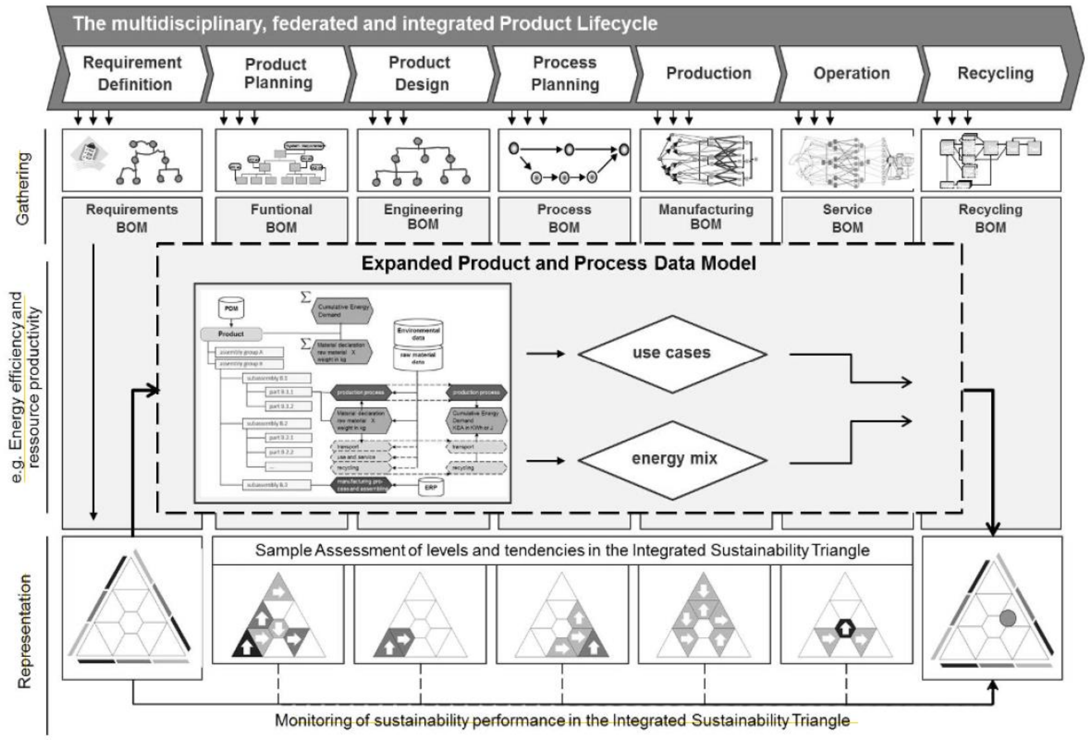

Figure 4 Model for sustainable Product Development [Eigner at al., 2011]

It allows the assessment and the quantification of sustainability in regard to the aggregation of economic, ecologic and social contributions for sustainable development. Within Sustainable Product Lifecycle Management, an IT infrastructure would be able to support product data, information and knowledge sharing. This will be the foundation of the business model needed to comply with sustainability requirements. The expanded Product Lifecycle Management represents an important approach for achieving a more sustainable product development. [Eigner et al., 2011]

2.2 Conceptual Overview of the Digital Twin

The Digital Twin (DT) concept can be understood as a virtual mapping of a physical product. In the following sections, its background, development and field of application are described. Within the literature there are different definition and scopes used for the DT. In this thesis, the DT concepts that are introduced by “Plattform Industrie 4.0” including the Asset Administration Shells are elaborated in more detail. Additionally, further developments and initiatives as well as supportive tools are briefly described.

2.2.1 Background and Development of Digital Twins

The idea of a digital twin for a physical product is a concept for managing product data throughout the product lifecycle. The concept was first proposed by Grieves at the University of Michigan in 2002. It focused on a "conceptual idea for PLM" that introduced the notion that each physical object has a digital counterpart and the two are synchronized by a flow of data between them. [Grieves and Vickers, 2017]

Today, the digital twin is often defined as a virtual representation of a physical product. This mapping can include the structure and properties defined during product development as well as the current configuration of a product and usage information. [Eigner et al., 2021]

DTs are a digital representation of a physical product or product-service system that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple life cycle phases. [Riedelsheimer et al., 2021]

As there is currently no fixed definition of a DT that could be used in a standardized form, there are many different terms and definitions used. In most cases the DT is sub structured into a Digital Model/Digital Master, a Digital Thread and a Digital Shadow/Physical Twin Data.

The Digital Master (DM) or digital model is more holistically containing all product relevant information and used to derive a particular product specific digital twin. The digital model contains for instance data from the planning phase and is managed in the PLM. [Riedelsheimer et al., 2021; Eigner et al., 2021]

The Digital Shadow (DS) or (Physical Twin Data) includes all data sent from the physical product to the digital twin and includes data from the production (e.g., operating data, process data), use and EoL phase. [Eigner et al., 2021]

The Digital Thread allows for overall traceability and connects the configuration items of a digital model, the corresponding DTs and also its physical twin over the entire product lifecycle. Therefore, the main objective of a the Digital Thread is the traceability over all product life cycles at any time. [Eigner et al., 2021]

The overall interrelationships between the above-mentioned aspects are shown in Figure 5.

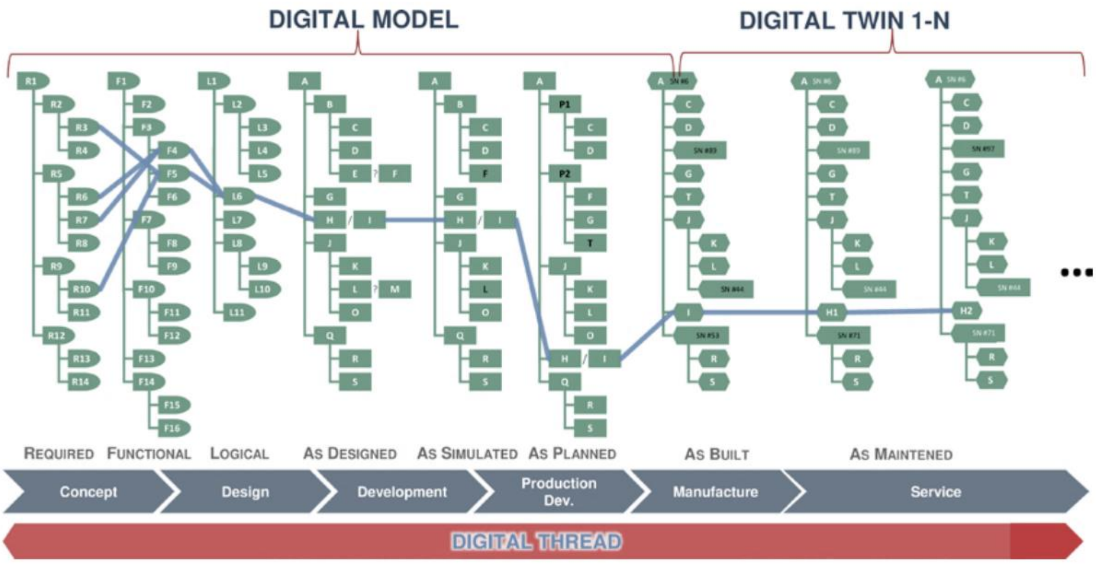

Figure 5 Interrelationship Digital Model, Digital Twin and Digital Thread [Eigner et al. 2019]

Generally Digital Twins provide the possibility to make use of the available data and enhance the systems individual sustainability as well as future product generations. However as described above there are different implementation concepts for the design and realization of DTs which require new approaches and capabilities which is currently an open research gap. [Riedelsheimer et al., 2021]

In addition, Eigner summarises, that a common basic understanding regarding the concept of digital twins can be identified throughout the existing literature. However, there has not yet been an agreement on a general definition of the digital twin in the research community. [Eigner et al., 2021]

Here the Platform Industrie 4.0 [PI4.0, 2022] comes into action. The Platform Industrie 4.0 is a German network that shapes the digital transformation in manufacturing. [PI4.0, 2022]

Industry 4.0 is about intelligent networking of machines and processes for industry by the use of information and communication technology. As such it can be used in different ways. For instance, for the improved collection and use of data. Production and processing data can be directly measured and used for data analysis. Moreover, resource efficient circular economy and sustainable production can be supported as the entire life cycle of a product can be assessed with the support of data. [PI4.0, 2022]

The overarching goal from Platform Industrie 4.0 is the development of core concepts to tackle the challenges on the pathway to Industry 4.0. It provides concrete recommendations for academics, companies and politicians to reach widespread use within industry. Most importantly, they drive national and international exchanges to pave the way for global standardization and IT security. [PI4.0, 2022]

Both is necessary if global interoperability should be enabled to allow data collection and exchange across the entire supply and value chain.

Digital Twin Implementation

The digital twin can be understood as a virtual mapping of a physical product or service and includes all information required for a specific product use case and the corresponding data collected throughout all life cycle stages, and IT systems. [Eigner et al., 2021]

However, the concept is not about merging all available data in a centralised database. Instead, the elements of a digital twin should remain in their corresponding source systems and are linked to the digital twin. Consequently, the digital twin can be considered a theoretical data structure where all available information regarding a product instance can be linked via unique product identifier. [Eigner et al., 2021]

The Asset Administration Shell (AAS) has for this purpose been developed by the Platform Industry 4.0 and is the implementation of the Digital Twin for Industry 4.0. An asset is defined as everything that requires a digital connection for an Industry 4.0 solution (supply materials, machines, processes, parts, products, etc.) to allow for the digital representation of the asset in the IoT world. [PI4.0, 2021]

The AAS has several appealing attributes as the establishment of cross-company interoperability, the coverage of the complete life cycle of products, devices, machines and facilities, the integration of value chains and is the basis for autonomous systems and Artificial Intelligence. Moreover, it's the first Digital Twin implementation that has reached international standardization (IEC 63278-1 Asset Administration Shell for industrial applications - Part 1: Asset Administration Shell structure). [PI4.0, 2019b]

Technically, the AAS consists of a number of submodels which provide all information and functionalities of a given asset. For instance, features, characteristics, properties, parameters and measured data is described. It allows the use of different communication channels and applications and therefore serves as the link between I4.0 objects and the connected digital world. [PI4.0, 2019]

The basic details of an AAS are shown within the meta information model as depicted in Figure 6.

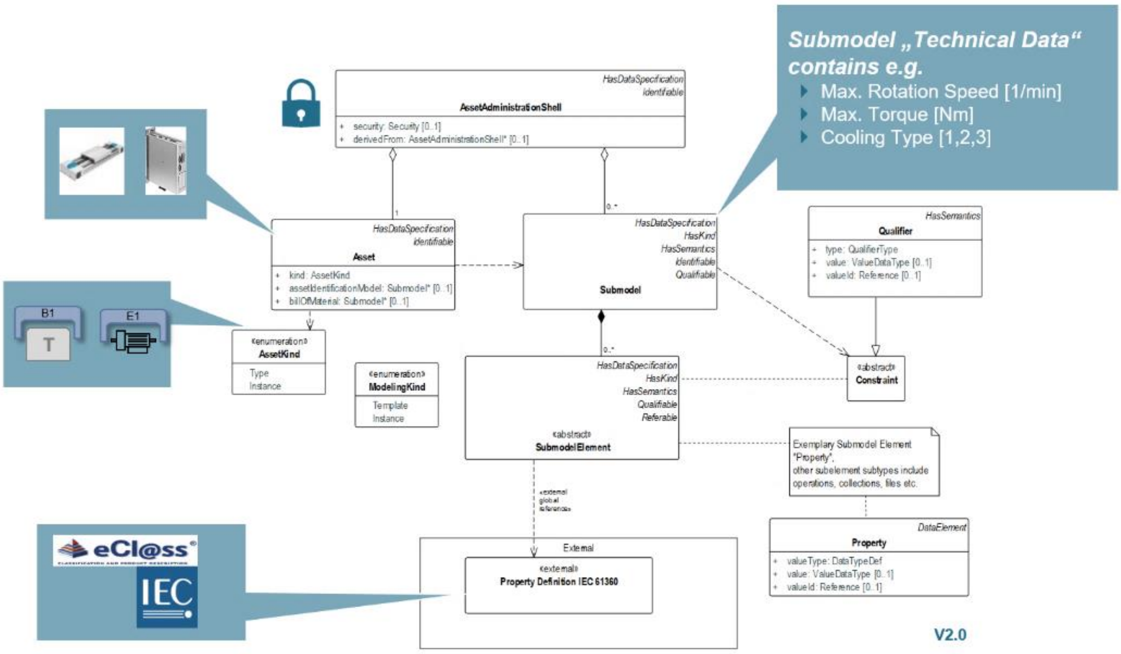

Figure 6 AAS Meta Information Model [PI4.0, 2019b]

PI4.0 provides detailed documentation on the meta information model of the AAS as well as a specified file exchange format. In addition, it describes the information content and serialization formats. Together with a technology neutral UML specification of the information model also several other formats for exchanging AAS are provided such as XML, JSON, RDF, AutomotionML and OPC US.[PI4.0, 2019c]

The general relation between the AAS and its submodels are also depicted in Figure 6. The AAS provides the correct form of an AAS in order to create, find access, modify the AAS and to link to relevant submodels. The Submodels provide the actual content and functional aspects of a component that is connected to the AAS. For each functional aspect a corresponding submodel is created as for e.g., technical data and documentation or shall be created in the future. [PI4.0, 2019b]

To secure interoperability between different companies and partners the Industiral Digital Twin Association (IDTA) provides official submodel templates (e.g., Contact Information, Bill of Material, Sensors, etc). Currently only few submodels are readily available but they aim to continuously extend the number of submodels available. [IDTA, 2022]

A sufficient coverage of standardized submodel templates will need to be available to cover the functional aspects of the different product types along the supply chain, to ensure common communication services and semantics across companies and sectors. Only this, will deliver the added value of the Digital Twin concept by enabling the exchange of all relevant information between value chain partners.

2.2.2 Current State regarding Digital Twin Concepts

For the industrial application of the DT concept further work is needed and a number of different projects, and integrative approaches is currently worked on to foster the use of DTs.

Similar to the activities performed by PI4.0 and IDTA to create standards and communication channels for the interoperability between supply chain partners the association Catena-X Automotive Network e.V. (**Catena-X**) is exploring and developing digital product passports. Catena-X is the first integrated, collaborative, open data ecosystem for the automotive industry of the future. It connects all players to end-to-end value chains. The mission of Catena-X is to enable the digital flow of information across the entire supply chain (e.g., digitally traceable material flows). [Catena-X, 2022]

Many suppliers in the automotive industry are extremely uncertain about the added value of sharing own data and rate the risk of data loss or the negative consequences very high. Consequently, there is a lack of business models, incentive mechanisms and the right technology. Therefore, Catena-X wants to connect automotive manufacturers, suppliers and service providers of the entire supply chain. [Catena-X, 2022]

Among other aspect a Digital Product Passport shall be created to carry sustainability related information along the value chain. Therefore, Catena-X describes a carbon-specific set of rules to form a uniform methodology. This allows to specify existing standards and procedures to record and compare carbon data. [Catena-X, 2022 b]

Eventually the Catena-X product passport should become something like a submodel template.

The **Digital Product Passport** is also further defined on the European level. The European Commission shortly released its Circular Economy Package which includes a proposal for an Ecodesign for Sustainable Products Regulation (ESPR). The ESPR identifies a Digital Product Passport (DPP) as key, enhancing the traceability of products and their components. [EU, 2022]

The European Commission (EC) defines a product passport as a product-specific data set, which can be electronically accessed through a data carrier to electronically register, process and share product-related information amongst supply chain businesses, authorities and consumers. The DPP would provide information on the origin, composition, and repair and disassembly possibilities of a product, including how the various components can be recycled or disposed of at end of life. This information can enable the upscaling of circular economy strategies such as predictive maintenance, repair, remanufacturing and recycling. It also informs consumers and other stakeholders of the sustainability characteristics of products and materials. [CISL, 2022]

While Catena-X and the DPP focus on smart data collection and exchange along the entire value chain, Riedelsheimer et al. develop a methodology that combines DT, MBSE and LCA from a methodological point of view.

They discuss the various scenarios for DT development and propose a general methodology by integrating existing approaches and methods (V-IoT, 8D-Model, Design Elements, MESSIAH, LCA, SCRUM). It specifically focuses on the development of a DT for the optimization of sustainability indicators along the product life cycle. [Riedelsheimer et al., 2021]

In Annex 1 an overview of the developed Digital Twin V-model is given where also the LCA and Sustainability related aspects are classified within the product development process.

The evaluation shows that open gaps from existing methods can be closed, and the suitability of the methodology for the development of DTs with a sustainability focus. However, the evaluation was only conducted up to a partial integration test. Further testing and especially data collection in the actual production and use phase would be necessary to assess the full potential from a sustainability perspective. Also, there is need for further research into the automation of processes. [Riedelsheimer et al., 2021]

2.3 Conceptual Overview of Environmental Product Declaration

The Environmental Product Declaration (EPD) method, its background, development, field of application and limitations are described. According to different industry domains and the level EPDs are established therein, the term EPD can be used to refer to different configurations of an EPD according to supplemental standards used. In this thesis the focus is set on Type 3 EPDs according to the ISO 14025. The ISO 14025 is used as baseline standard that can be further detailed by using supplemental standards like the DIN EN 15804.

2.3.1 Background and Development of EPDs

Environmental Product Declarations (EPDs) are ecolabels that disclose the environmental performance of products and services over their life cycle. EPDs read like a nutrition label, reporting impact indicator results such as carbon footprints, and water consumption. They can also include other information such as content of toxic materials or recycled content. The EPD does not assert that the product is environmentally preferable, but it discloses its environmental performance. [Schenck, 2009]

To date, EPDs are mostly voluntary. They have been undertaken by companies that were interested in disclosing their products environmental performance. All have been undertaken following the guidance of international ecolabel and LCA standards. In France, however, a law was passed requiring that all high-volume consumer products sold in France must bear an EPD, designed in accordance with the guidance produced by the

French Standardization body, AFNOR (Association Française de Normalisation). [Schenck, 2009]

In the Netherlands an environmental performance assessment method for construction works produced by the Nationale Milieu Database is required for new construction tenders and beyond [NMD, 2022]

The European Commission is currently developing the Product Environmental Footprint where chances are high that this will become mandatory in some way on the European market once the transition phase has ended.

Just to highlight what impact this will have on the industry it is important to understand the need for product specific rules. There must be a separate product category rule for each kind of product that share the same functional unit. This means the products provide the same social benefit for consumers, and direct comparisons can be made between different products. [Schneck, 2009]

The UNSPSC, a database of product names used for international trade, already has over 40,000 different products listed. These product names are identified at a high level already: for example, at the level of men's trousers. The UNSPSC seems like a good first estimate of the number of PCRs that need to be developed which could be anything between 40,000 and 100,000 PCRs. [Schenck, 2009]

Apart from changing regulations that will make EPDs become more common in the future the pure number of products and corresponding Product Category Rules as well highlight the need for increased automation.

Environmental Product Declaration

An Environmental Product Declaration (EPD) transparently reports objective, comparable and third-party verified data about products and services and relating environmental performances from a lifecycle perspective [EPD, 2022].

Where the EPD is the final report, the foundation of any EPD is a lifecycle assessment (LCA). This LCA allows to evaluate the product's environmental performance over its entire lifecycle. It typically takes into consideration the full value chain, from material extraction through to manufactured product, its usage stage and end of life. (EPD, 2022)

The LCA method is described in the ISO Standard 14040/44 [DIN EN ISO 14040; DIN EN ISO 14044]. An LCA is performed in an iterative process (as displayed in figure 1). The quality of the results is increasing in each iteration. However, more time and resources are required.

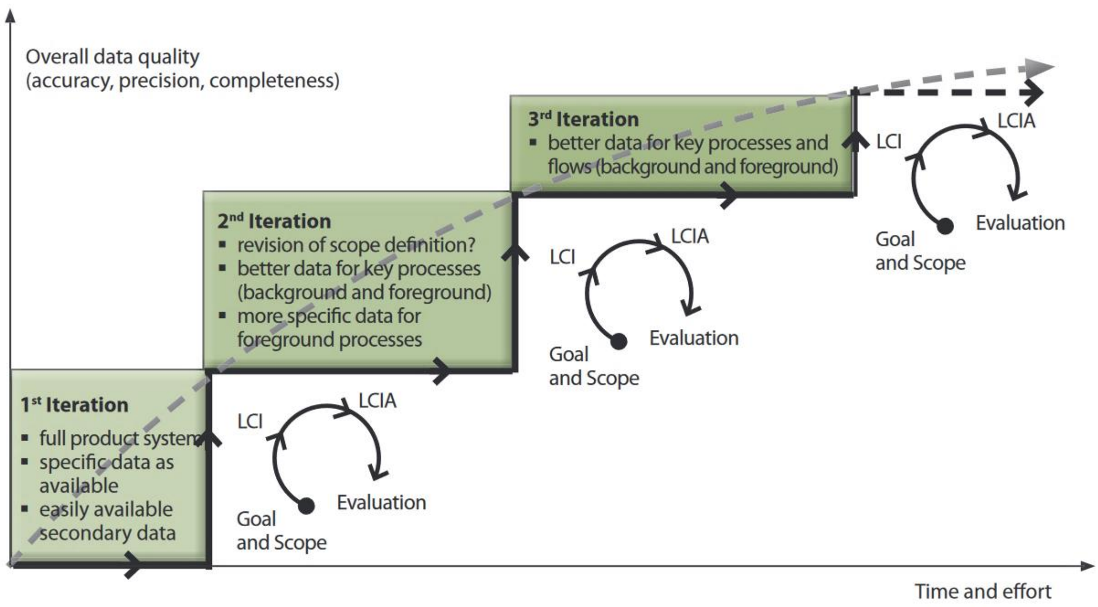

Figure 7 Iterative Approach of an LCA [Del Duce et al., 2009]

The LCA assesses a first life cycle model of the product system. Primary data at hand is used. Most process data come from secondary sources. The results of the study provide a good estimation of the environmental impacts. The results show the materiality of certain aspects and do also highlight further necessary primary data demand in order to increase the data quality. The result is shown in a range of results based on the different assumption in the analysis. [Del Duce et al., 2009]

In further iterations the data quality is increased. All activities with a significant influence on the results shall be based on the best data available. This process is documented in every detail in order to realize a maximum level of transparency [Del Duce et al., 2009]. Only the results of a full LCA with an independent third-party critical review can be communicated to end-users as ISO 14040/44 compliant [ISO 14040; ISO 14044].

An EPD is a so-called type III environmental declaration that is compliant with the ISO 14025 standard. A type III environmental declaration is created and registered in the framework of a programme (e.g., the International EPD® System, the Institut Bauen und Umwelt e. V., etc.)

In physical terms, an EPD consists of two key documents:

- EPD background project report (LCA Study Report), a systematic and comprehensive summary of the LCA project to support the third-party verifier when verifying the EPD.

- Public EPD document that provides the results.

The EPD standard requires that a Product Category Rule (PCR) is developed for each product or system type.

According to EPD International [EPD, 2022b] the PCR provides the instructions for how the life-cycle assessment (LCA) should be conducted. It sets out what needs to be considered, including but not limited to:

- System boundaries, i.e., which processes, and stages of the product's life cycle need to be considered
- Declared/functional unit: the amount, weight and service life of the product being assessed
- How to define e.g., the use phase and end-of-life options
- What impact categories need to be assessed in addition apart from the standard set as described in the general program instructions

Product Category Rules (PCRs) are used as complements to the general programme instructions e.g., in terms of calculation rules, building scenarios, and EPD contents. They ensure that functionally similar products are assessed in the same way when conducting the LCA and for product comparison. I.e., a PCR should enable different practitioners using the PCR to generate consistent results when assessing products of the same product category. They are a key part of ISO 14025 as they enable transparency and comparability between EPDs. [EPD, 2022b]

2.3.2 Current State of Environmental Product Declaration

Based on the ISO 14025 there a several approaches and programs currently being developed in order to cover many different products with corresponding EPDs. In this regard the most influencing initiative is coming from the Product Environmental Footprint. For smart and intelligent products electronics are of focal interest. Here the PEP Eco Passport initiative is coming into place for electric and electronic products.

Product Environmental Footprint (PEF)

"An important effort towards the harmonisation of LCA has been made by the European Commission Joint Research Centre with the development of the European International Life Cycle Data System (ILCD). The aim of the ILCD was to provide in depth guidelines for the application of LCA to the European context, both from a procedural and a scientific point of view, defining specific rules for the many options left open by the ISO, in order to enhance scientific robustness, consistency, reproducibility, and comparability of LCA studies. Based on this background, the European Commission adopted in 2013 the Recommendation on the Product and Organisation Environmental Footprint capitalizing on the methodological foundations of the ILCD, and advancing on scientific development to measure and communicate the life cycle environmental performance of products and organisations, in support to the European market and policymaking." [EC, 2021]

The development of the PEF is divided into four phases according to [iPoint, 2022]:

- <u>2008-2013: Preparatory Phase</u>
  Definition of Product Environmental Footprint Category Rules (PEFCRs) and Organisation Environmental Footprint Sector Rules (OEFSRs)
- <u>2013-2019: Pilot Phase</u>
  First practical test of PEFCRs in pilot projects for readjustment and further specification
- <u>2019-2024: Transition Phase</u>
  Application of the PEFCRs on a larger scale and implementation of a uniform labelling
- <u>From 2024: Implementation Phase</u>
  Decision where and when PEF is required by law and communication of the results with the public

Figure 8 provides an overview on the steps needed to create a PEF/OEF study and are analogue to the steps performed for and EPD according to ISO 15025.

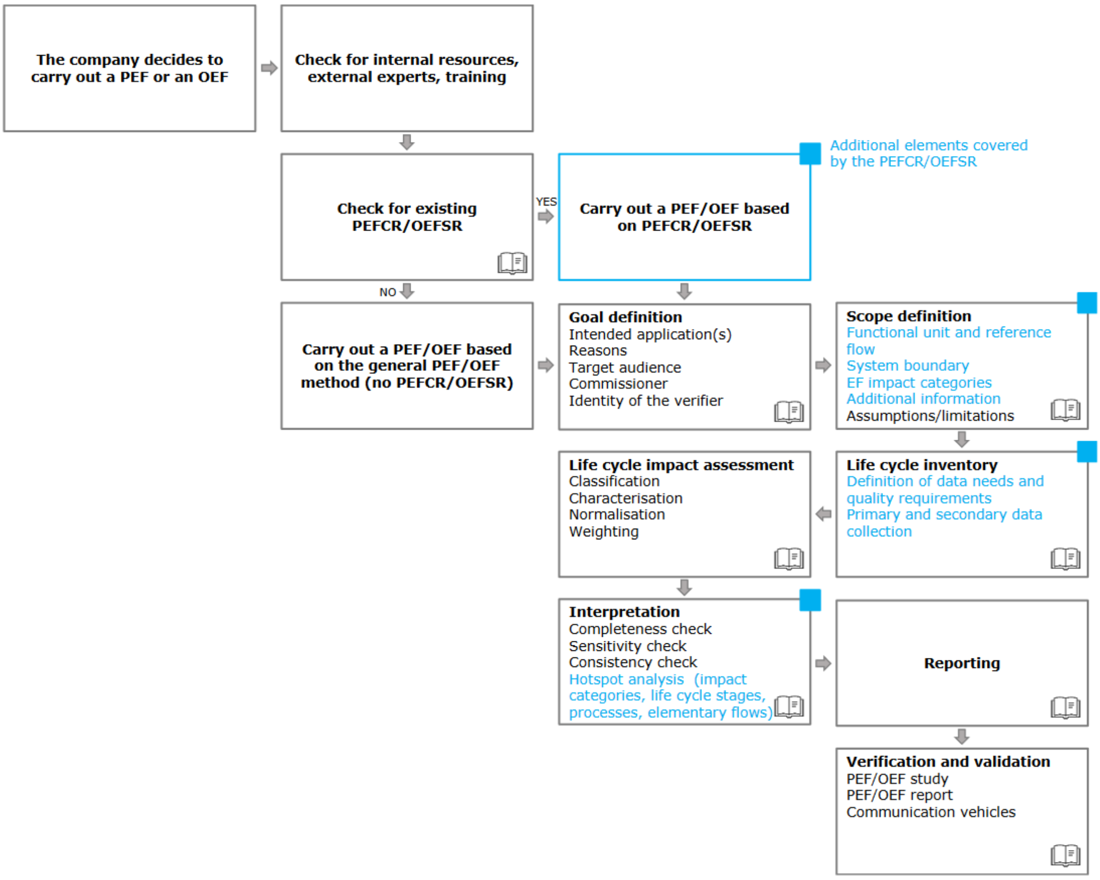

Figure 8 Key steps in a PEF/OEF study development [EC, 2021]

“The PEF and the OEF are designed to measure and communicate the life cycle environmental performance of products and organisations. Together, the PEF and OEF, constitute the EF methods, grounded on the LCA standard methodology. A calculation based on the general PEF/OEF methods gives quantitative information on the impacts of the product or organisation, taking into consideration the entire value chain (from the extraction/growing of resources to the end-of-life stage), i.e. following a life cycle approach. Following the framework standardised by ISO 14040-44, the EF is structured in similar steps, yet providing further specifications necessary to achieve a higher degree of robustness, consistency, reproducibility, and comparability.” [EC, 2021]

PEP Eco Passport

The mission of the non-profit P.E.P. Association is to develop internationally the Environmental declaration Program PEP ecopassport concerning electrical, electronic and HVAC (heating, ventilation, air-conditioning, refrigeration) products.

The association defines, in compliance with the ISO 14025 requirements, the PEP ecopassport with General Instructions Rules and Rules for Product Environmental Profile (PEP) elaboration, verification and publication rules similar to PCRs. [PEP, 2022]

The PEP ecopassport® Program is based on a 3-tier document architecture:

- Tier 1: General Program Instructions that define the general framework of the approach and set out the procedures used to draft, verify and publish a PEP in accordance with ISO 14025,
- Tier 2: PCR - Product Category Rules. Drafting rules that provide a method of environmental data recovery and analysis, and the declaration format used to generate the data in the form of a PEP.

In order, to produce an environmental declaration for a product, the common rules and where necessary the specific rules for the product category shall be applied.

- Tier 3: The PEP which declare the environmental characteristics of products, in accordance with the requirements of the PEP ecopassport Program. [PEP, 2017]

2.4 Current Practice regarding Integrative Methods for automated EPD

Literature research on current approaches for integration and automation reveal that especially LCA tool provider such as iPoint and Sphera work on the automation of the core LCA/ EPD workflow. On the other side Obeo works on an integration of LCA aspects with an MBSE tool. On a research level especially the inclusion of sustainability assessment related indicators into MBSE and DT approaches is looked at. In the following the different approaches are described in more detail.

2.4.1 LCA/EPD automation

iPoint is developing an automated LCA process workflow as shown in Figure 9 that allows the automation of LCA creation once the input/output inventory data on intermediate or elementary flow level is available here referred to as data input tables. Within the LCA software tool iPoint Product Sustainability an automated mapping approach is used to link inventory entries to corresponding Life Cycle Inventory (LCI) datasets. Then, an integration into a product category specific Meta-Model where calculations and Life Cycle Impact Assessment are performed, and results prepared for export.

LCI databases such as ecoinvent provide datasets with full elementary flow inventories for goods and services on a unit and result process level while ensuring the use of coherent and consistent modelling approaches throughout all datasets in a given database. Ecoinvent is a non-for-profit organisation supporting and developing environmental data. [Ecoinvent, 2022a]

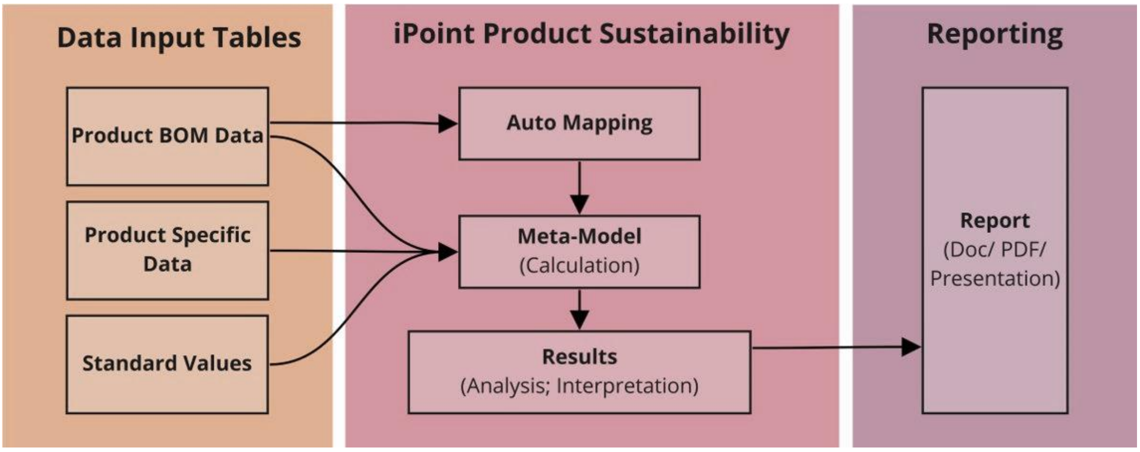

Figure 9 iPoint LCA Procces Workflow Automation [iPoint, 2022]

iPoint Product sustainability enables APIs to company ERP systems and tools for data collection. However, the different ERP Systems and set ups mostly hinder the direct use of such data in an automated way unless structured and modified within the initial LCA data collection phase. [iPoint, 2022]

Shpera has worked on automating the EPD core processes as shown in Figure 10.

Analogue to the iPoint approach initial data needs to be collected from the manufacturer and is fed into the GaBi LCA Software tool where the entries need to be mapped and an LCA model created to perform the underlying LCA. LCA results are then transferred in the EPD report and can automatically be transferred to the company’s website for publication. [Sphera, 2022]

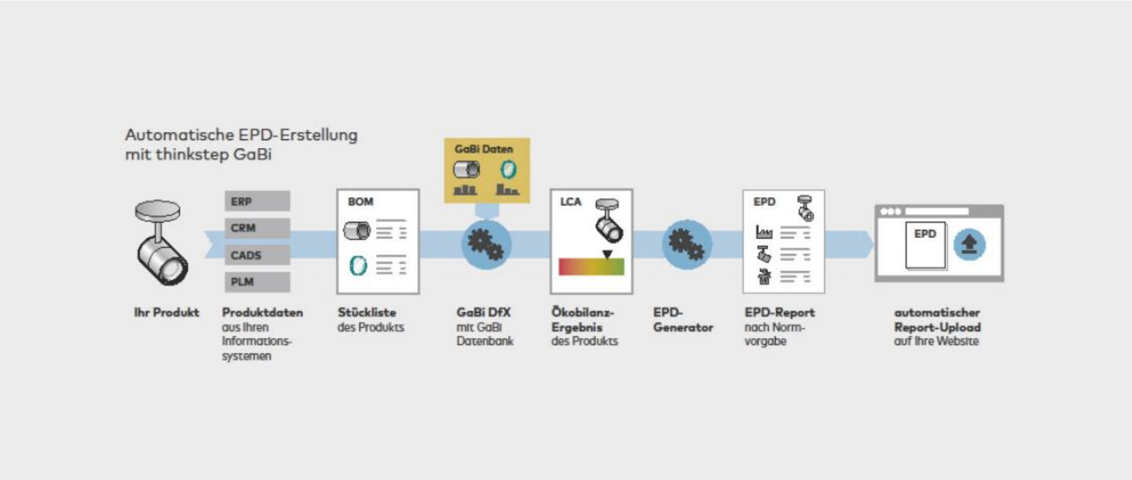

Figure 10 Automated EPD Creation with GaBi (Sphera, 2022)

Even though both approaches work on the automation of LCA and EPD they are both missing a smart integration of inventory data.

2.4.2 MBSE/ DT/ EPD Integration

Obea has worked on an LCA extension for its MBSE tool Eclipse Capella as shown in Figure 11.

They also state that for complex products the data collection and inventory phase is very time consuming. Additionally if appplied during the design phase its challenging to keep the LCA and the product development synchonized at all times to avoid wrong conclusions are done [Madiot, 2020]

For the LCA extension additional concepts are added to the Capella model elements for inventorying the compontent physical charcteristics like energy quantitties. As such the attached components allow for characterizing input and output flows regadring quantity, material, energy, etc.). This information can then be automatically exported as an intial inventory analysis to LCA tools used by environemntal experts to perform the LCIA. [Madiot, 2020]

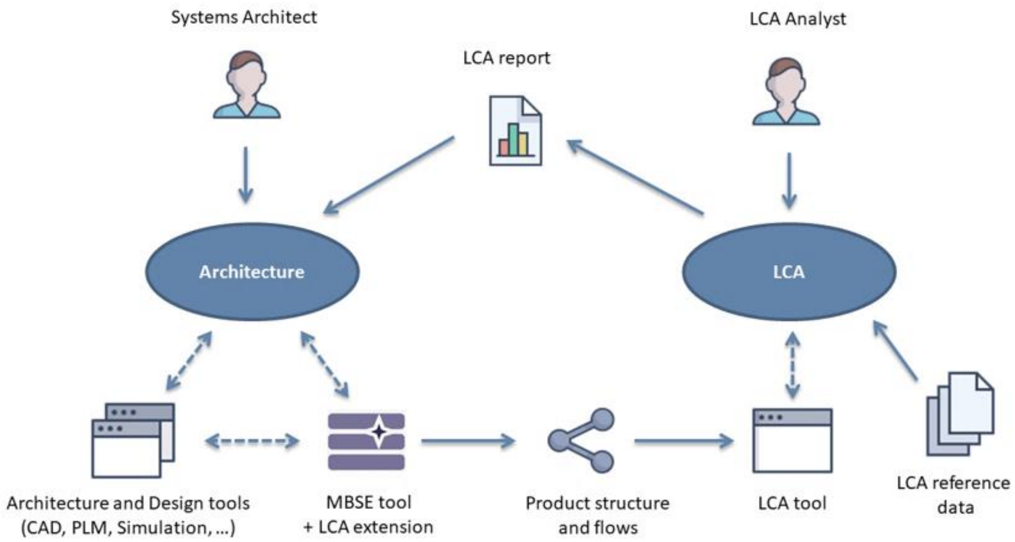

Figure 11 Capella LCA Extension Overview [Madiot, 2020]

With the Capella extension an import link is created to get already gathered data from an MBSE tool into an LCA tool. Nevertheless, most of the data collection as well as the later LCA workflow remain a manual activity.

Especially in scientific papers and research the integration of sustainability related indicators into the DT and MBSE concept is worked on.

Halstenberg provided a concept for leveraging circular economy through a methodology for smart service systems engineering. The main goal is the inclusion of circular economy metrics within the NPD process and how this can be supported by MBSE tools. For this a MESSIAH CE methodology is introduced. It is specifically designed to be combined with MESSIAH and to address the integration of CE goals in the development of smart services. [Halstenberg et al., 2019]

For instance, Riedelsheimer proposed a methodology to develop DT for energy efficient IoT-Products. The focus is put on smart product development with the V-model where an initial LCA is conducted for the delivered parts. Based on this, this LCA activities are highlighted across the V-model development. [Riedelheimer et al., 2021]

This is an important step to get CE and LCA requirements already placed in the new product development phase where currently this is not considered per default, but it still misses concepts regarding automation and streamlining of the LCA workflow.

Chen proposed a conceptual framework for estimating building embodied carbon based on DT and LCA. Here the use of a BIM-based DT and the creation of data mapping between BIM and LCA databases is done. Additionally, a formula for the LCA calculation is proposed. [Chen et al., 2021].

From a workflow point of view this is very interesting as it depicts the entire workflow from BIM modelling up to LCA creation using digital twins. However, it focusses too much on building specific requirements that find no application in other industries and is therefore not usable for generic product workflows. Also, the formula for LCA calculation seems redundant as this is already covered by building sector specific PCRs.

Within Industry 4.0 development and the provision of submodel templates for sustainability related AAS there is currently only one submodel looking at the Product Carbon Footprint as well as one submodel template that generally covers the BOM data. However, both are not yet available and still in development. [IDTA, 2022]

3 Conceptual Model for automated EPDs

This chapter introduces a holistic view on the entire Environmental Product Declaration (EPD) workflow combining Life Cycle Assessment (LCA), Product Life Cycle Management (PLM), Model-Based-Systems Engineering (MBSE) and Digital Twin concepts. Starting with an overview of the multi-level requirements regarding the EPD process the Method level, LCI Level, PLM Level, Supply Chain Level, and Product level requirements are depicted in more detail. Based on the general workflow as of today with many manual activities further solutions are identified that are needed to allow automated EPDs in the future. After the key elements are defined a concept for automated EPDs using Asset Administration Shells is derived according to the requirements and described in a generic aEPD workflow overview together with an AAS Submodel configuration. Four different Software tools are used as application examples within the aEPD workflow. Each tool is explained to give an overview of the main functions and the reasons for its development. Based on the MBSE EPD workflow system model and the selected tools an overview combining the EPD workflow and toolchain is introduced to close the gap for the automation of EPDs. Even though the general aim is to develop an automated approach the scope of the project imposes some restrictions on the applicability of this approach which are further detailed in limitations and challenges for an aEPD.

3.1 Method Evaluation and Decision Rationale

The analysis and evaluation of currently available tools and methods reveals that no consistent tool integration or automation along the EPD process workflow exist. Tool provider currently focus on process automation in areas where they have direct control but are reaching limits regarding standardization necessary to also automate data collection phase. This is also true for product specific rule development across a wide range of products. Most PCRs are specific to the building sector and are only slowly broadened to other industries and product groups.

Especially due to the emerging importance of sustainability assessments within the NPD process there are several approaches to bring sustainability related indicators and requirements into NDP relevant tools and approaches such as the MBSE and DT. Here the aspect of automation along the entire workflow is not looked at and mostly concentrates on improving manual LCA input into the extended methodologies. Or on the opposite as currently the case for the AAS there is a development regarding standardization and interoperability taking place, but sustainability related requirements still need to be developed and integrated.

There are several activities ongoing to integrate or automate specific aspects along the product life cycle assessment but as of today there is no general overview on the entire EPD process that shows the interconnection of this large and complex system on a multi-level approach from cradle-to-grave.

As a result, the thesis at hand explores possible ways to connect and automate the entire workflow on a meta level. The goal is to use existing developments where possible and to identify and call out gaps where further development is still necessary.

3.2 Holistic EPD Workflow and multi-Level Requirements

The aim of this subchapter is the development and definition of a holistic EPD workflow which is needed to delimit the scope and the range of functionalities necessary to meet the demands across all life cycle stages, stakeholders, and technical solutions currently in place. The most important steps needed are highlighted and grouped within a multi-level system. The development and the description of the workflow starts with the evaluated product as the final output of the EPD process. From there on the EPD workflow is depicted backwards. Starting on the Method Level showing the methodological requirements for an EPD. The Life Cycle Inventory Level is addressed next to summarise the data input needed for the impact assessment. The Product Life Cycle Management Level shows the life cycle stages of a product and refers back to the Supply Chain Level that links the activities of different companies and suppliers along the value chain. The entire value chain is broken down from a company level over processing level to product level.

Along this complex system different stakeholders and tools need to exchange and gather data which is finally needed to derive the Life Cycle Inventory for the final product assessment as mentioned above. The requirements considered along the EPD workflow come from a complex system with many interactions. Therefore, this multi-level breakdown is chosen to reduce the overall complexity into defined levels even though many of the requirements cannot always be clearly assigned to one or the other.

3.2.1 Method Level Requirements

The description of the EPD workflow starts with methodological requirements for an EPD as defined in corresponding standards (shown in Figure 12). The final EPD is used to compare the environmental performance of comparable products. To allow comparison, standards as the ISO 14025 or EN 15804 define harmonized modelling principles (e.g., type of allocation approach for dealing with multifunctionality) and imply the use of Product Category Rules (PCR) with further defined modelling principles (e.g., functional unit, use phase energy consumption models, etc.) and often provide templates for the final EPD Report. In some cases, ISO standards as well as existing PCRs will not be sufficient to provide all product relevant information and further data will be needed from external sources (e.g., waste treatment fractions or thermal efficiency rate) but also when data gaps occur for relevant materials or processes that cannot be closed by primary or secondary data.

The general LCA activities require data collection which is further defined within the LCI Level as well as setting up an LCA model. The LCA model contains all information to derive a Life Cycle Inventory on elementary flow level for a defined product or service. With this methodological specifications and modelling principles are implemented in a central place and eventually used for the actual product impact assessment calculations. Within the model also the LCI Mappings are deposed that link e.g., materials to the representing secondary datasets. Again, secondary datasets allow a generic representation of intermediate materials that are bought in during the supply chain without direct access to primary data that should be used ideally.

Once the model is final the Life Cycle Impact Assessment is performed by calculation and LCA results are transferred to the EPD report as well as the LCA Study Report as thorough documentation of the entire LCA. The LCA study report is structured according to the requirements of the corresponding ISO Standards (ISO 14040 and ISO 14044) and allows to trace back all specifications, modelling principles and data sources used for the LCA.

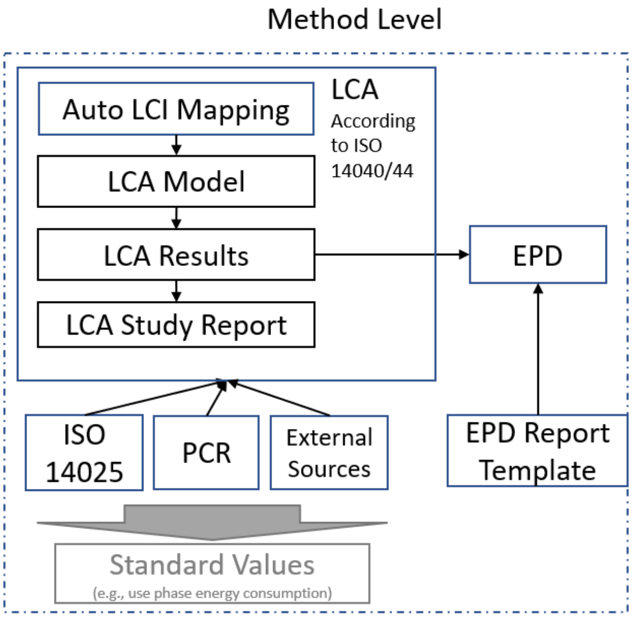

Figure 12 Method Level Requirements for EPD Workflow

3.2.2 LCI Level Requirements

The Life Cycle Inventory Level describes all data needed to perform the LCA and thereof creating the EPD. A full LCI should be a summary of all relevant input and output flows along the entire life cycle of the assessed product (shown in Figure 13). Generally, the LCI can be based on elementary flows or on intermediate flows. Whereas most primary data collected is available on an intermediate flow level, the elementary flow level is needed to perform the LCIA. In order to come from an intermediate flow-based inventory (e.g., product BOM) to a detailed elementary flow-based inventory LCI datasets from LCA database providers such as ecoinvent are used. Such datasets contain the entire supply chain for a given intermediate product and provide an aggregated list of all elementary input and output flows for the production of the intermediate product. The challenging part is to find an appropriate dataset for a given intermediate product. Appropriate in the sense of providing the best possible representation of the actual intermediate product used. The input data is divided into Product BOM Data, Product Specific Data and Standard Values which can originate from different sources along the entire Workflow.

Product BOM Data is corresponding to the actual product BOM. A BOM is well defined, used for many products during production and therefore mostly available for product evaluation. All materials directly used for a given product are given together with its quantity needed and can directly be used as input for the LCA

Product Specific Data are corresponding to further product relevant data that is less structured available (e.g., a processing data, scrap rates, number of defects, etc.). Often this data is spread over different data sources, not clearly allocated to a specific product or not measured at all but can contribute to a significant share of the overall product impact such as the production energy consumption.

Standard Values are corresponding to product generic data and parameters used to harmonize certain activities in a way that it can be representative for several products within a product group (e.g., harmonized use phase energy consumption models) and/or to harmonize in a way that products become comparable from a methodological point of view (e.g., unified product reference lifetimes).

For the workflow it is assumed that all standard values are created on a method level to streamline product related data that is otherwise difficult to be determined. Apart from harmonization this is sometimes also needed to define predictive behaviour within life cycle stages that are not known on a product level at the time of product evaluation (e.g., country of destination which can have very different EoL splits).

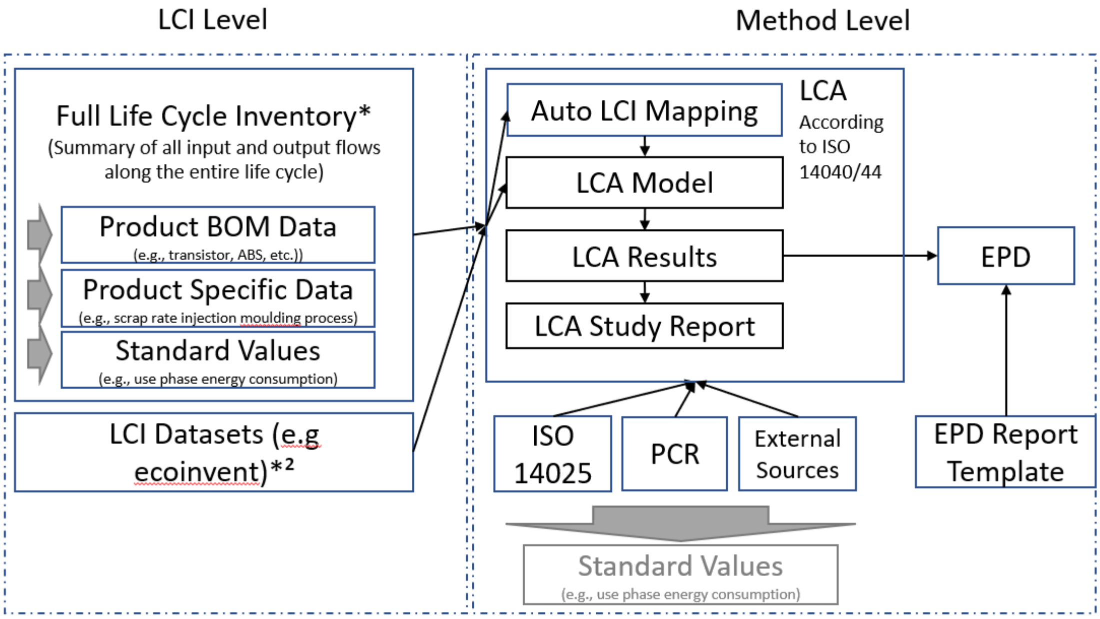

Figure 13 LCI Level Requirements for EPD Workflow

3.2.3 PLM Level Requirements

The PLM Level Requirements separate out all product relevant life cycle stages (shown in Figure 14). For a comprehensive product assessment all product life cycles need to be considered to avoid burden shifting from one stage to another.

When comparing different approaches like the PLM, LCA and DT it becomes apparent that all approaches highlight the importance of looking at the entire product life cycle, however the terms used, and the scope of life cycle stages can be different from one concept to another. Therefore, the workflow contains the terms of the three different concepts and distinguish the different scopes.

From a PLM perspective the product life starts with the new product development process (NPD) such as concept, design, development and prototype/launch before the actual product undergoes the manufacturing, distribution, use and EoL. The DT concept mostly differentiates between the As-Design-Phase analogue to the new product development, the As-Build-Phase analogue to the manufacture and finally the As-maintained-Phase analogue to distribution, use and EoL. The LCA relevant product life cycle stages are mostly similar to the PLM stages after the NPD. However, a particular focus is set on the raw materials as input for manufacturing and also transportation that may take place across all life cycle stages.

The NPD process is not individually separated out within the LCA ISO 14040/44 standards even though the NPD can be part of an LCA. This is different for an EPD. EPDs are used to compare final products for the end-user of the product. In other words, EPDs are used for established products on the market that allow customers to derive purchase decisions based on sustainability criteria. Therefore, the NPD is normally not considered for final product evaluation and depicted as point of cut-off for EPDs within this workflow.

At this point, it should be emphasised that standard LCAs are not made for direct comparison which is mentioned within the ISO 14040/44 standards. As such companies performing LCAs are mostly doing this as an internal activity. Especially for the development of new products the NPD stage should be integrated into the LCA as the biggest leverage can be achieved in early design phases.

Companies learn about the product and production and can take decisions based on the LCA for optimization and can run scenarios for design decisions. Once the product is final for product launch, the EPD assessment can be “added” to the LCA to get harmonized and comparative EPD results.

When looking at the entire product life cycle there is a lot of interaction taking place between different companies along the entire supply chain and in most cases, they all will need to share product relevant data

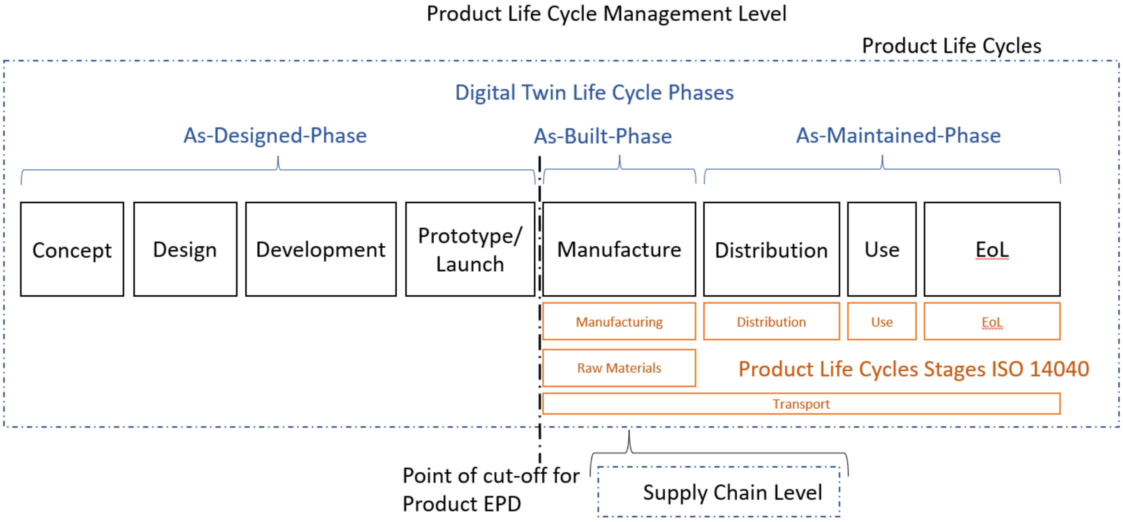

Figure 14 PLM Level Requirements for EPD Workflow

3.2.4 Supply Chain Level Requirements

The Supply Chain Level Requirements depict the interaction between companies along the supply chain but also the structural breakdown of the value chain on a corporate level. When looking at the supply chain level the system boundary used (e.g., cradle-to-gate, cradle-to-grave, etc.) determines the number of companies involved (e.g., supplier, B2B., B2C) and for each company the value chain breakdown becomes relevant as the final product for company A might be a single component for the final product of company B.

The value chain level can itself further be subdivided depending on product complexity and company size. The foreground value chain of product starts on a company level and may be subdivided across different departments, processes and machines before the product level is reached that allows access to product specific information (e.g., BOM).

Additionally, a reference to the materials processing level provides an overview on the level of value creation a given material can go through before it ends up in a or as a final product. Apart from defining the scope of different material processing levels (raw, material, intermediate product, waste and final product) also the type of multi-functionality is an important aspect along the value chain and changes the way companies can treat burdens coming from their activities.

During the material transformation processing inputs like fuel, power and auxiliaries are consumed which cannot always be directly allocated to a specific product. In order to derive product specific data allocation rules are used to come up with product specific shares of the processing input.

On a product level information and data is directly linked to the product and for composed products available as a product BOM. The BOM structure can vary depending on the product complexity and be a hierarchical artifact with further groupings into electrical, mechanical and packaging components. At the end it's a list with BOM entries, Identifiers and materials with a specific quantity and unit used per product.

The Product BOM Data is linked to the LCI Level

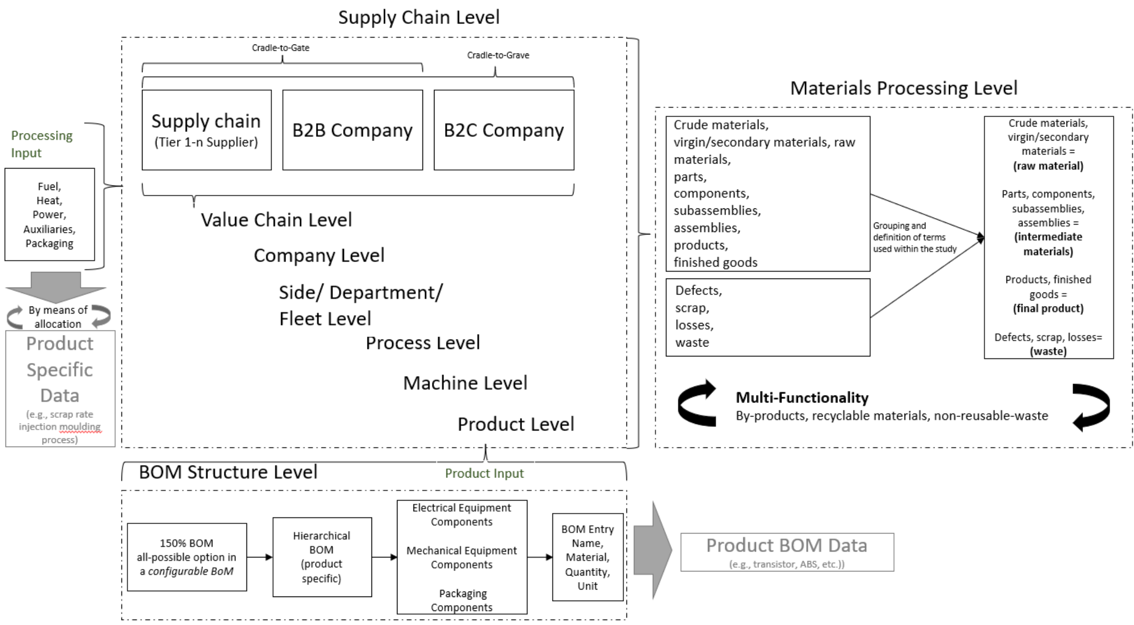

Figure 15 Supply Chain Level Requirements for EPD Workflow

3.2.5 Holistic EPD Workflow

For the holistic EPD workflow all levels and requirements are connected to visualize the overall complexity associated to creating a single EPD (see Figure 16). Even though the single levels itself contain well known relations the overall connection of the different disciplines is rarely done. As elaborated in Section 2.4 and **Fehler! Verweisquelle konnte nicht gefunden werden.** new approaches for integration and/or automation focus mostly on partial aspects of the entire EPD workflow. Especially for the LCA creation the data collection remains a mostly manual process that needs to be done by the LCA practitioner or the LCA commissioner. Even though most of the data needed is already available in a digital form within the companies its mostly hidden in many different tools and Excel Spreadsheets.

Within the EPD workflow data is grouped into three categories (Product BOM Data, Product Specific Data and Standard Values) and highlighted by big grey arrows within the LCI Level. In other Levels these arrows are used again to visualize where this data along the workflow is sourced from. Part of the data could also be gathered at other levels, but the current work focuses on these three areas for completing the EPD workflow.

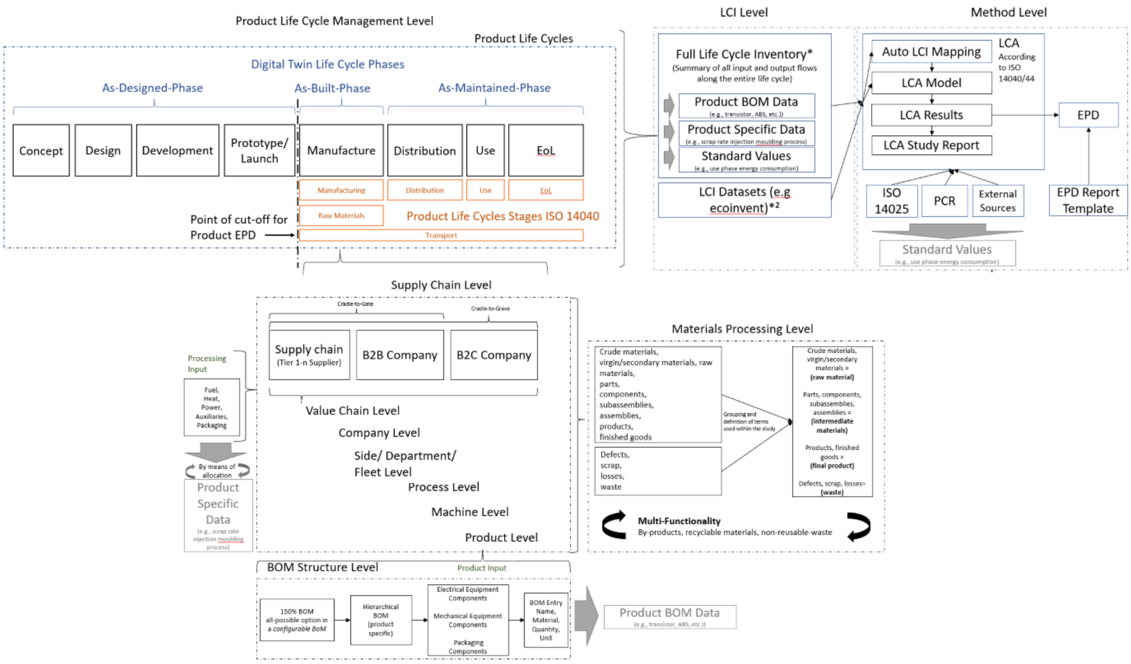

Figure 16 Holistic EPD Workflow

3.3 Software Tools for EPD, MBSE and Digital Twins

For the solution Design and prototypical development of an automated EPD workflow different software solutions were chosen. All of them are used within product analysis and represent state of the art solutions for the three main approaches of LCA, Digital Twin and Model-Based Systems Engineering. In the following the software tools iPoint Product Sustainability, AASX Package Explorer and Enterprise Architect are introduced. For each tool its main functions and applicability with regard to the automation and integration process is explained.

iPoint Product Sustainability

iPoint Product Sustainability (PS) is a web-based LCA software, developed by iPoint-Systems GmbH, in order to assess environmental impacts and efficiencies of production and products as shown in Figure 17. PS as the web application is part of a basic cloud system that connects to different tools, databases and data sources to allow:

- automation of LCA by parameterization, import of bill of materials and auto mapping with LCI data

- enhanced data collection by combining & re-using compliance data as well as connection to internal and external sources and systems like ERP, CAD, etc.
- business integrated and role specific result export and views for sustainability information

[iPoint, 2022 b]

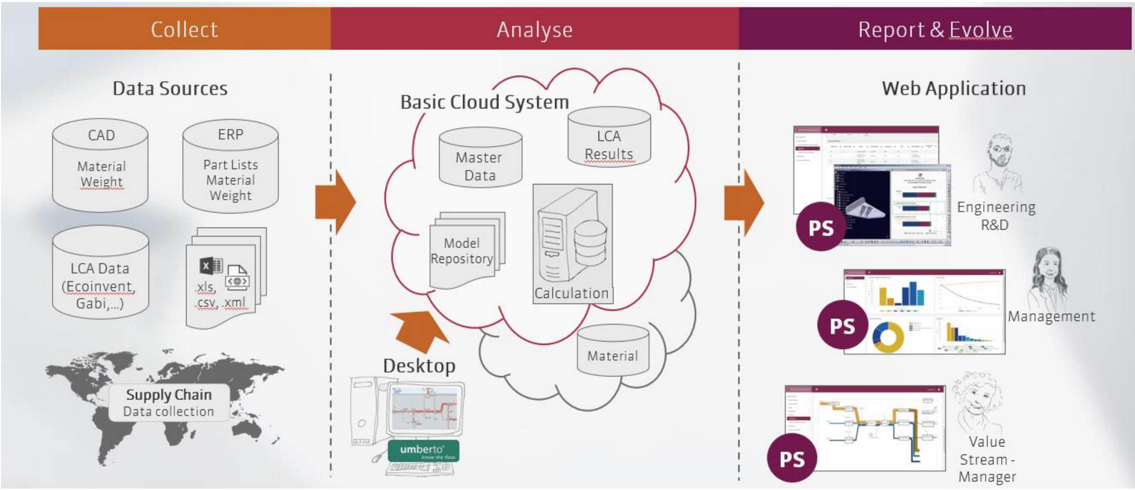

Figure 17 iPoint Product Sustainability

The PS basic cloud system also connects to the desktop application Umberto which builds the foundation for LCA modelling and extension of generic LCA models that can afterwards be used for automated processes. [iPoint, 2022 b]

Umberto itself is based on a graphical system modelling approach in which models are drawn using a Petri-net structure. Transitions are used for processes and can be specified with input and output coefficients, or functions and places allow connecting different processes with each other. This way a model for the manufacturing of certain products or production steps can be created and be used to calculate all material and energy flows which occur according to a functional unit. Thus, it allows performing a material and energy flow analysis based on input/output balances. The tool is also used to perform Life Cycle Assessments. The material and energy flows are used to calculate the impact the production has onto the environment using Life Cycle Inventory (LCI) data, thus, allowing a combined eco-efficiency analysis. [ifu, 2022]

AASX Package Explorer

The AASX Package Explorer is an open source browser and editor for creating Asset Administration Shells as ".aasx" packages for specific use cases in the XML and JSON formats. Concept descriptions are automatically created and referenced. Import and export functions for example for AutomationML and OPC UA allow the integration of other data formats and relevant company data.

The AASX Package Explorer is an open-source implementation that can be downloaded as a compiled software that is licensed under Eclipse Public License 2.0. [PI4.0, 2019]

Enterprise Architect

Sparx Systems Enterprise Architect is a multi-user graphical modelling and design tool based on the OMG UML.

With built-in requirements management capabilities, it helps to trace high-level specifications to analysis, design, implementation, test and maintenance models using UML, SysML, BPMN and other open standards. It supports, the design and construction of software systems; modelling business processes; and modelling industry-based domains.

Enterprise Architect is used by individuals, businesses and organizations to not only model the architecture of their systems, but to process the implementation of these models across the full application development life cycle. In addition, it helps to model and manage complex information. By integrating and connecting a wide range of structural and behavioural information in visual form coherent and verifiable models can be built. [Sparx, 2022]

4 Solution Design for automated EPDs

In the previous section the entire EPD workflow was introduced level by level. Three data types were introduced as well as the need for mapping this data to LCI datasets. Both is necessary to perform the EPD and both, data collection and LCI dataset mapping remain mostly manual activities. The following subsections describe what is needed to transition from a partly manual EPD to an automated EPD.

Three different concepts are explained in more detail. The first elaborates the use of Asset Administration Shells for more consistent and automated data collection along the product life cycle. The second approach focuses on the automation of mapping LCI datasets to intermediate materials for the input output inventory. The third approach examines the need and role of Product Category Rules for enabling automation in areas where data is unavailable, or harmonization needed for comparable EPDs

4.1.1 Consistent and automated data collection

Out of personal experience, data collection for an LCA is in many projects the most resource consuming activity. This is the case for both, the LCA practitioner but also the data provider (often the LCA commissioning company). As already mentioned above, the challenge is the high and detailed data need as well as the situation that in most companies such data is spread across various spreadsheets and departments which makes data review and collection a tedious work. In other cases, especially concerning the supply chain data is not known or validated.

Data collection is an activity that needs to be done across all product life cycle stages, however, for most products product specific data is collected during the manufacturing phase from manufacturer and if needed suppliers.

Asset Administration Shells as introduced in Section 2.2 enable integrated value chains and cross-company interoperability and is therefore potentially the digital basis for automated data collection along the entire supply chain. If AAS are consistently used within the supply chain, each material, intermediate product and final product would contain the information needed to build out the LCI. Each product owner would only need to make sure its own AAS are consistent. Based on that later players within the value chain can reference this information and add on further information in further developed product AASs.

Consistently applied along all product life cycle stages LCA calculations can be supported, automatically launched and results fed back into the product AAS. This would be a huge potential for eco-design during NPD as the source materials AASs already contain Impact Assessments Indicators.

In Figure 18 the EPD workflow is extended in regard to the use of AAS on the supply and value chain level. Different AAS capture business, process and product data and refer to each other wherever connections exist. This allows a machine AAS to store its processing input parameter and energy consumption as well as the number of products produced. A product AAS links to a BOM Submodel and also to the machine AASs that were used for its production.

The AAS can be used for further life cycle stages including transportation, distribution, use and EoL. However, from an EPD perspective the biggest potential lays within the raw material and manufacturing phase as real data can be used in a post-production EPD (i.e., for an EPD it is assumed that products are already on the market and real manufacturing data is available). For later life cycle stages, assumptions and predictions need to be taken or standardized (please refer to section 4.1.3). Still, at the end of the product life AAS data from the remaining life cycle stages could be compared a posteriori with the assumptions taken.

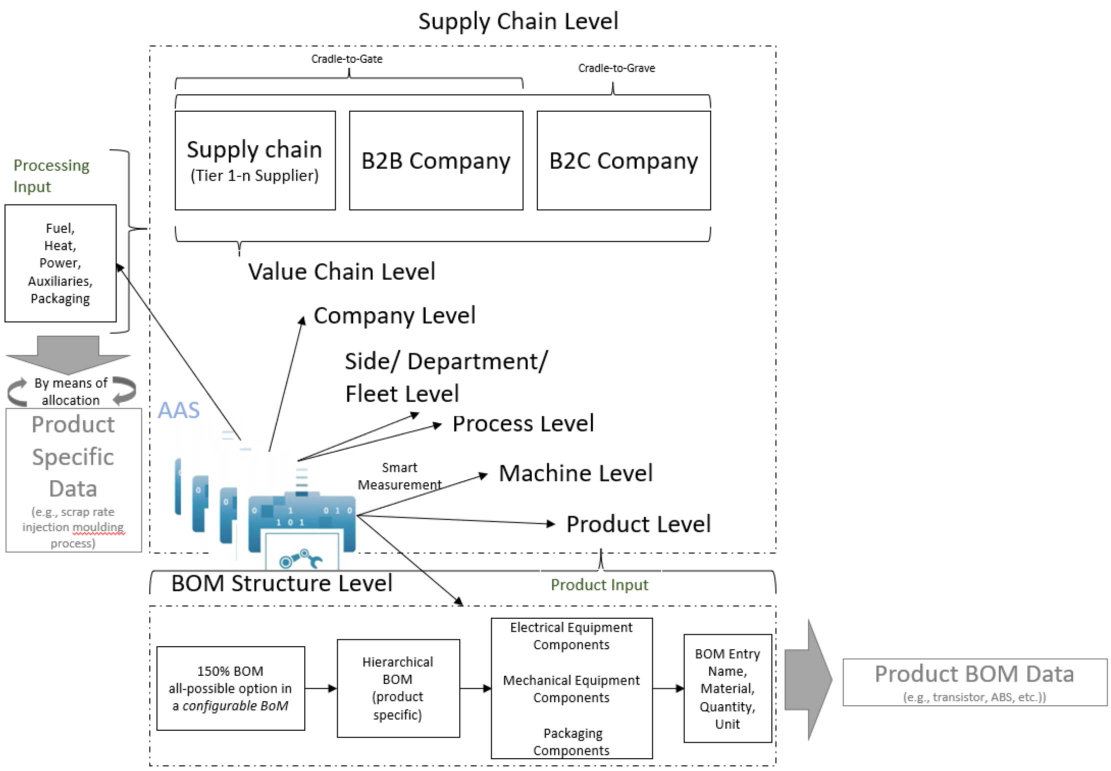

Figure 18 Application of AAS on Supply and Value Chain Level

Overall, the application of AAS can leverage huge potentials for automating data collection for EPDs. At the same time the development of AAS specifications and templates that could be used for such exercises are still at the very beginning and even basic templates (e.g., product BOM Template) are yet to be developed.

More information on concrete AAS developments needed is given in section 4.2

4.1.2 Auto LCI Dataset Mapping

The quality of the LCI data mapping to materials used for production is directly impacting the quality of the overall LCA results at the very end. Only if the materials used are appropriately mapped, it will provide meaningful results. Again, LCI datasets are used whenever primary data regarding the use of certain raw materials and intermediate products is available but the pre-chains itself are unknown. This is for instance often the case for electronic components such as Printed Circuit Boards. At the same time the pre-chain of the PCBs must somehow be known in order to build out the entire LCI of a PCB production. Whenever this information is missing LCI dataset providers such ecoinvent provide LCI datasets that already capture the pre-chains of thousands of materials. Also for PCBs. However, there may be several datasets for different types of PCBs. Consequently, the person doing the mapping will need a good understanding of the actual PCB used for the product (e.g., surface-mount, through-hole-mount, number of layers etc.) as well as a good understanding of the LCI dataset coverage for being able to do the best possible mapping. In cases, where no ideal mapping is possible the mapping person should also know the limitations and possible effects of ‘not so good’ mappings.

It becomes clear that this activity requires a lot of expertise and resources in different domains and a lot of interactions between LCA practitioners and manufactures. For complex products with many different components, material types and complex supply chains this becomes an almost never-ending iterative approach.

Confidentiality can be an issue too as NDAs between manufacturers and suppliers don’t allow to share compositions and datasets with third parties (e.g., the LCA consultant) that would need this information to do good fitting mappings.

In order to resolve those challenges, LCA software developer and consultants such as iPoint work on improving and automating mappings. A functioning automated mapping will therefore increase the current status in many ways:

- Enable non experts to create high quality LCAs
- Reduce the manual effort that is needed to create high quality mappings
- Improve the overall quality of mappings and thereof the LCA study results

iPoint currently works on a feature for automated LCI Mappings that combines the use of mapping hints with search algorithms, artificial intelligence and shared Library Creation for best available (most representative) LCI dataset mapping. The use of mapping hints and search algorithms scan for instance BOM entry specifications like materials part name and part specifications for information that is checked against available LCI datasets. The use of AI and shared libraries store and dynamically update a mapping library that grows with the number of datasets available, and the number of mappings already performed.

At the end, the level of detail known regarding a certain material will influence the quality of an automated mapping. Here again, AAS can be useful if they contain standardised specifications that can be used for the automated mapping process.

4.1.3 Creation of harmonised PCRs

Product Category Rules allow for harmonisation and standardisation in situations where product category specific data gaps or uncertainties exist. This can be among others:

- Suggested LCI Dataset mappings (e.g., fixed national energy grid mixes if final product destination is unknown)
- Harmonized Product Modelling Assumptions (reference product lifetime, predicted EoL split, etc.)
- Defined Product Modelling principles (use of avoided burden approach for handling multifunctionality)
- Defined Product Impact Assessment (e.g., the use of given evaluation methods and impact categories)

From a PCR perspective the overarching goal is to obtain comparability between products of the same product category. At the same time this supports the automation process as PCRs can be transferred to LCA software.

So far, the use of EPDs is most progressed within the building sector where EPDs are in some cases already required (Quelle). Here a specific standard EN 15804 is already well established and many PCRs for different types of building products are available. EPD Program Holders (e.g., IBU, Environdec, etc.) exist and further develop and streamline the process. They coordinate the consistent creation of new PCRs and validate the correct application in mandatory critical review processes before an EPD can be published.

The European Union is developing Product Environmental Footprints for consumer products (batteries, wine, cleaning detergents, etc.), acts like a program holder and goes one step further by even providing corresponding LCI datasets to be used within PEF studies.

All in all, the use of PCRs and the derived standard values is crucial to allow increased automation of the LCA and EPD creation and further development of PCRs in all kinds of domains is needed.

4.2 Conceptual Development for automated EPD using AAS

Within the following subsections the above-mentioned concepts are integrated into the EPD workflow providing the final representation of the automated EPD workflow. The three integrated concepts are put into perspective and a rational given for the continuing work on AAS.

Additionally, the current state of AAS for sustainability evaluation and available templates is depicted and further AAS submodel configurations and templates needed are outlined considering the requirements of an aEPD.

4.2.1 Generic aEPD Workflow Overview

All three concepts for automating the EPD workflow are combined in Figure 19. The general use of AAS is visualized on the different sublevels. Between the Method Level and the PLM Level an additional link is introduced as EPD data itself should be fed back to the AAS concerning the product of interest. Eventually, the different AAS would link to all three data types needed (Product BOM & Product Specific Data as well as Standard Values) and the manual activity of LCI dataset mapping is replaced by an auto LCI mapping.

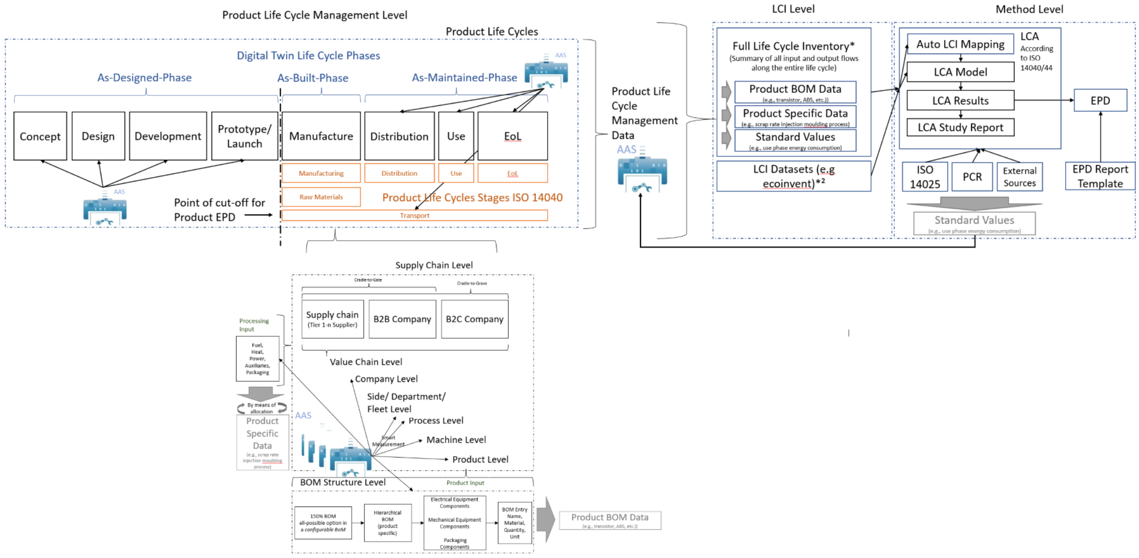

Figure 19 Complete aEPD Workflow

4.2.2 Rationale for Focussing on AAS concept within aEPD Workflow

As seen above the automation of EPDs still requires further work in different areas and three main concepts are highlighted. Within the scope of this work only the AAS concept is further looked at in more detail due to several reasons:

- AAS is an emerging discipline with great potential to allow automation of the entire EPD workflow.
- Automation of data collection and exchange has the biggest improvement potentials for an EPD creation. Especially, here AAS is promising as an enabler
- The Industry 4.0 development activities including the further design of AAS has just started. Generally, sustainability aspects should be considered in early design phases. This is also true regarding LCA requirements for AAS template development. Therefore, LCA experts and tool developers should get involved to contribute with their requirements into the Industry 4.0 development
- For AAS there are some links to Product carbon Footprint and BOMs and many potential use-cases are called out but the actual development of templates that can be used for EPD creation is yet to be done.
- Automated LCI dataset mapping is currently being developed
- EPD program holders and EU already extend their spectrum for PCRs and verification

4.2.3 AAS Submodel Templates for aEPD

For the use of AAS within the aEPD workflow a number of different submodels is needed to describe the content-related or functional aspects of the assets. Generic and specific submodels are available via “Plattform Industrie 4.0” and “The Industrial Digital Twin Association (IDTA)”. With about 30 open submodels and only 5 of those being released [IDTA, 2022] only a very limited set is currently available. In the following, a list of submodels is given which would be needed as minimum requirements for allowing the consistent application of AAS for the aEPD workflow. Additionally, the submodels are grouped into Product Related AAS, Process Related AAS and Overhead Related AAS.

Product Related AAS Submodels

Product related AAS submodel templates define content-related product information and allow to derive the input/output flow inventory.

- Hierarchical Structures enabling Bills of Material
    - currently in development by IDTA
    - internal version available to Fraunhofer IESE [IDTA, 2022b]
    - “This Submodel template aims at interoperable provision of hierarchical entities and relations which are applicable for industrial equipment. This industrial equipment, for example production lines, modules and sub systems, are provided by partners in the value chain, such as suppliers, equipment manufacturers and systems integrators and used in specific applications by industrial operators and end users, both in factory as also process automation. Industrial equipment can be composed of sub systems down to material and component level, described on type or instance level and can include produced products.

      Already in the design phase, assets are composed and aggregated into hierarchical structures. As some assets are parts of larger assets, they may each have their own AAS. Since nesting of AAS and Submodels is forbidden by the meta-model, this submodel shall describe the internal structure of an asset. It shall allow the consumer to identify components and find their respective AAS if they exist. The submodel serves as an index pointing to Assets and AAS in a distributed network capable of transcending the limits of a single organization. Instances, of this Submodel Template shall be the authoritative source for topological structure within an AAS during all lifecycle phases. Complementing information about each component and their own lifecycle phase shall be made discoverable into the n-th tier, depending on the design of the Submodel Instance." [IDTA, 2022b]

  - Output needed: Defined structure for a generic part topology

- Specific BOM
  - Not currently existing
  - As the above mentioned hierarchical submodel only defines the structure for a generic part topology an additional submodel is needed for modelling a specialized type of BOM.
  - Output needed: Specification for a detailed structure for any specialized type of BoM
- Unit/Result Process Elementary Flow LCI
  - Not currently existing
  - All elementary input and output flows for the unit/result process of the product. The aggregated elementary flow inventory contains all flows across the supply chain but does not allow any inferences to confidential data
  - Output needed: List of elementary input and output exchanges as well as quantity and unit used
- Product Carbon Footprint
  - Proposal Submitted by IDTA
  - internal version available to Fraunhofer IESE [IDTA, 2022c]
  - "This Submodel template provides the means to exchange an asset`s Carbon Footprint (CF) between the partners along a value chain. The aim of this Submodel is to increase the interoperability between the parties, who are interested in documenting, exchanging, evaluating or optimizing the environmental footprint of their assets. These parties can for example be manufacturers, users/consumers or logistic partners. The CF might be part of larger initiatives such as the Digital Product Passport or the Product Environmental Footprint. It is not the scope of this Submodel template to provide the details of the CF-calculation and it does not substitute the relevant certificates." [IDTA, 2022c]

- A more detailed analysis of this submodel is given below in Section 4.2.4
- Would need further extension to cover all EPD impact categories

Process Related AAS Submodels

Process related AAS submodel templates define content-related sensor, machine or process information and need to be allocated to the evaluated product to complete the input/output flow inventory.

- <u>Foreground Consumables</u>
  - Not currently existing
  - Primary data on energy, heat, auxiliaries consumed during foreground production
  - Output needed: List of fuel, heat, power and auxiliars as well as quantity and unit used
- <u>Sensor</u>
  - Proposal submitted by IDTA
  - No further definition by IDTA
  - Allowing to get processing asset specific sensor data on various different sensor types for continuous production
- <u>Process Batch</u>
  - Proposal submitted by IDTA
  - “The objective is to propose a model for the definition of AAS for industry-specific assets of batch-manufactured products based on the ISA 88 standard, which makes it possible to digitally represent information related to the production recipe, as a step towards the digitization of the product life cycle.” [IDTA, 2022]

Overhead Related AAS Submodels

Overhead related AAS submodel templates define content-related corporate and infrastructural consumables or functional aspects to allow for specific product allocation of overhead or process induced consumptions.

- Material Integration
  - Proposal submitted by IDTA

  - "Generic integration of material and product information as an ontology to provide a uniform data model on needed usage levels in different steps" [IDTA, 2022]
- Plant Asset Management
  - currently in development by IDTA
  - "The submodel describes the plant asset management aspects of production plants in the process industry. It refers to the condition and criticality of assets in production processes, as well as to functions and methods for providing all relevant information to asset managers. It also forms the basis for the development of PAM methods."
  - Output needed: Allocation rules for overhead and process related data for product specific inventory
- IT Asset Management
  - Not currently existing
  - IT infrastructure is needed for smart production and the use of Industry 4.0. The submodel template shall aim at providing functions and methods as well as links to IT assets used for providing relevant information on the material and energy consumption.

From an inventory perspective the above stated submodels should be sufficient to derive the data needed. However, only during development and application of the submodels the final confirmation can be made that this list is overall sufficient. Also, because the current list tries to use current developments as far as possible even though the general descriptions of some submodels remain vague. Therefore, they may eventually provide other aspects then currently assumed.

4.2.4 AAS Carbon Footprint Submodel Details

As the Carbon Footprint submodel is coming closest to the impact assessment requirements that are needed for the creation of an EPD it is assessed in more detail.

The basic design of the Submodel template can be used to address the carbon footprint using different standards, calculation methods or assumptions. For the development of the submodel template a number of different standards was considered such as: [IDTA, 2022c]

- ECLASS
- ISO 14067 - Greenhouse gases — Carbon footprint of products

- ISO 14040, 14044 - Environmental management — Life cycle assessment
- EN 15804 - Building Sustainability — Environmental Product Declarations — Basic Rules for the Product Category of Building Products
- EN 16258 - Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)
- IEC TS 63058 - Switchgear and control gear and their assemblies for low voltage - Environmental aspects
- GHG Protocol - Greenhouse Gas Protocol
- PEP Ecopassport - Product Environmental Profile Ecopassport
- World Business Council for Sustainable Development (WBCSD)
- Catena-X

Therefore, it is in line with most of the standards referenced already for the EPD creation. Especially, the EN 15804 is one of the most important standards for EPD creation as mentioned in Section 2.4 and its consideration within the submodel templated allows the direct use for the EPD workflow outlined so far. However, the PEF standard as one of the most important emerging EPDs is not further accounted for.

According to IDTA the first version of the Submodel specification focusses on the ECLASS model and therefore distinguishes between the Product Carbon Footprint (PCF) and the Transport Carbon Footprint (TCF) calculation. It is additionally stated that it currently supports EN 15804, ISO 14040, ISO 14044, ISO 14067, IEC TS 63058, GHG Protocol, PEP Ecopassport for the PCF and EN 16258 for the TCF. [IDTA, 2022c]

The outline of the current draft for the PCF submodel is shown in Table 1 for better understanding as excerpt of the original table within the CF submodel template document.

Table 1 Product Carbon Footprint Template as excerpt from [IDTA, 2022c]

idShort:	ProductCarbonFootprint{00} Note: a different idShort might be used, as long as it is unqiue in the Submodel.
Class:	SubmodelElementCollection (SMC)
semanticId:	[IRI] 0173-1#01-AHE694#001
Parent:	SM CarbonFootprint (0173-1#01-AHE689#001)

<table>
<tr><td>Explanation:</td><td colspan="3">Balance of greenhouse gas emissions along the entire life cycle of a product in a defined application and in relation to a defined unit of use</td></tr>
<tr><td>[SME type]</td><td>semanticId = [idType]value</td><td>[valueType]</td><td>card.</td></tr>
<tr><td>idShort</td><td>Description@en</td><td>example</td><td></td></tr>
<tr><td>[property]
PCFCalculationMethod</td><td>[IRI] 0173-1#02-ABG424#001
PCF calculation method. Standard, method for determining the greenhouse gas emissions of a product
List of suggested values
<table><tr><td>Value Code</td><td>Value</td><td>Value id</td></tr><tr><td>1</td><td>ISO 14067</td><td>0173-1#07-ABO271#001</td></tr><tr><td>2</td><td>PEP Ecopassport</td><td>0173-1#07-ABO273#001</td></tr><tr><td>3</td><td>GHG Protocol</td><td>0173-1#07-ABO274#001</td></tr><tr><td>4</td><td>IEC TS 63058</td><td>0173-1#07-ABO275#001</td></tr><tr><td>5</td><td>EN 15804</td><td>0173-1#07-ABO276#001</td></tr></table></td><td>String
“ISO 14067”</td><td>1</td></tr>
<tr><td>[property]
PCFCO2eq</td><td>[IRI] 0173-1#02-ABG425#001
Sum of all greenhouse gas emissions of a product according to the quantification requirements of the standard</td><td>Double [kg]
17.2</td><td>1</td></tr>
<tr><td>[property]
PCFReferenceValueForCalculation</td><td>[IRI] 0173-1#02-ABG426#001
Quantity unit of the product to which the PCF information on the CO2 footprint refers
<table><tr><td>Value Code</td><td>Value</td><td>Value id</td></tr><tr><td>1</td><td>piece</td><td></td></tr><tr><td>2</td><td>Cbm</td><td></td></tr><tr><td>3</td><td>g</td><td></td></tr><tr><td>4</td><td>kg</td><td></td></tr><tr><td>5</td><td>l</td><td></td></tr><tr><td>6</td><td>ml</td><td></td></tr><tr><td>7</td><td>qm</td><td></td></tr><tr><td>8</td><td>t</td><td></td></tr></table></td><td>String
“piece”</td><td>1</td></tr>
</table>

<table>
<tr>
<td>[property]
PCFQuantityOf-MeasureFor-Calculation</td>
<td>[IRI] 0173-1#02-ABG427#001
Quantity of the product to which the PCF information on the CO2 footprint refers</td>
<td>Double
5.0</td>
<td>1</td>
</tr>
<tr>
<td>[property]
PCFLiveCyclePhase</td>
<td>[IRI] 0173-1#02-ABG428#001
Life cycle stages of the product according to the quantification requirements of the standard to which the PCF carbon footprint statement refers
List of suggested values
<table>
<tr><th>Value Code</th><th>Value</th><th>Value id</th></tr>
<tr><td>1</td><td>A1 – raw material supply (and upstream production)</td><td></td></tr>
<tr><td>2</td><td>A2 - cradle-to-gate transport to factory</td><td></td></tr>
<tr><td>3</td><td>A3 - production</td><td></td></tr>
<tr><td>4</td><td>A4 - transport to final destination</td><td></td></tr>
<tr><td>5</td><td>B1 – usage phase</td><td></td></tr>
<tr><td>6</td><td>B2 – maintenance</td><td></td></tr>
<tr><td>7</td><td>B3 – repair</td><td></td></tr>
<tr><td>8</td><td>B5 – update/upgrade, refurbishing</td><td></td></tr>
<tr><td>9</td><td>B6 – usage energy consumption</td><td></td></tr>
<tr><td>10</td><td>B7 – usage water consumption</td><td></td></tr>
<tr><td>11</td><td>C1 – reassembly</td><td></td></tr>
<tr><td>12</td><td>C2 – transport to recycler</td><td></td></tr>
<tr><td>13</td><td>C3 – recycling, waste treatment</td><td></td></tr>
<tr><td>14</td><td>C4 – landfill</td><td></td></tr>
<tr><td>15</td><td>D - reuse</td><td></td></tr>
</table>
</td>
<td>String
“C4 - landfill”</td>
<td>1..*</td>
</tr>
<tr>
<td>[SMC]
PCFGoodsAddressHandover</td>
<td>[IRI] 0173-1#01-AHF552#001
Town, city or address where the product is handed over
(use structure defined in Fehler! Verweisquelle konnte nicht gefunden werden. Fehler! Verweisquelle konnte nicht gefunden werden.)</td>
<td>n/a</td>
<td>1</td>
</tr>
</table>

Whereas it's stated that for instance ISO 14067 and EN 15804 are supported the template, however, does not allow further segregation of the CF into biogenic and fossil carbon. Both ISO 14067 and EN 15804 require separate GHG emissions reporting. For instance, ISO 14067 states within "6.4.9 .2 Fossil and biogenic carbon" that fossil GHG emissions and biogenic GHG emissions should be expressed separately [ISO 14067, 2018].

Apart from the above-mentioned standard compliance issue, further challenges remain regarding the missing impact categories that are needed for a full EPD containing a defined list of impact indicators where the GWP is only one of many.

For the application of the submodel within the automated EPD workflow there would therefore be an extension be needed or similar submodels with additional impact categories.

4.3 Limitations and Challenges for an aEPD

Work on the development of the aEPD workflow followed the objective of delivering a solution that allows creating automated EPDs with the smallest achievable effort. As temporal and personnel resources are limited by the scope of a master thesis, the functions and scope of the aEPD workflow had to be limited and sometimes compromised. Consequently, the aEPD workflow has several limitations in regard to the usability of IoT, the data availability and methodological completeness. In the following, the categorised limitations are listed and described.

The IoT usability limitations originate from the level of acceptance, implementation and use of smart manufacturing requirements in the industry

- The Industry 4.0 approach including the AAS development is still at the very beginning regarding submodel development and not yet applied on a broader industry. Submodel templates are however needed to guarantee the level of standardization and interoperability. Full industry adaptation can only take place if sufficient models are available and practical prove of concept is generated.
- The specific submodel template content is currently estimated on short general descriptions if available. There is a risk that the actual outline once

available is different to what is exactly needed for the EPD workflow. Therefore, after the release of each submodel the actual content needs to be checked.

- There is uncertainty on the level of industry acceptance and application regarding the Industry 4.0 activities due to the diverse concepts currently developed regarding digital twin approaches on a national and international scale.
- Smart manufacturing infrastructure needs to be implemented across the value chain to allow for the consistent application of the Industry 4.0 concept.

Further limitations come from restricted, missing, or erroneous data availability along the entire product life cycle.

- Certain data is missing and/or not captured at all (e.g., often the case for manual and handmade activities
- Confidentiality may restrict the exchange of product and process related data even though data is generally available. (e.g., recipes and allocation methods)
- Potential risk that data that is available at first glance turns out to be faulty. For instance, BOM data or ERP data is not always usable due to inconsistencies or wrong specification along different workflows. This appears across different companies but even within companies.

Methodological completeness

Lastly limitations come from restricted coverage of the underlying approaches used.

- An EPD only considers environmental LCA without looking at economic and social aspects for allowing a sustainability LCA. Whereas, the data handling and automation will also support this aspect, it is not currently covered by the EPD standard. And especially the social LCA is still under further development and missing a standardization process. Standards however are critical to allow automation.

Generally, it should be mentioned that data availability and data processing is very specific to each product case. This still may require the manual entry of initial data into the workflow even though there is an aEPD workflow implemented.

4.4 Model-Based Approach for Automated EPDs

The model-based approach for automated EPDs is based on the full EPD workflow system model and the connection to the data model. The data model contains the toolchain of the above introduced software tools. Figure 20 shows the overall Model-Based approach for automated EPDs.

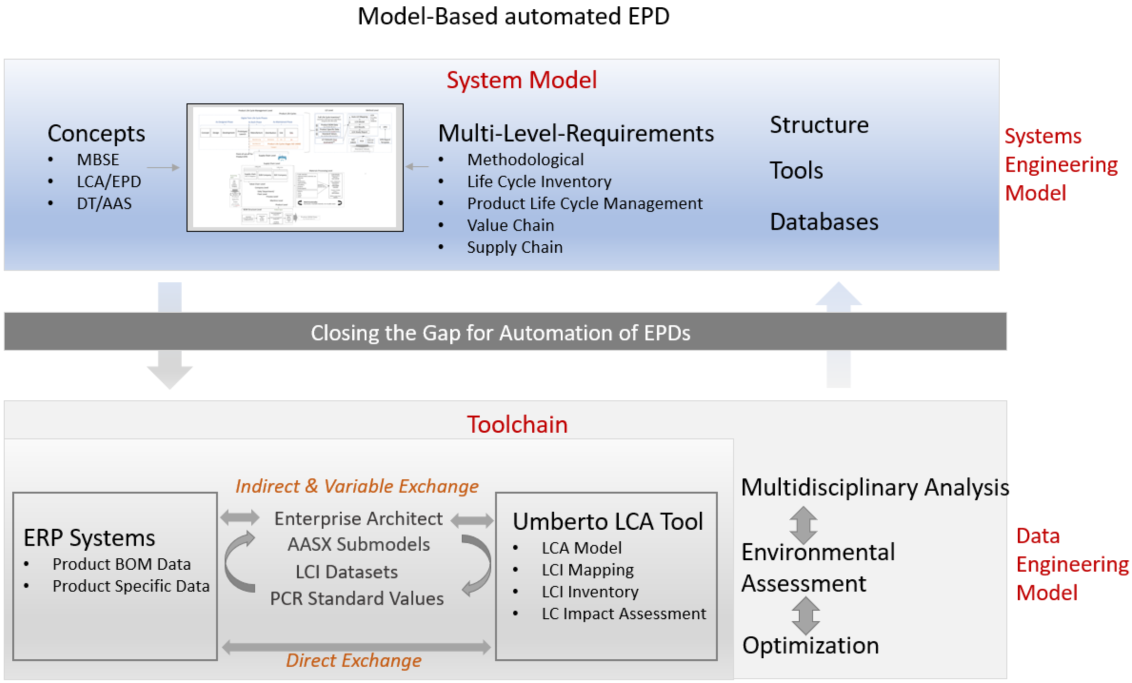

Figure 20 Model-Based Approach for Automated EPDs

The central piece is the automated EPD workflow system model containing the multi-level requirements engineering derived form the core disciplines such as MBSE, LCA and DT. In addition, the system model contains references to its structure, tools and databases. For actual implementation the EPD workflow needs to be connected to the defined toolchain as data engineering model. Here connection to product data from ERP Systems is realized via a combination of Enterprise Architecture, AASX submodels, LCI Datasets and PCR data that is indirectly and directly used by the LCA Software Umberto for LCA Model creation and LCI Mapping to build out the products full LCI Inventory as baselined for the final impact assessment and EPD creation. As such, the system model with a connected toolchain eventually closes the gap for automation of EPDs. MBSE is in this set up the overarching concept to address and manage the multi-level requirements engineering along the entire product lifecycle coming from different disciplines and bringing this is in alignment with the toolchain for practical application.

Whereas the system model is well defined during the concept development and the solution design of the holistic EPD workflow regarding the different levels and life cycle stages with fixed references to Product Bom Data, Product Specific Data and Standard Values, the actual approach for data retrieval within the toolchain is variable in a case specific manner. This means that the exact interconnection of the company data with the LCA tool via SysML modelling, AAS submodels, LCI datasets and PCR Standard Values can vary with each product type as well as with the conditions for the value chain partners where automation is targeted. This is due to the situation that the level of digitalization along the value chain for instance determines if and to what extend AAS submodels are available on the one hand. Or on the other hand what PCRs and LCI datasets are generally available regarding the different product types. Therefore Figure 20 shows the indirect and variable data transfer solutions that can be used in different combination and to different extend by varying product types and associated companies.

The prototypical implementation in the next chapter will show defined exchange settings for a given product for further reference.

5 Prototypical Implementation of an aEPD for an Electric Motor

After the new concept for a model-based automated EPD workflow was introduced in the previous chapter a partial application of the automated workflow is performed on an electric motor. The objective of the case study is to prove the concept and its applicability in a real case as well as providing product specific data for better understanding of the conceptual workflow with real data. In addition, this case study can serve as a guide for other companies that may want to implement the workflow in future projects. The main focus is on the automation of the data collection, and an analysis allowing the identification of open research items for further automation potentials in the future.

5.1 Overview: of an Electric Motor EPD

In the following the entire workflow for the prototypical solutions is outlined in a use case diagram. The diagram provides a general overview of the Stakeholders involved, their interactions and the different use case steps needed for the creation and finalisation of an aEPD. In the subsequent sections, the individual steps are then addressed in more detail to allow traceability of the specifications for the electric motor product specific aEPD implementation.

The use case diagram shown in Figure 21 depicts the general procedure for the creation of an electric motor Environmental Product Declaration. The initiation of an EPD is coming from the motor manufacturer that decides to create a product specific EPD for a given product. This can be depending on the company size for instance the CEO, sustainability department, product owner, etc. The motor manufacturer firstly gets in contact with an LCA practitioner to request the creation of an EPD. The LCA practitioner can be an external LCA consultant or an internal LCA expert that is commissioned to perform the underlying LCA.

In a first step the LCA practitioner and motor manufacturer agree on a data collection and exchange approach that iteratively is used to collect and gather all necessary data. To a large extend this will be primary data from the manufacturer but where necessary further data from the supplier. Supplier data is collected via the manufacturer with direct supplier connection or via the LCA practitioner. Where no or not sufficient data is available, LCI datasets are used to close open data gaps. In most cases the LCI data provider that disseminates generic datasets such as ecoinvent is not involved within the EPD creation. However, as an automated approach will eventually also allow to feed back primary data to the LCI data provider for the extension of product generic data coverage, this is included within the diagram.

Together with the start of data collection also the corresponding PCR is selected. In this case the DIN 50598-3 is mainly used as available PCR and PSR for electric motors. Based on the product data coming from the motor manufacturer and the supplier the LCA practitioner creates an LCA model in accordance with the ISO 14040/44 and the extended assumptions, requirements and modelling principles provided by the PCR.

The LCA model creation is performed with iPoint Product Sustainability including Umberto to gather all data and modelling decisions in an established tool which also ensures to be in line with the basic principles stated in EN ISO 14040ff and ILCD guidelines as required by EN 50598-3.

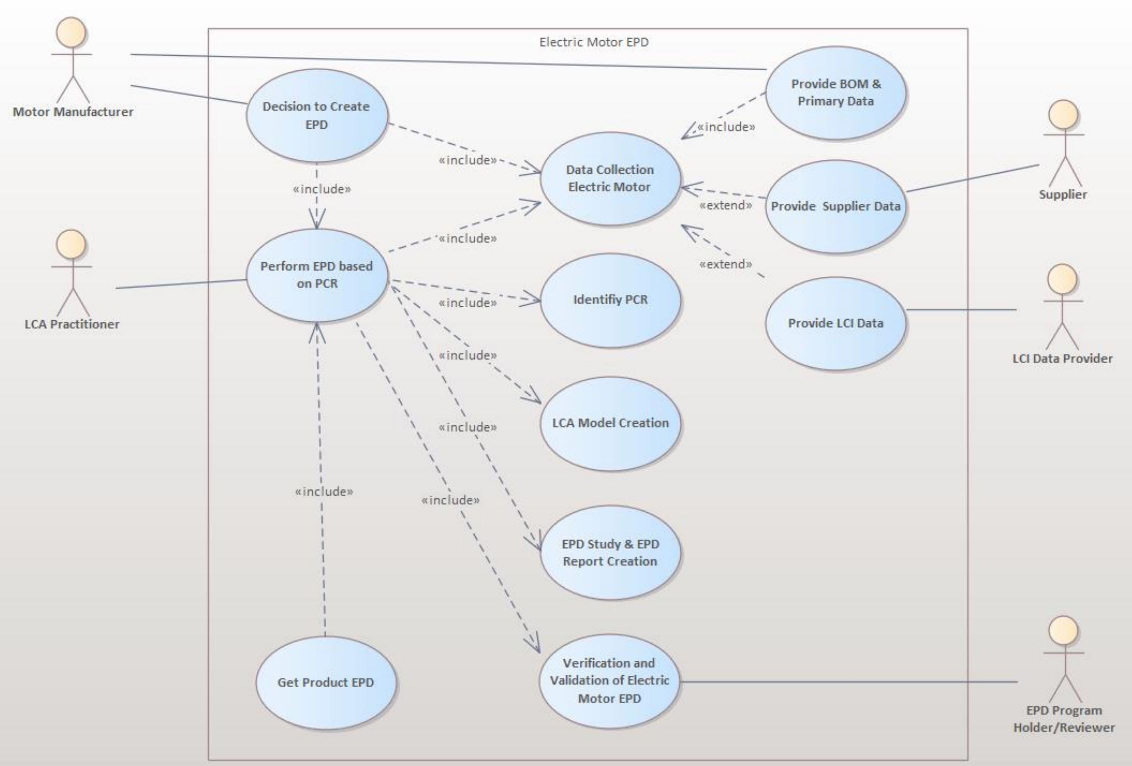

Figure 21 Use Case Diagram for the Creation of an Electric Motor EPD

Once all relevant data is collected according to the environmental hotspots the LCA study report documentation is finalized as well as the corresponding EPD report. Both is sent to the EPD program holder that performs a critical review and if approved also publishes the EPD.

As the EPD initiation phase and the EPD finalisation phase are standard procedures that are clearly described by the corresponding standards and program holder guidelines, the following subsections focus on the overall data collection and management that is needed to perform and automatize the core EPD creation.

The outlined use case and workflow is representing a real case project set up. However, the underlying data is collected from different sources as publicly available. Therefore, it is important to highlight that the outcome generically proves the feasibility but does not provide real EPD results. This also means that no other stakeholder was directly involved to get primary data and that no third-party review was performed regarding this specific electric motor use case.

5.2 General Product Information on Electric Motor

The examined electric motor is assumed to be a generic asynchronous motor as a combination of a gearmotor and a frequency inverter shown in Figure 22. Consequently, the product contains mechanical, electromechanical and also purely electronic components and parts.

SEW Eurodrive publishes technical data sheets, product descriptions and motor designs that are used as basic information for the motor type and the motor composition [SEW, 2022 a, b, c]. Generally, the asynchronous motor consists to a large extent of copper (windings), gray cast iron and aluminum (housing), sheet metal (rotor, stator).

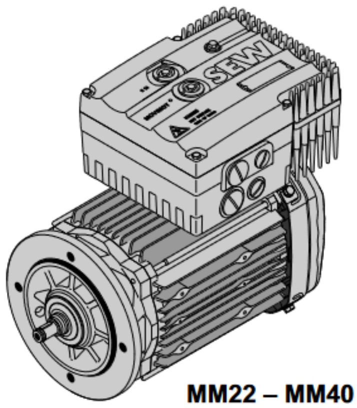

Figure 22 Generic Motor including Inverter [SEW, 2022 a]

In Appendix 2 the basic structure of the AC motor is shown as well as a technical specification sheet that allows the derivation of nominal power consumptions and conditional parameters such as efficiency grades.

5.2.1 Product BOM Data

Based on the information available a general BOM extract is created in a block definition diagram shown in Figure 23. Here the hierarchical BOM elements are shown and how the final product is assembled from parts and components such as the stator and screws.

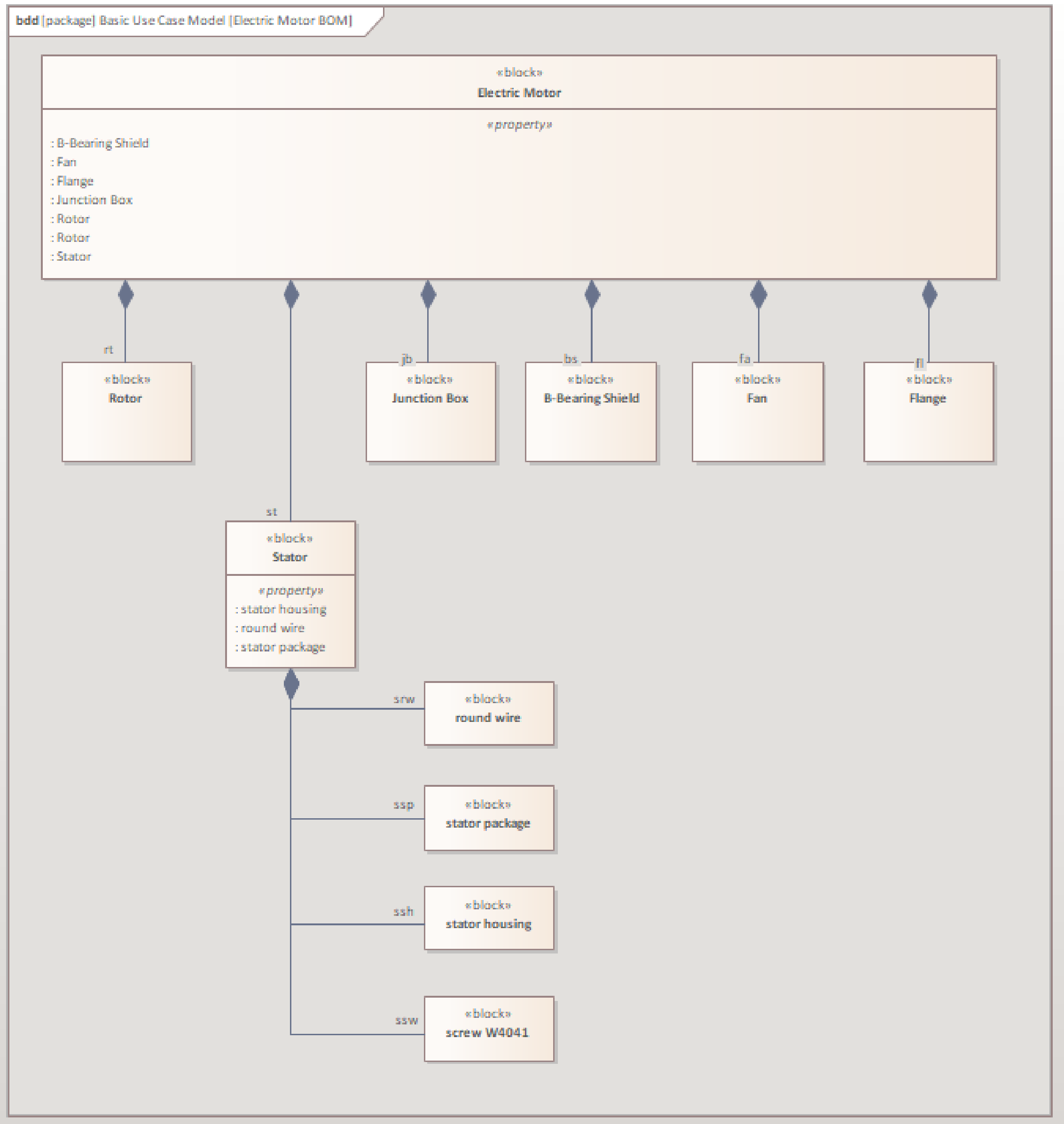

Figure 23 Basic BOM Structure for Electric Motor

The same excerpt is also shown for the Umberto BOM import that allows to import product BOMs into the LCA model shown in Table 2. As the product BOM structure provided by the motor manufacturer is different from the import structure used by the LCA tool, the BOM information currently need to be restructured manually or semi-automated by using macros. The Umberto BOM import is representing the same information in a tabular format that connects product parts and components together with its quantity.

Currently company specific automation is possible by ERP system integration but depending on the systems and set ups used this is different for each company. Here the AAS together with submodel templates such as the “IDTA 2011-1-0 Hierarchical Structures enabling Bills of Materials” [IDTA, 2022b] will eventually allow full automation between any organisation if this template is fully integrated. The above-mentioned template however only defines the structure for a generic part topology but does not specify a detailed structure for a specialized BOM type.

Table 2 Umberto Production Order for BOM Import

Production Order Electric Motor

Name	Elctric Motor	
Final Product	Electric Motor	
Quantity	1	pcs
Start	2022-02-09T00:00:00+01:00	
Completion	2022-02-09T00:00:00+01:00	

Assembly	Quantity	Unit	Process	Component	Quantity	Unit
Electric Motor	1	pcs	Motor Assembly	Rotor	1	pcs
				Stator	1	pcs
				Junction Box	1	pcs
				B-Bearing Shield	1	pcs
				Fan	1	pcs
				Flange	1	pcs
Rotor	1	pcs	Rotor Assembly	Rotor	1	pcs
Stator	1	pcs	Stator Assembly	Round Wire	1	pcs
				Stator Package	1	pcs
				Stator Housing	1	pcs
				Screw W4041	1	pcs
Junction Box	1	pcs	Jubction Box Assembly	Junction Box	1	pcs
B-Bearing Shield	1	pcs	B-Bearing Shiled Production	B-Bearing Shield	1	pcs

Fan	1	pcs	Fan Assembly	Fan	1	pcs
Flange	1	pcs	Flang Production	Flange	1	pcs

For this prototypical implementation no motor manufacturer was involved to get a complete product BOM. Therefore, the exact electric motor composition is approximated by using secondary LCI data from ecoinvent (Version 3.8 Allocation, cut-off, EN 15804) [Ecoinvent, 2022b]. Here, the "electric motor production, vehicle (electric power train)(GLO)" dataset is used. The exact specification on tier-1 level is shown in Table 3. The input/output specification shows all inputs and outputs for the electric motor production.

Table 3 Input/Output Process Specification Electric Motor BOM Excerpt

Input	Quantity	
aluminium oxide, non-metallurgical	0.43	kg
aluminium scrap, new	-6.32	kg
aluminium, wrought alloy	31.59	kg
brass	0.47	kg
copper, cathode	17.61	kg
nylon 6	0.62	kg
permanent magnet, for electric motor	4.88	kg
polyester resin, unsaturated	0.27	kg
polystyrene, high impact	0.12	kg
printed wiring board, for through-hole mounting, Pb containing surface	0.06	m2
printed wiring board, for through-hole mounting, Pb free surface	0.06	m2
printed wiring board, surface mounted, unspecified, Pb free	0.10	kg
resistor, auxilliaries and energy use	0.42	kg
selective coat, aluminium sheet, nickel pigmented aluminium oxide	0.01	m2
steel, chromium steel 18/8, hot rolled	15.85	kg
steel, low-alloyed, hot rolled	88.17	kg
Output	**Quantity**	
electric motor	130.50	kg

This includes all sourced materials like different metals as well as plastics and the electronic components used for the production of the motor. The size of the motor with 130.5 kg is scaled to fit an approximately 1.5 t vehicle according to [Ecoinvent, 2022 c].

5.2.2 Product Specific Data

The dataset used does not only contain the electric motor BOM information but also the processing information (i.e., product specific data) as shown in Table 4 that otherwise needs to be reported by the manufacturer. The product specific data is shown regarding the electricity and energy consumption for the production and assembly of the electric motor as well as generic processing datasets for transformation processes where otherwise primary data is not known (sheet rolling, aluminium). Assuming that an aluminium metal working supplier does not provide information on the material and energy consumption for the aluminium sheet rolling process, this type of generic processing data can be used as proxy. In this case it links to another dataset that contains the entire input /output specification for the sheet rolling of 31.59 kg aluminium. In addition, also scrap and waste streams coming from the assembly and metal transformation are reported.

Table 4 Input/Output Process Specification Electric Motor Production Excerpt

Input	**Quantity**	
electricity, low voltage	2.0E-02	kWh
electricity, medium voltage	65.30	kWh
heat, central or small-scale, other than natural gas	53.41	MJ
heat, district or industrial, natural gas	55.03	MJ
sheet rolling, aluminium	31.59	kg
sheet rolling, steel	104.03	kg
wire drawing, copper	17.61	kg
Output	**Quantity**	
iron scrap, unsorted	20.80	kg
waste plastic, industrial electronics	0.02	kg

Again, ideally this data comes from the manufacturer and supplier directly. However, confidentiality issues, missing allocation procedures or simply missing data measuring and acquisition capabilities challenge automated data collection at this point. Here, appropriate AAS and submodel templates allow data collection at the point of data generation and exchange of data along the value chain where needed.

A currently available submodel template for “Technical Data” is used in Figure 24 as an example for the specification of the SEW DR100 motor including references to the published technical datasheets.

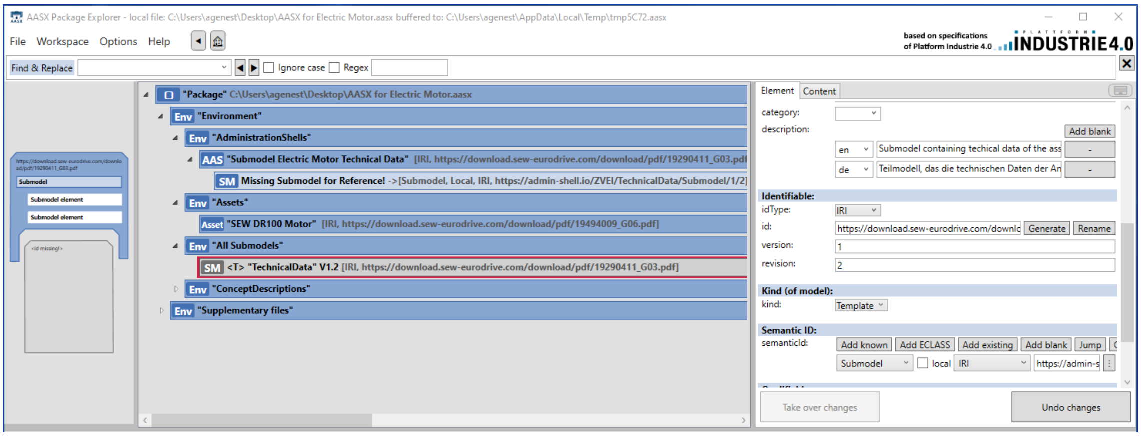

Figure 24 AASX Submodel Technical Data for SEW DR 100 Electric Motor

The IDTA for instance currently creates further submodel templates for sensors, foreground consumables and process batch as already indicated in section 4.2.3. This will enable the data collection and allocation as needed.

However, data collected at that level of detail is likely to be hold back due to confidentiality issues across different stakeholders along the value chain or competitors. In order to overcome this risk, the provision of input/output tables on an aggregated elementary flow level (see Table 5) can be a solution as equally introduced in section 4.2.3.

Table 5 Full Elementary Flow LCI for 1 kg Sheet Rolling Aluminium

Input	**Quantity**	
aluminium oxide, non-metallurgical (IAI Area, EU27 & EFTA, market for aluminium oxide, non-metallurgical)	0.061568241	kg
aluminium oxide, non-metallurgical (RoW, market for aluminium oxide, non-metallurgical)	0.363664778	kg
	-	
aluminium scrap, new (GLO, aluminium scrap, new, Recycled Content cut-off)	6.318169811	kg
Aluminium, in ground (resources from ground, unspecified)	27.16032384	kg
aluminium, wrought alloy (GLO, market for aluminium, wrought alloy)	31.59084906	kg
Anhydrite, in ground (resources from ground, unspecified)	1.84321E-05	kg
Antimony, in ground (resources from ground, unspecified)	7.10912E-06	kg
Argon-40 (resources from air, unspecified)	0.432652034	kg
…….		
Yttrium, in ground (resources from ground, unspecified)	6.30725E-06	kg
Zinc, in ground (resources from ground, unspecified)	2.0230202	kg
Zirconium, in ground (resources from ground, unspecified)	0.019024721	kg
Output	**Quantity**	
electric motor, electric passenger car	261	kg
sheet rolling, aluminium	1	kg
sheet rolling, steel	1	kg
1,3-Dioxolan-2-one (emissions to water, unspecified)	1.1459E-05	kg

1,4-Butanediol (emissions to air, urban air close to ground)	2.2776E-08	kg
1,4-Butanediol (emissions to water, surface water)	5.23846E-08	kg
1-Pentanol (emissions to air, urban air close to ground)	1.31254E-08	kg
1-Pentanol (emissions to water, surface water)	3.15013E-08	kg
…….		
Zinc, ion (emissions to water, unspecified)	0.00023633	kg
Zinc-65 (emissions to air, non-urban air or from high stacks)	1.18376E-06	kBq
Zinc-65 (emissions to water, surface water)	0.015566729	kBq
Zirconium (emissions to air, non-urban air or from high stacks)	1.35668E-07	kg
Zirconium-95 (emissions to air, non-urban air or from high stacks)	2.54378E-06	kBq
Zirconium-95 (emissions to water, surface water)	0.08050686	kBq

The full life cycle inventory lists all elementary flows that are associated to the sheet rolling process for the rolling of 1 kg aluminium. In such representation product and process specific information can be used for sustainability and compliance related assessments without direct insides into confidential content. Via a corresponding AAS submodel template the material name nomenclature would need to be standardized to allow interoperability between different partners and corresponding LCI datasets for the derivation of such elementary flow LCIs as long as this is not already available along the entire supply chain.

5.2.3 Standard Values

One of the first steps when creating an EPD is the identification of existing PCRs that can be used to derive relevant modelling principles and standard values to allow comparability across different studies of the same product type using the same PCR.

Regarding relevant PCRs for an electric motor EPD four different standards were found.

- DIN EN 50598-3 - Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Part 3: Quantitative eco design approach through life cycle assessment including product category rules and the content of environmental declarations [EN 50598-3, 2015]
- EN 50693 - Product category rules for life cycle assessments of electronic and electrical products and systems [EN 50693, 2019
- PCR-ed4-EN-2021 09 06 – Product Category Rules for Electrical, Electronic and HVAC-R Products [PEP, 2021]
- PCR 2022:06 – Electrical Motors and Generators and Parts thereof (for Industrial Applications) [EPD, 2022 c]

For the electric motor assessment in this study the PCR 2022:06 and DIN EN 50598-3 were used as guiding PCRs because it's very specific to power drive systems and motors. Even though the DIN EN 50598-3 document can only be used for Typ II+ EPDs it is considered to be more beneficial compared to the other documents that do allow Type III EPDs but do not provide PSR for motor applications. This however shows that even the methodological foundation still needs to be evolved for common products (such as electric motors) as this is crucial for standardized modelling principles and automated assessments thereof.

The EN 50598-3 PCR provides guidelines to create among others, the functional unit, system boundaries, and harmonized approaches for the different life cycle phases. For the specific motor in this assessment some excerpts are provided in the following:

Functional Unit: Electric motor used for an electric passenger car. The electric motor has a maximal output power of about 100kW. The specific motor weights 130.5 kg to fit the needs of a 1.5 t vehicle.

System Boundaries: Life cycles and system boundaries of a motor shall contain the raw material and manufacturing, transportation, use and End-of-Life phase (cradle-to grave).

Standardized Use Phase Scenario:

Annual Operating Time in [h]	5.000 h	
Product Service Lifetime in [a]	15 years	
Nomminal Power [kW]	100kW	
Operating Points and Loading Gauge		
Operating Points	Time [%]	Loading [%]
OP1	20	100 (100 % Speed, 100 % Torque)
OP2	70	50 (50 % Speed, 25 % Torque)
OP3 (Standby)	10	0 (0% Speed, 25 % Torque)

This results in a total energy consumption of 2.460 MWh according to the implementation in Umberto. Table 6 shows the parameters used in Umberto and Figure 25 shows the functional relation.

Table 6 Parameters used for Use Phase Energy Calculation

Parameters

Var	Name	Quantity	Unit
L1	Operating Point 1	100.000	kW
L2	Operating Pont 2	12.500	kW
L3	Operating Point 3 (Standby)	0.000	kW
LFT	Reference Service Lifetime	15.000	year
OPT1	Time OPT 1	0.200	%
OPT2	Time OPT 2	0.700	%
OPT3	Time OPT 3	0.100	%
OT	Operating Time	5,000.000	hour/year
P_L1	Power Loss OPT 1	9.906	kW
P_L2	Power Loss OPT 2	2.639	kW
P_L3	Power Loss OPT 3	2.327	kW

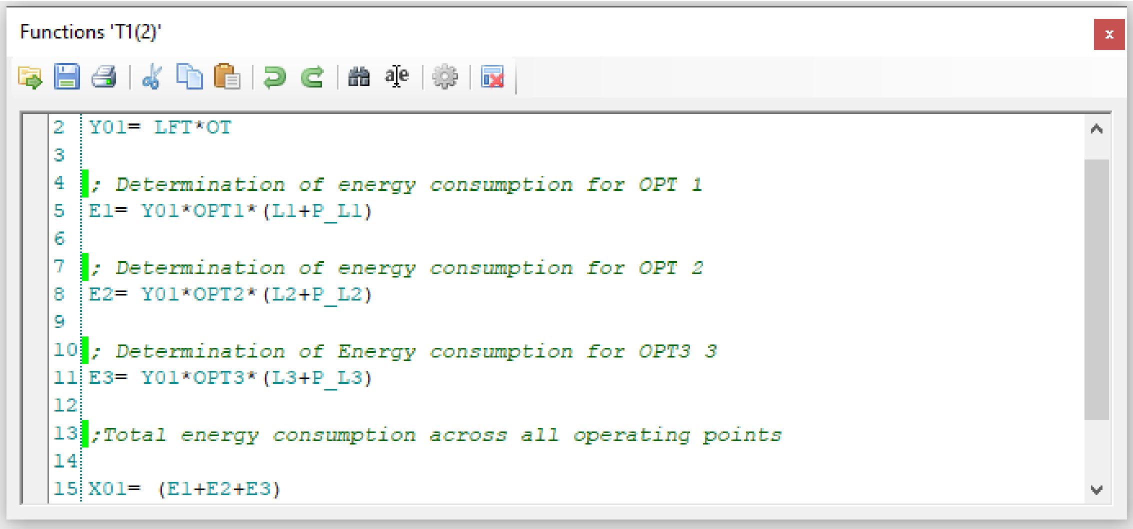

Figure 25 Functional Description of Use Phase Energy Calculation

The above excerpts of standard values from the corresponding PCR highlight the importance of such standardized approaches as these lay the foundation of automatized assessments. As such standard values allow automatized specification of LCA models. In addition, the PCRs often also provide defined report structures that can then be used to automatically export the determined results in a harmonized format.

5.2.4 LCI Data Mapping

As already mentioned above LCI datasets need to be used in many cases for product BOM data, product specific data and standard values if primary information for a certain intermediate product is not available that would allow to assess the entire supply chain. The LCI dataset mapping is mostly a manual activity where for instance the motor BOM entries such as screws are connected to the corresponding steel type and metal working process. The correct matching can have a high impact on the overall data quality. This is highlighted by taking the resistor as an electronic component listed in Table 3 as an example.

In practice many different resistor types exist as for instance thick film flat chip and thin-film flat chip resistors which can then further be specified into surface-mount and through-hole-mount technologies. To highlight the importance of the right mapping to the overall data quality in Figure 26 a comparison between ecoinvent [ecoinvent, 2022a] and GaBi [Sphera, 2022b] surface mount resistor datasets is shown.

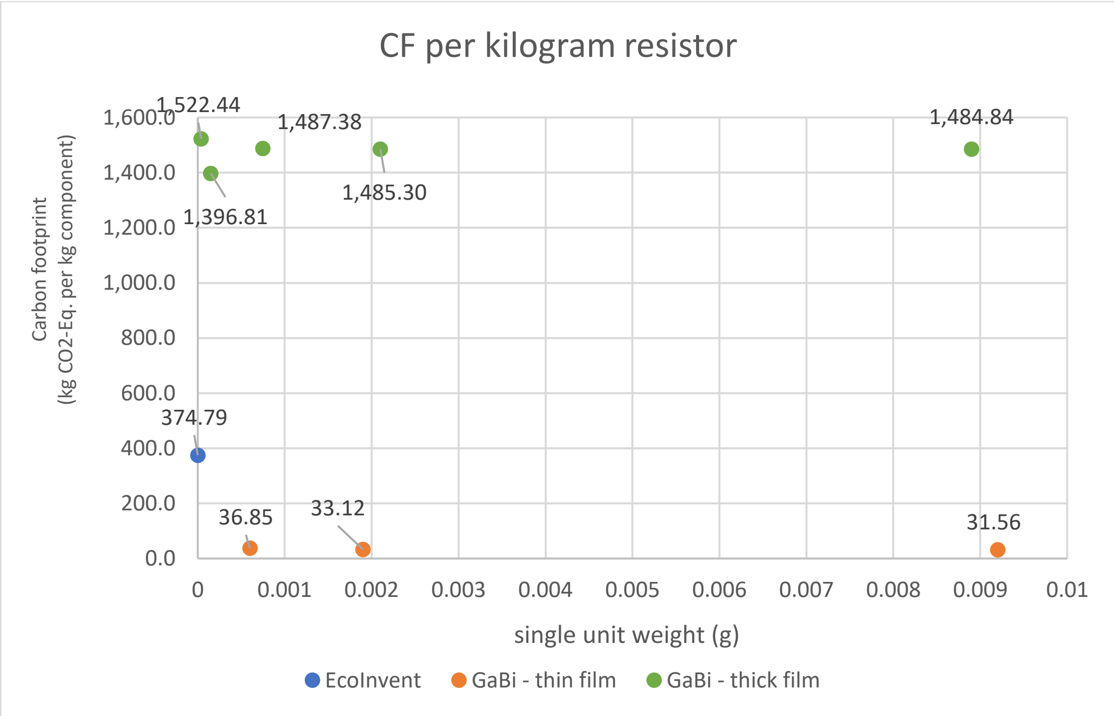

Figure 26 Carbon Footprint Comparison of Resistors

The figure shows the carbon footprint of the ecoinvent resistor compared to the different GaBi resistor types per kilogram of resistor. On the x-axis the single resistor component weight is shown. As such it becomes obvious that the exact resistor type such as thin film or thick film have largely different impacts. For a device as the motor where the electronic component is only having a marginal impact overall this can be neglected but considering this difference for a hotspot component it can become a game changer for the entire product design and the related environmental impact. As described in 4.1.2 iPoint Product Sustainability uses a combination of hints used for mapping of classifications where classifications represent sets of generic datasets as well as machine learning to create master mapping libraries. Those libraries contain already performed mappings and those that can be derived from hints and specifications already available with BOM entry specifications. While this already tremendously reduces the amount of manual work needed to connect for instance the entire electric motor BOM to corresponding datasets, there will often be cases where this automated approach fails. Here again the use of AAS can further enhance the mapping process. If the AAS links the BOM entries to their specific component or material data sheets, then this information can be used for supporting the use of mapping hints in all cases where BOM information is not sufficient to complete the mapping.

As LCA is an iterative approach all data collection and dataset mapping are evaluated in several assessment cycles to determine influencing parameters and hotspots from materials and processes. For the hotspots, the used input data, the corresponding LCI dataset mappings and if used related assumptions are revaluated or assessed in more detail. This ensures to increase the overall data quality up to a level where uncertainties are manageable, and the reviewers will pass certification of the final EPD.

5.3 EPD Creation

The derived input and output data during data collection is gathered in the LCA model. The LCA model allows for holistic documentation, visualisation and calculation of the EPD core data. An overview of the motor model is given in Figure 27 and in Appendix 3 with higher solution.

The LCA model separates the activity according to the different life cycle stages (raw materials, manufacture, distribution, use phase, disposal) and shows with green input places where materials enter the system boundary and with red places where materials leave the system boundary.

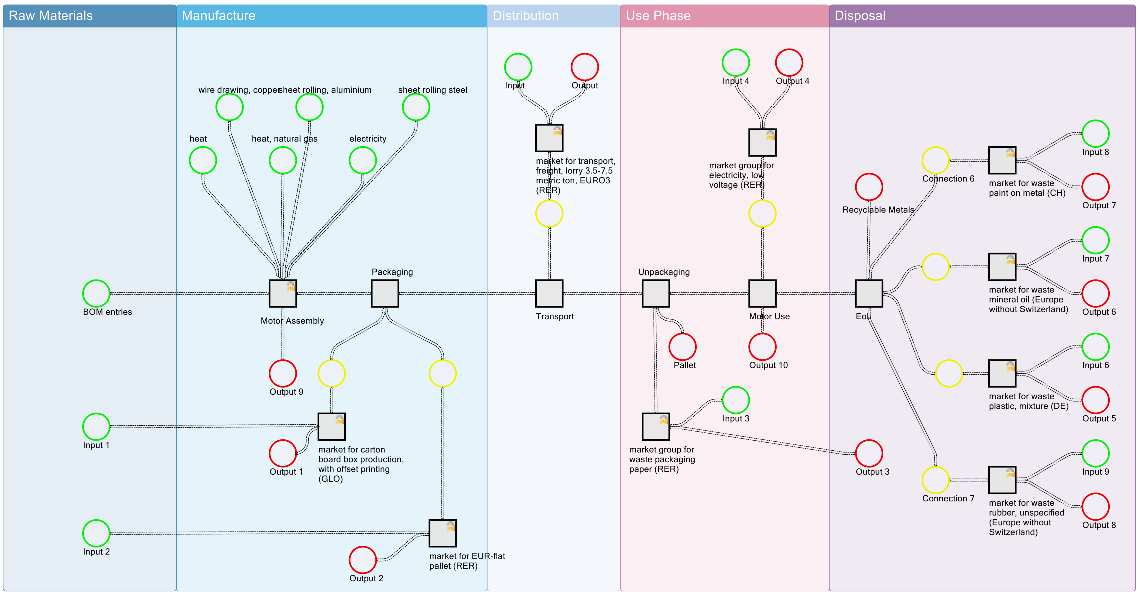

Figure 27 Overview of LCA Model in Umberto

As described above, the set up of the model hast to be in accordance to the PCR underlying standards but they also provide a predefined report structure that shall be used to export and represent the results in a harmonized manner. The following part for instance describes the Environmental Impacts of the assessed motor according to the example of a product's environmental declaration given in the EN 50693 -Annex F:

Environmental Impacts:

The assessed potential environmental impacts through an LCA of an electric motor are given in Table 7 *below. For instance, the global warming, which is evaluated in CO2 equivalents, is the rising of the global temperature due to emissions of greenhouse gases like carbon dioxide and methane among others. The LCA was performed according to the EN ISO 14040 / EN ISO 14044 standards and the product category/specific rules described in EN 50598-3 with software Umberto and the ecoinvent EN 15804 3.8 database.*

Table 7 Electric Motor EPD Results for Selected Impact Categories

Impact Category	*Unit*	*Raw Materials*	*Manufacture*	*Distribution*	*Use Phase*	*Disposal*
Climate change - Total	*kg CO2-Eq*	*1.03E+03*	*1.41E+02*	*1.35E+02*	*4.25E+06*	*2.30E+02*
Freshwater and terrestrial acidification	*mol H+-Eq*	*1.58E+01*	*1.02E+00*	*8.46E-01*	*2.17E+04*	*4.98E-02*
Freshwater ecotoxicity	*CTUe*	*1.37E+05*	*6.59E+03*	*1.83E+03*	*5.50E+07*	*7.25E+03*

Freshwater eutrophication	*kg P-Eq*	*1.17E+00*	*8.52E-02*	*1.30E-02*	*4.15E+03*	*1.60E-03*
Marine eutrophication	*kg N-Eq*	*5.36E+00*	*1.44E-01*	*3.14E-01*	*3.76E+03*	*1.42E-01*
Ozone layer depletion	*kg CFC-11-Eq*	*5.37E-05*	*6.99E-06*	*2.95E-05*	*1.93E-01*	*6.37E-07*
Photochemical ozone creation	*kg NMVOC-Eq*	*5.21E+00*	*5.39E-01*	*9.46E-01*	*8.97E+03*	*8.22E-02*
Terrestrial eutrophication	*mol N-Eq*	*1.73E+01*	*1.53E+00*	*3.42E+00*	*3.28E+04*	*2.07E-01*

Table 7 shows a selection of EPD impact categories and their distribution across the different life cycle stages. Many other indicators need to be declared in the final EPD which is not further exercised in this study to keep the focus on the overall workflow. Generally, all required indicators can be determined and exported into the EPD report structure via the LCA tool. For insides into a complete motor EPD officially published and available EPDs can be used as reference such as the EPD of an ABB DMI type DC Motor [ABB, 2003].

5.4 Implementation Contribution

The practical implementation of the aEPD workflow described in the previous sections provide an overview on how best-practice EPD creation can be combined with promising digital twin concepts such as AAS submodel templates for further automation of the entire workflow. The ongoing development of existing submodel templates as well as the creation of new templates for elementary flow LCI is outlined on a specific processing step such as metal rolling for the motor production. This should in further activities be fed into the Industire 4.0 development process to allow for future applicability in sustainability assessments.

The entire workflow for an automated EPD of an electric motor is enriched with links, documents and references which shall highlight and support interdisciplinary cooperation between the digital twin, MBSE and the LCA community. Every domain brings its specific requirements, standards and notations which need to be further aligned to allow real interoperability.

Regarding the electric motor EPD a general use case is examined and implemented in succinct manner to concentrate on the important aspects regarding automating the entire workflow. Therefore, the important steps are described and practically implemented. However, the entire extent of a real EPD is not shown in all profoundness and most importantly from the perspective of an LCA practitioner. For this a real electric motor EPD creation including all relevant stakeholders should follow and be supported by DT and MBSE practitioners to establish an Industry 4.0 EPD example for AAS.

6 Conclusion

This chapter evaluates and summarises the content and results of the thesis. The developed automated Environmental Product Declaration workflow will be evaluated against the multi-level requirements and against the results of the prototypical solution. Based on this, the feasibility of the aEPD workflow to enable large scale sustainability assessments is discussed. Finally, recommendations for future application and further research and development will be given.

6.1 Evaluation

From the comparison of the existing literature and on the basis of the experience made while solution development and conducting the prototypical implementation the automated Environmental Product Declaration workflow will be evaluated and discussed against the research questions initially developed. For recapturing the research questions, they are listed again in the following starting with the primary research question.

1. How can the full workflow of an Environmental Product Declaration be automated to decrease the need for manual work?
2. What does the full workflow of an EPD look like?
3. Which methodologies and concepts are currently being worked on that support automation?
4. How can these concepts and methodologies be used for automation if available?
5. What is still needed to allow their application to enable automation?

For the evaluation however, research questions 2 and 3 are addressed first as they pave the way for the primary research question.

The general workflow of an EPD is clearly defined within the corresponding standards and was also graphically represented in Figure 8 during the EPD review activity in section 2.3. Here all steps necessary to perform an EPD are included but kept on a meta level, providing requirements on what data is needed and what the data quality should look like in relation to the most impacting materials. To address the question “What does the full workflow of an EPD looks like” the concept development of the full EPD workflow in section 3.2 additionally includes more detailed steps regarding the actual value stream process of a product by extending the view to product life cycle management and digital twin perspectives including their detailed view on the supply chain and the value chain for enabling a harmonized data collection for a given product. EPD standards only tell what kind of data should be collected but leave it open to manual activities by the LCA practitioner and the manufacturer to somehow get the required data. This means that for new EPDs the entire process of data collection has to be set up as an initial and manual project activity. The full EPD workflow in Figure 16 additionally provides a clear picture on where the data can be gathered from and what type of data can be collected at the different product levels to allow standardized data collection measures.

This partly answers the third question "Which methodologies and concepts are currently being worked on that support automation?". The MBSE is used as overarching concept that allows to address and manage the complexity associated to a process development that is cross-sectoral to combine requirements and data needs from different disciplines (e.g., LCA, PLM and DT) as well as their corresponding stakeholders. The connection of different disciplines is then used to allow solution integration from specific disciplines such as the industry 4.0 AAS implementation of the digital twin to enable product specific data collection across several value chain partners and the supply chain. PCRs as part of the LCA are constantly being updated and newly developed for new products. The harmonized modelling assumptions, and standard values enable the development of IT algorithms to configure tools and software in a way that for specific products their individual PCRs are referenced for the EPD creation. Lastly, the development of smart mapping algorithms is used for connecting intermediate materials with appropriate supply chain data where this is not available as primary information.

Eventually, the primary research question "How can the full workflow of an Environmental Product Declaration be automated to decrease the need for manual work?" is answered by the solution design for an automated EPD that connects the above-mentioned disciplines and design concepts along the entire workflow where needed as shown in Figure 19. The prototypical implementation of an aEPD for an electric motor shows the interconnection of the different disciplines regarding the entire life cycle stages from DT, PLM and LCA as well as the specific solution concepts for automation such as the use of different AAS submodel templates along the collection of Product BOM Data and Product Specific Data. Furthermore, the derivation of Standard Values from existing PCRs is shown as well as the dataset mapping with corresponding datasets. All input is gathered in a central LCA model and used for the final electric motor EPD assessment shown in Table 7.

However, it also becomes clear that many aspects yet remain a theoretical exercise and practical implementation is not possible at the current state due to missing concepts. Therefore, full automation cannot yet be met with the developed aEPD workflow. For further analysis, the different concepts and solution designs used within the aEPD workflow are evaluated regarding their implementation readiness level. This also answers the question “How can these concepts and methodologies be used for automation if available?” and “What is still needed to allow their application to enable automation?”.

- **AAS**
  While the main AAS is available and readily applicable with some corresponding submodel templates, the requirements of the solution design for an aEPD cannot be met with the existing set of submodel templates as addressed in section 4.2.3. While some submodel templates such as the hierarchical BOM and PCF are currently being developed some others like a generic BOM structure and templates regarding other impact categories then GWP are not yet available or in development by IDTA. Not only the availability of the templates is an issue but also the current level of application within the industry. At the time being the AAS is conceptually being developed and first use cases are created but when and if real industry application can be reached is still uncertain. Even if industry application can be reached in the near future, then the AAS need to be applied at all value chain partners to allow full automation. For some other information such as the BOM entries it remains questionable if value chain partners will agree to share potentially confidential data. Here the development of elementary flow submodels seems to be a promising concept. When all partners along the supply chain use AAS elementary flow submodels, aggregated elementary result or unit processes information would be available. The aggregated information will not allow to trace back on specific processes and materials used so that confidentiality is not an issue any longer but full availability of elementary flows for broad sustainability assessments. At the same time this also requires alignments with program holders for underlying PCRs and verification schemes. In addition, an elementary flow submodel would make many submodels redundant from an LCA perspective. Currently many different submodel need to be used as shown in section 4.2.3 to cover all data needed for deriving the product LCI as long as no better fitting submodels are available.
  To sum it up, the AAS is a great concept that would allow full automation of data collection. Also, the general structure is already standardized, and feasibility already proven in use cases. However, it is unlikely that this will be available within the near future as even the basic submodels still need to be developed.

- **PCR**
  Even though some PCRs are already available and allow to include related modelling guidelines and standard values into the aEPD workflow, it is still a relatively small number compared to the total number of different products that would need PCRs. However, the PCRs available are already applied within industry and allow automation of the PCR content for the products where they are available. At the same time for many products PCRs are not yet available.
- **LCI Dataset Mapping**
  The LCI mapping is ready to be applied and can already serve to automatically create appropriate mappings for the majority of intermediate materials used. However, for cases where appropriate LCI datasets are missing, generic approaches currently need to be used to find approximations that can be used instead. For this a conservative approach needs to be used to ensure that related impacts are over- instead of underestimated. In cases where no appropriate datasets and no approximations can be mapped, indication must take place to guide manual data collections and/ or literature research to close corresponding data gaps.

As long as capabilities of Industry 4.0 do not allow full automation of data collection, both, improved LCI mapping and extensive PCRs can be used as bridging technologies. Where Industry 4.0 does not yet allow to automate all manual activities, this can for the time being at least partly be covered by PCRs and smart LCI mappings. Both are used to deal with primary data gaps and therefore activities that either request for manual data collection or if available the application of appropriate generic data such LCI datasets or harmonized procedures.

While the above-mentioned limitations are corresponding to the readiness level of the used concepts itself there are further limitations of this work due to the limited scope of a master's thesis

- The thesis at a hand elaborates the different aspects of an aEPD workflow creation and uses the prototypical implementation of an electric motor aEPD as prove of concept. The prototypical implementation does show the current and future potentials for automation and guidance on the different activities for the EPD creation. However, the EPD of the electric motor is not an entirely consistent performed LCA and EPD according to the extensive set of ISO and PCR requirements. For instance, for the different methodological requirements one or two examples are used for the electric motor EPD but there are still further similar requirements that are left out (e.g., the standard values for the use phase energy consumption are used but the standard values for transportation are not further explained). This is done to keep the focus on the entire workflow and to cut off certain complexity which is not within the key focus of this work. This, however, means that the electric motor EPD results shown in Chapter 5.3 can only be used as indicative figures. The underlying LCA study is not performed in a way that it will withstand critical review and the results are not to be published as “official” EPD results.

- The goal of the developed aEPD workflow was to automate the EPD activities, this is only the case for the core manual activities for performing the underlying LCA according to the EPD requirements as shown by the aEPD workflow in Figure 19. Other activities that are also required for the creation of the EPD such as for instance the selection and creation of the right PCRs, and the review process as shown in the use case diagram in Figure 21 are not being considered.
- Even within the core EPD activities for which the EPD workflow is developed, full automation is currently not possible. This is partly due to the early-stage phases of the used concepts as outlined in the beginning of this chapter (e.g., to be developed AAS submodel templates and PCRs) but also due theoretical approach of this thesis. Practical IT implementation of the suggested concepts is not being addressed. In other words, the aEPD workflow is a theoretical exercise that shows available concepts and current gaps for actual implementation in a real case but does not provide practical, ready-to-use concepts for the mentioned gaps.
- The use of MBSE and DT concepts for the automation of an EPD creation are described regarding specific concepts such as the AAS submodels and focus on their implementation within the outlined workflow. In spite of that, Integration of the mentioned automation concepts into the existing tool chain (e.g., LCA software tool) is not further addressed. If AAS are to be used then all currently used tools within the toolchain need to be further developed or combined with middleware (e.g., BaSys [BaSys, 2022]).
- The overall data quality is not further assessed. The current workflow assumes correct data at each point where data is accessed from. This can be data from ERP systems, Excel Spreadsheets or from AAS submodels. For instance, ERP BOM data is not always consistent for all listed components. In some cases, they don’t

represent the exact weights along the supply chain (e.g., electronic component weights can just be an indicative figure form data sheets without representing the specific component weight). In other cases, manual input is needed to complete required ERP related data entry forms. Manually entered data however increases the risk for wrong (not on purpose) data entry. The wrong data occurrence check, its evaluation and if needed the correction or indication of wrong data is crucial for automated systems.

- Whereas the biggest influence on eco design and sustainability indicators can be ensured in early phases of the NPD, this is cut off for the core EPD process. While this is sufficient for an EPD itself, this is not in the interest of overall sustainable solutions. Here the NPD should clearly be in central focus. MBSE can be a central concept to allow integrated feedback solutions that use what if- scenarios to find optimisation potentials for NPD where at relatively low costs alternatives can be assessed.

6.2 Summary

Global resources are reduced faster on average then they can be recreated by natural processes. This fact is largely recognised by science and politics which increase their efforts to transform the global linear economy to become more circular and more sustainable overall. To enable consumers and industry to manage this transformation, metrics and indicators must be determined and reported in order to allow all stakeholders controlling their impacts along the product life cycles. For this Product Environmental Declarations were developed and are already applied within industry. EPDs support companies in eco design and deliver customers a supportive tool for taking sustainable purchase decisions based on defined sustainability metrics.

The use of EPDs will significantly increase as more and more countries change from voluntary to mandatory EPD assessments. Therefore, the entire EPD workflow will need to be automatized to allow large-scale application of product environmental assessments. Only this will bring down the costs and personal resources to a level that creating EPDs for many new products becomes possible.

One of the biggest current challenges is related to the product specific data collection to allow a sufficiently complete product specific life cycle inventory. Even worse, currently data collection is in most cases a manual activity. Therefore, product specific data collection in a global manufacturing network of increasingly complex products require extensive personnel resources. Consequently, automation is needed to enable the large-scale application of EPDs.

Automation of workflows and certain activities is already a focal point of interest but currently limited to individual concepts or interfaces and mostly looked at from only one perspective. The full workflow to support automation of the EPD process has not yet been considered.

Proceeding from this background, this master's thesis developed an automated workflow for Environmental Product Declaration by combining Model-Based-Systems Engineering, Digital Twin and Life Cycle Assessment concepts. The core EPD workflow was visualised and the most important activities within the data collection that need increased levels of automation were identified such as

- Primary data collection along all life cycle stages and along the entire value chain of the product
- LCI dataset mapping for connection of intermediate materials with its specific supply chain impacts
- Harmonization and standardization regarding EPD methodological requirements for comparable and standardized assessments.

While the above aspects were addressed within the developed a EPD workflow by using MBSE for the multilevel requirements analysis the focus was set on automating data collection for Product BOM Data and Product Specific Data along the supply and value chain using the AAS 4.0 Implementation of the Digital Twin concept.

The thesis resulted in an overview on how best-practice EPD creation can be combined with digital twin concepts such as AAS submodel templates for further automation of the entire workflow. Moreover, the ongoing development of existing submodel templates as well as the creation of new templates for elementary flow LCI was outlined.

The applicability of the aEPD workflow was proven in the prototypical implementation of an aEPD for an electric motor. In addition, the automated EPD of an electric motor was enriched with links, documents and references to highlight and support interdisciplinary cooperation between the DT, MBSE and the LCA community. As such, the developed workflow and the multi-level requirement analysis should find entrance to the Industry 4.0 development process to ensure target-oriented solutions towards smart and automated sustainability assessments.

In summary, the automated Environmental Product Declaration represents a holistic workflow for achieving more automated Environmental Assessments by using Asset Administration Shells.

6.3 Outlook

Even though great progress has been made to develop a holistic aEPD workflow for automating the LCA and EPD creation, it also revealed various gaps and research should be continued in following areas:

- Development of further AAS Submodel templates
- Addressing data confidentiality issues
- Creating an EPD use case for AAS Implementation
- Development of further PCRs
- Enabling of the EPD toolchain Industry 4.0 requirements
- Extension to new product development for enabling product eco design at early design stages
- Assessment of rebound effects due to digitalization

Hereafter, the above listed items are explained in more detail

The development of further AAS submodel templates such as a structural BOM or a product digital passport are key for allowing practical implementation in industry for sustainability assessment. Regarding the development of submodel templates for sustainability assessments further research should be done on identifying potential templates such as an elementary flow submodel to comprehensively address the biggest data needs for sustainability assessments rather than creating templates for each individual impact category such as a template for PCF only. Or if doing so, directly considering requirements that will come by other impact categories and could be added at a later stage.

Also, data confidentiality remains a big issue for LCA. Even though the AAS contains different concepts for partner communication along the value chain that allows to manage confidential data, the challenge with an EPD in combination is that life cycle inventories need to be traceable, and hotspots need to be transparently analysed according to the impact contribution. Both can make it necessary to handle and publish data that might originally had been rated as confidential. Here further research should be done on identifying solutions and mechanisms that allow the application of AAS for assessments that have to be published. Within this thesis the use of an elementary flow AAS is proposed, which should equally be assessed in further detail regarding its feasibility.

In order to further assess the EPD needs regarding an AAS implementation a real product (e.g., electric motor) EPD creation including all relevant stakeholders should follow and be supported by DT and MBSE practitioners to establish an Industry 4.0 EPD example for AAS. Interdisciplinary cooperation between MBSE, DT and LCA community is important to allow interoperability across different disciplines as every discipline brings its specific requirements, standards and notations which need to be further aligned to allow real interoperability. Additionally, this can support the identification of further requirements as well as necessary links within the used toolchain. At the end, this can be used as practical guide for companies and EPD practitioners to establish and further on expanding the creation of automated EPDs with limited resources for initial set up.

Regarding automation support, the development of further PCRs has to be accelerated as they can be used as bridging instruments to allow automation as long as the Industry 4.0 concept including AAS has not reached industrial state of the art. As this is currently being done already by different program holders, such as (e.g., Environdec) this shall not be specified at this point.

For practical automation the EPD toolchain needs to be enabled for Industry 4.0. This means that not only manufacturing companies need to be able to use and provide submodels with data but also LCA tool providers and LCI data providers to allow their solutions to integrate submodel information. The contains the requirements engineering for tool connection or the development/extension of middleware such as BaSys.

Whereas the above-mentioned aspects mostly consider the automation and application of EPDs there are further research needs regarding scope extension.

Whereas core EPDs start its assessment with an established product, it is important to extend the assessment of an automated EPD to also include the new product development to leverage the optimisation potentials at early stage.

Lastly, rebound effects need to be assessed regarding additional environmental impacts coming from data mining, automation and digitalization such as for example the energy consumption of involved servers. It is important to measure the current environmental impact of products, but it is also important to understand what impact is coming from automated assessments and smart manufacturing overall to ensure that expected reduction potentials can be realised.

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List of Appendices

Appendix 1: Extended Digital Twin V-Model (high resolution)

In Figure 28 the extended Digital Twin V-Model is shown as methodology developed to use Digital Twins for energy efficient customizable IoT-Products.

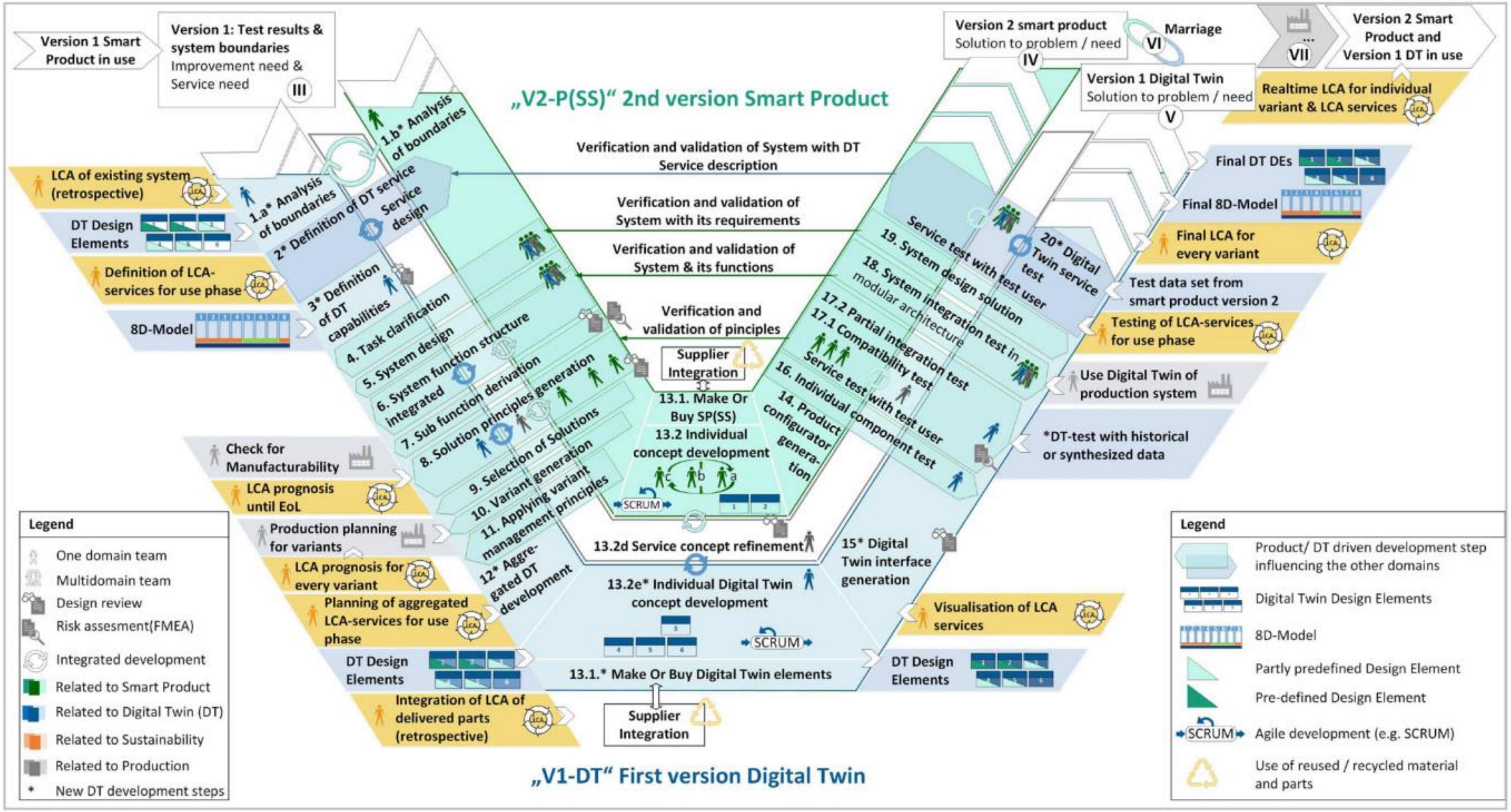


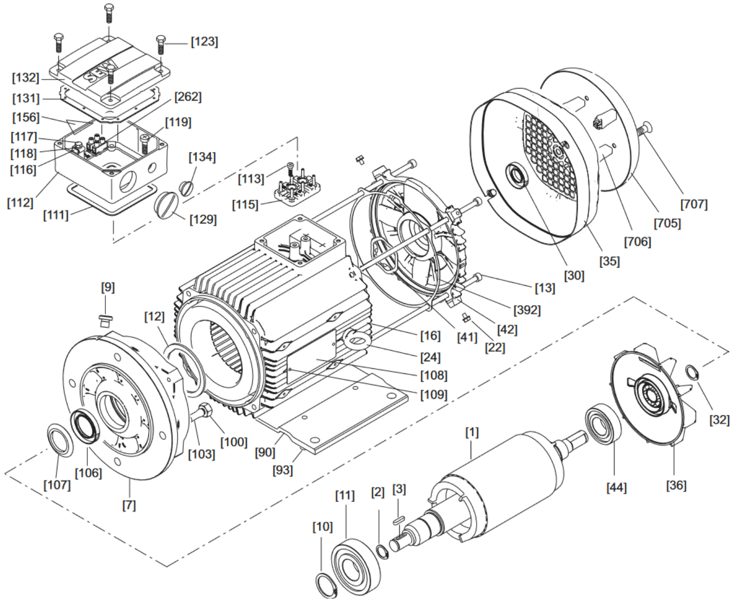
Figure 1: Development cycle 2 of the Smart Product and DT as part of the DT-V-model - "V2-P(SS)" and "V1-DT"

Figure 28 DT-V-Model with Sustainability Focus [Riedelsheimer et al., 2021]

Appendix 2: Technical Specification of SEW DR Motor

In the following some publicly available reference data for an electric motor is given.

Figure 29 shows the detailed composition of the SEW electric motor together with technical specifications in Figure 30 and efficiency data in Figure 31 concerning the use phase energy consumption estimations.



[1] Rotor
[2] Circlip
[3] Key
[7] Flanged endshield
[9] Screw plug
[10] Circlip
[11] Deep groove ball bearing
[12] Circlip
[13] Machine screw
[16] Stator
[22] Hex head bolt
[24] Eyebolt
[30] Oil seal
[32] Circlip
[35] Fan guard
[36] Fan
[41] Shim washer
[42] B-side endshield
[44] Deep groove ball bearing
[90] Base plate
[93] Pan head screw
[100] Hex nut
[103] Stud
[106] Oil seal
[107] Oil flinger
[108] Nameplate
[109] Grooved pin
[111] Gasket for lower part
[112] Terminal box lower part
[113] Pan head screw
[115] Terminal board
[116] Terminal clip
[117] Hex head bolt
[118] Lock washer
[119] Pan head screw
[123] Hex head bolt
[129] Screw plug with O-ring
[131] Gasket for cover
[132] Terminal box cover
[134] Screw plug with O-ring
[156] Information sign
[262] Terminal clip, complete
[392] Gasket
[705] Protective cowl
[706] Spacer
[707] Pan head screw

Figure 29 Basic structure of DR71-DR100 [SEW, 2022 c]

290 – 2900 1/min △ 3 x 380 – 500 V (400 V) *IEC oder* c UL us

Typ	P_n [kW]	M_n [Nm]	M_a/M_n f > 5 Hz	n_n [1/min]	I_{n1} [A]	cosφ	J_{mot} [10^{-4} kgm^2]		M_{Bmax} [Nm]	m[1] [kg]	m[2] [kg]
							ohne Bremse	mit Bremse			
DRE80S4 /../MM03	0,37	1.22	1.5	2900	1.3	0.99	14.9	16.4	5	12.7	15.7
DRE80S4 /../MM05	0,55	1.81	1.5	2900	1.6	0.99	14.9	16.4	5	12.7	15.7
DRE80M4 /../MM07	0.75	2.47	1.5	2900	1.9	0.99	21.5	23	10	15.5	18.5
DRE80M4 /../MM11	1.1	3.62	1.5	2900	2.4	0.99	21.5	23	10	15.5	18.5
DRE90M4 /../MM15	1.5	4.95	1.6	2900	3.5	0.99	35.5	40	20	19.6	24.2
DRE90L4 /../MM22	2.2	7.25	1.6	2900	5.0	0.99	43.5	48.5	20	23.7	28.2
DRE100M4 /../MM30	3.0	9.9	1.6	2900	6.7	0.99	56	62	28	28.3	34.2
DRE100LC4 /../MM40	4.0	13.2	1.6	2900	7.3	0.99	90	96	40	34.1	40.0

Figure 30 Technical Specification of electric motor [SEW 2022 c]

Motors	Lowest power rating	Highest power rating	Sticker
2-pole DRE.. motors	from 0.75 kW	to 9.2 kW	Grade 3
4-pole DRE.. motors	from 0.75 kW	to 200 kW	Grade 3
4-pole EDRE.. motors	from 0.75 kW	to 45 kW	Grade 3
6-pole DRE.. motors	from 0.75 kW	to 5.5 kW	Grade 3

Figure 31 Power Ratings and Efficiency Grades of Electric Motors [SEW, 2022 c]

Appendix 3: EPD Workflow and aEPD Workflow (high-resolution)

The complete EPD workflow is shown in Figure 32 according to the conceptual EPD workflow model development in Chapter 3. The holistic aEPD workflow with integration of the solution design is shown in Figure 33. Both figures are identical to Figure 16 and Figure 19 just with high resolution for better readability.

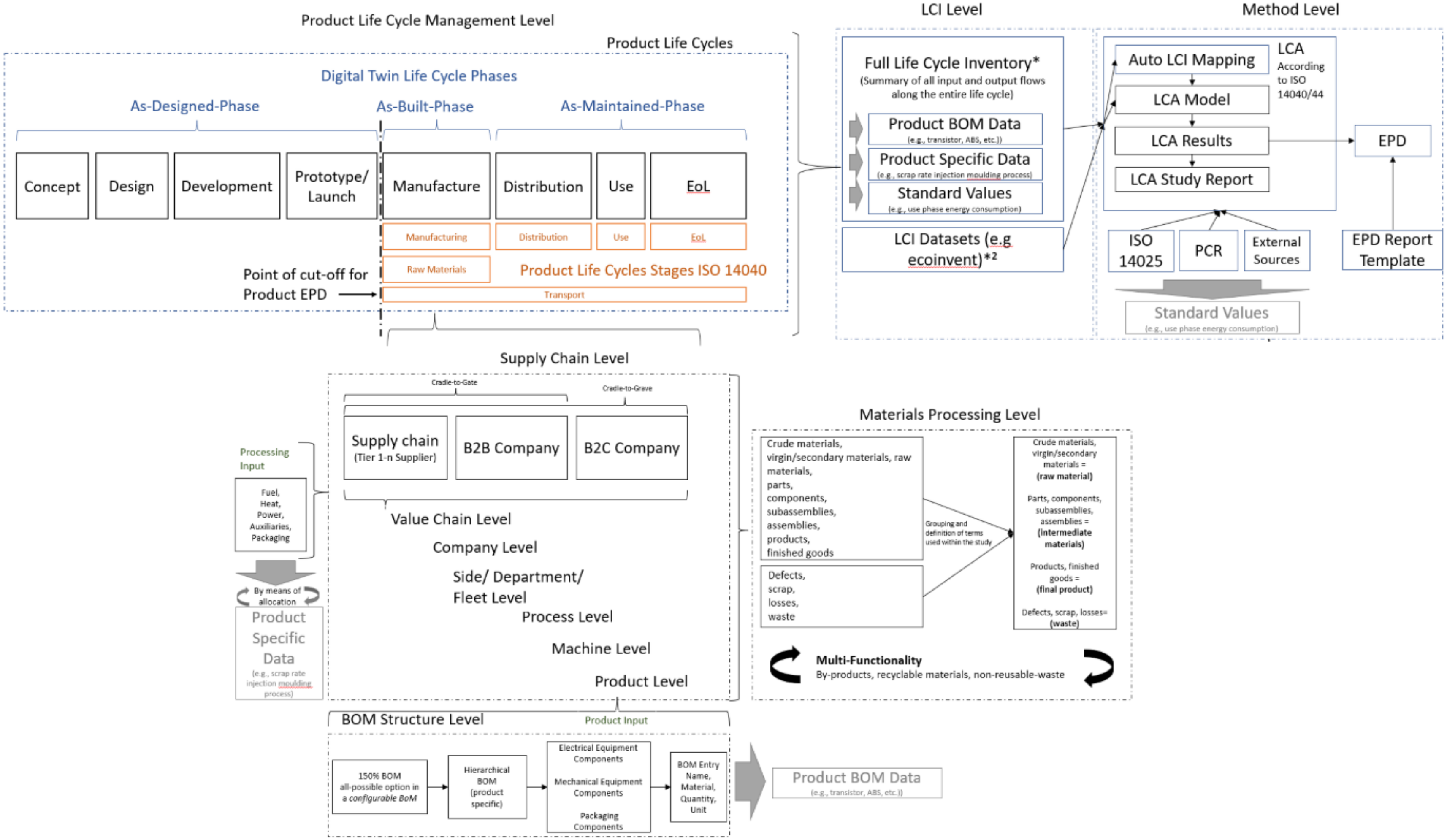


Figure 32 Complete EPD workflow (high resolution)

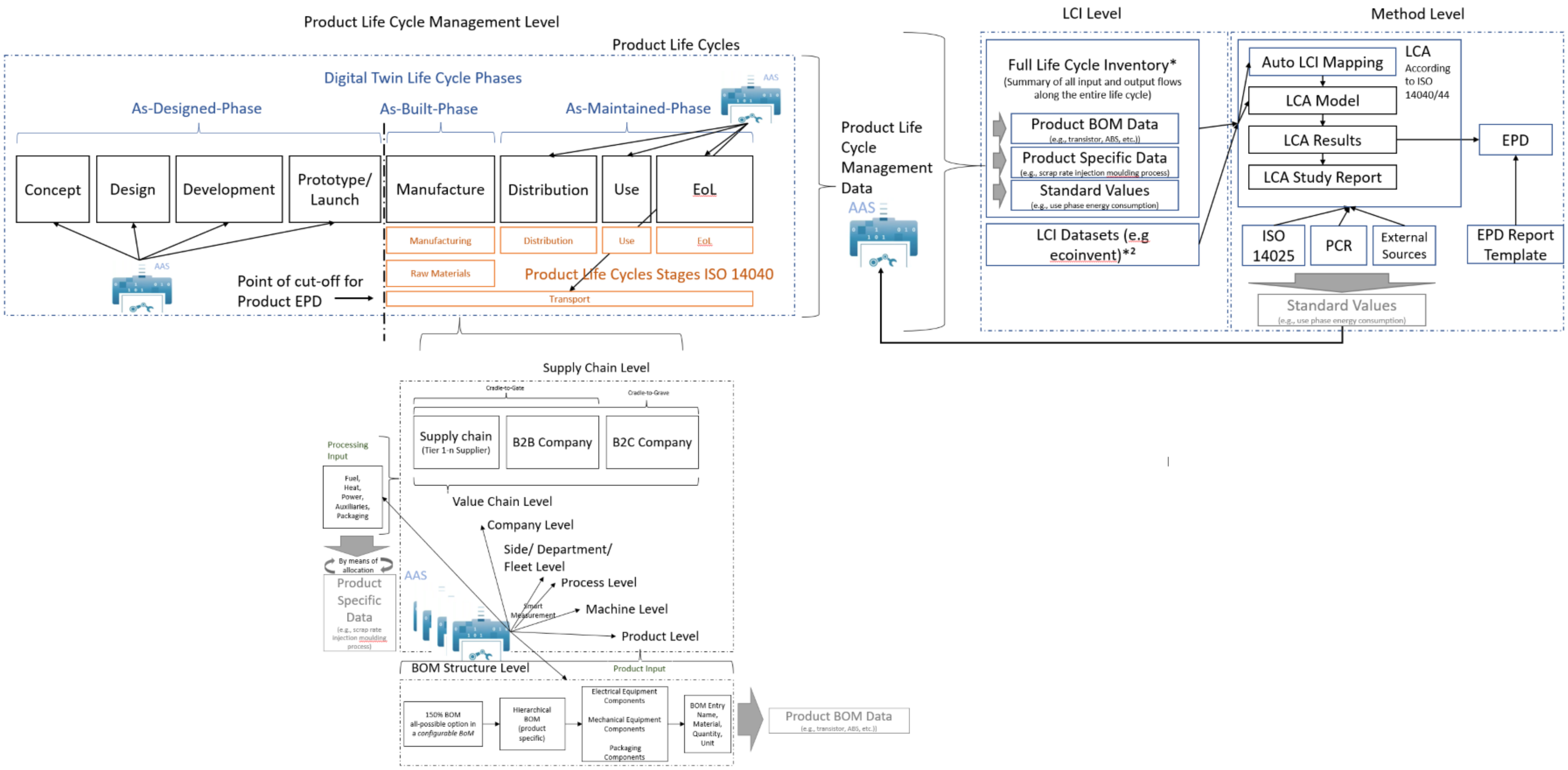


Figure 33 Holistic aEPD workflow (high resolution)

Appendix 4: LCA Model Specification and full EPD results

In the following, the electric motor LCA model specifications are shown to allow traceability regarding the data sets and process specifications used. In Figure 34 an overview of the entire Umberto LCA model of the electric motor is shown. Figure 35 up to Figure 40 show the process specifications for the different life cycle stages. Finally, Table 8 shows a complete overview of the electric motor EPD results.

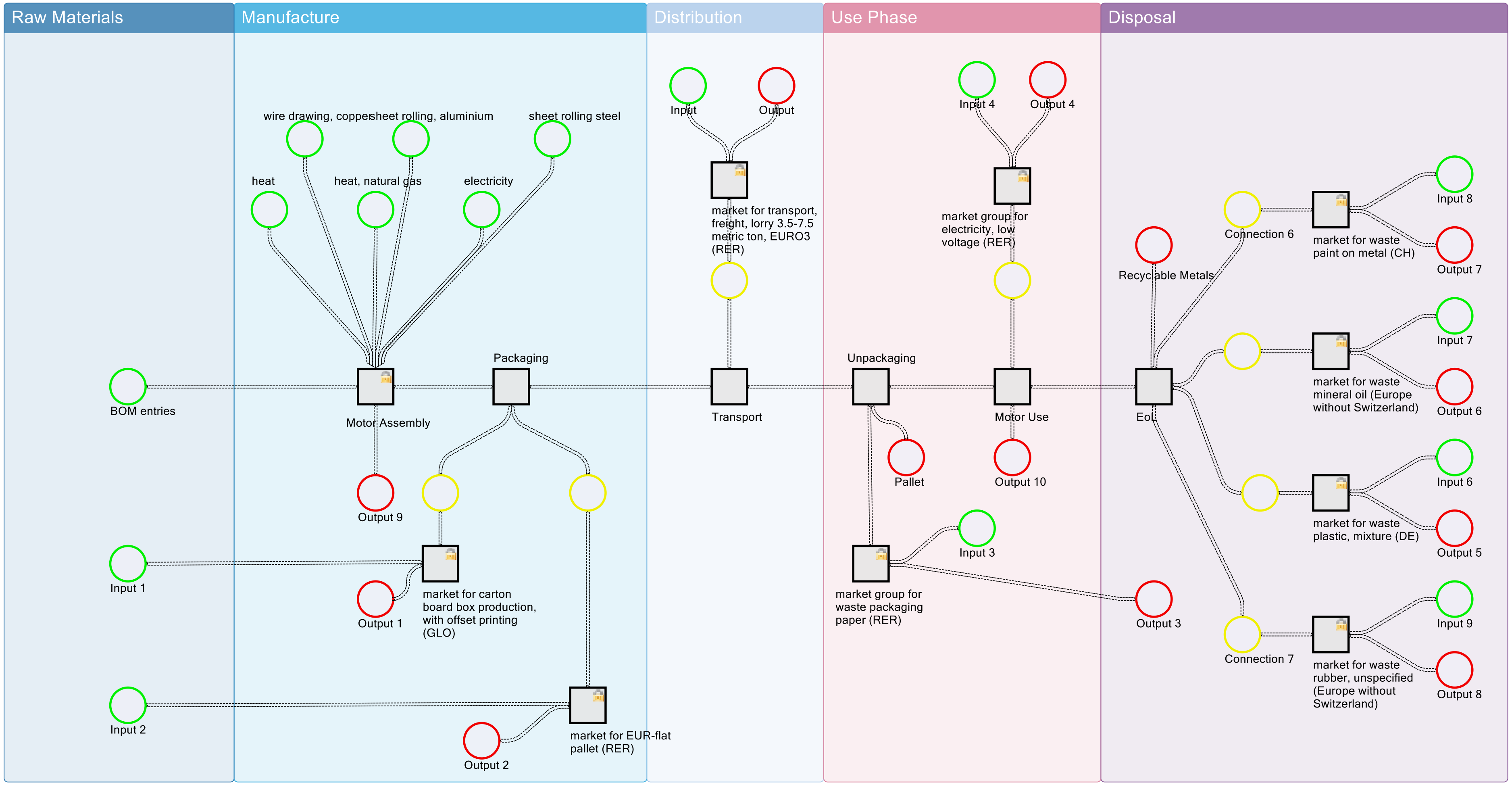
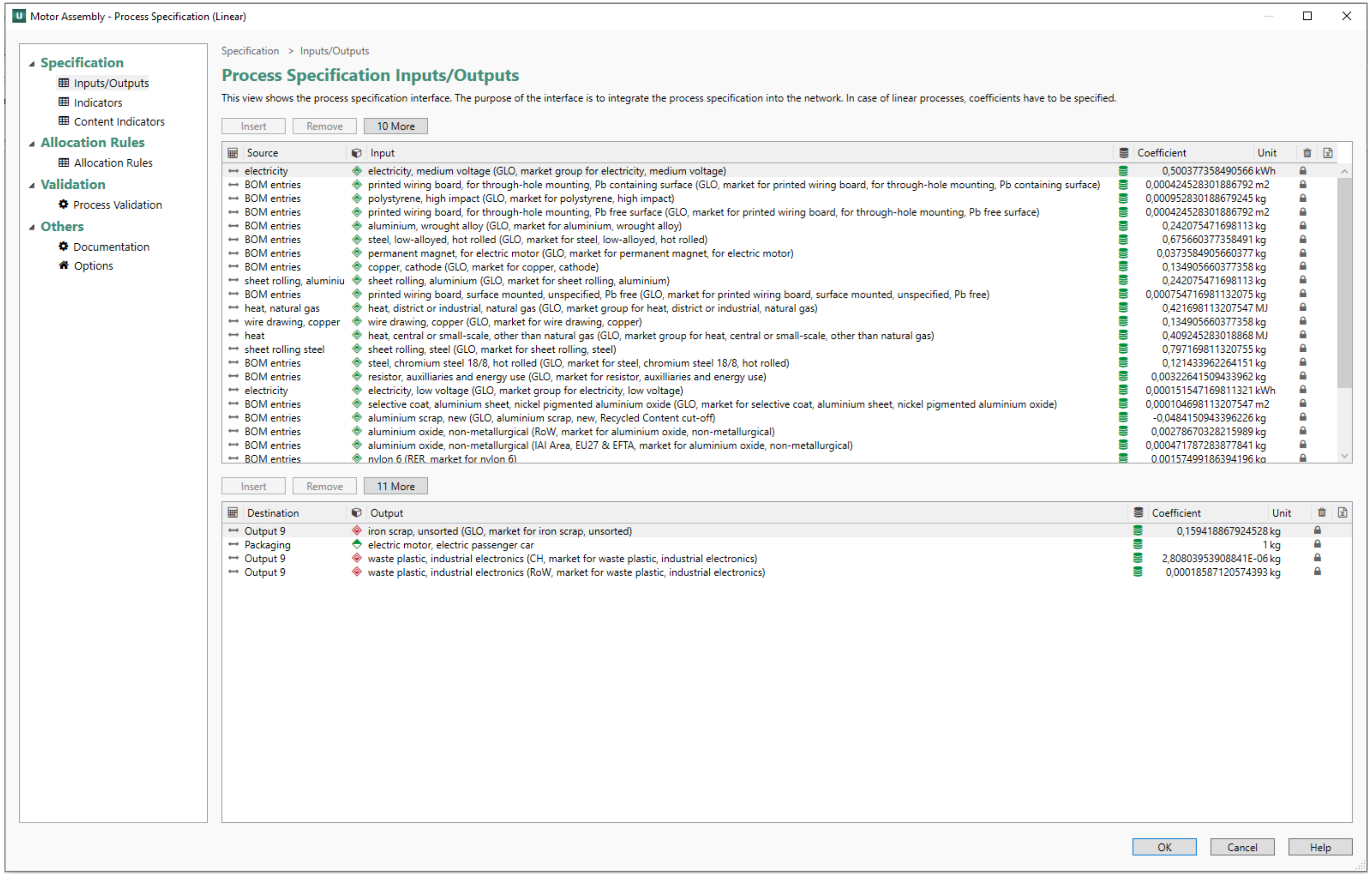


Figure 34 Electric Motor LCA Model Overview



Motor Assembly - Process Specification (Linear)

Specification > Inputs/Outputs

Process Specification Inputs/Outputs

This view shows the process specification interface. The purpose of the interface is to integrate the process specification into the network. In case of linear processes, coefficients have to be specified.

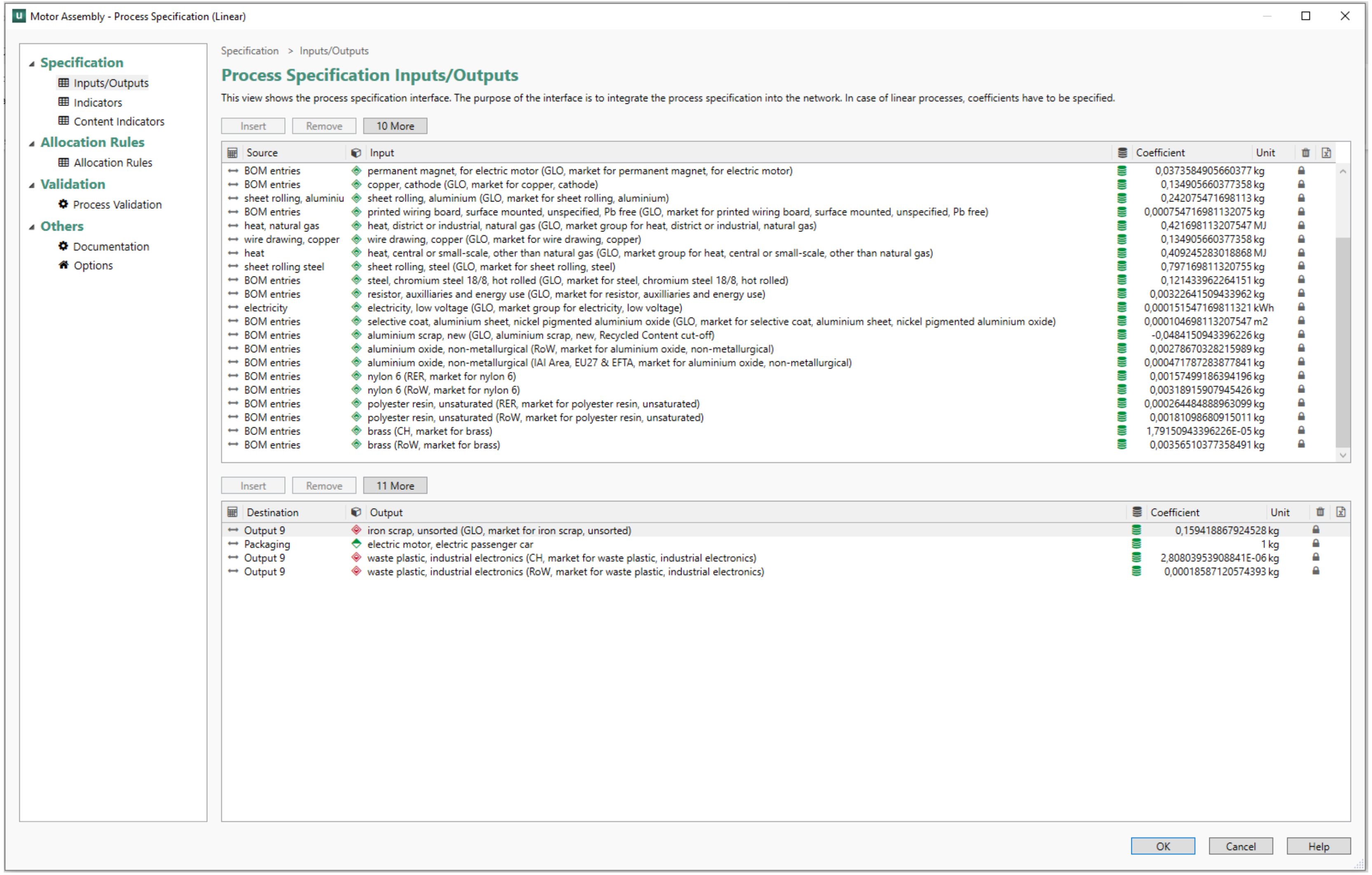
Insert | Remove | 10 More

Source	Input	Coefficient	Unit
electricity	electricity, medium voltage (GLO, market group for electricity, medium voltage)	0,500377358490566	kWh
BOM entries	printed wiring board, for through-hole mounting, Pb containing surface (GLO, market for printed wiring board, for through-hole mounting, Pb containing surface)	0,000424528301886792	m2
BOM entries	polystyrene, high impact (GLO, market for polystyrene, high impact)	0,000952830188679245	kg
BOM entries	printed wiring board, for through-hole mounting, Pb free surface (GLO, market for printed wiring board, for through-hole mounting, Pb free surface)	0,000424528301886792	m2
BOM entries	aluminium, wrought alloy (GLO, market for aluminium, wrought alloy)	0,242075471698113	kg
BOM entries	steel, low-alloyed, hot rolled (GLO, market for steel, low-alloyed, hot rolled)	0,675660377358491	kg
BOM entries	permanent magnet, for electric motor (GLO, market for permanent magnet, for electric motor)	0,0373584905660377	kg
BOM entries	copper, cathode (GLO, market for copper, cathode)	0,134905660377358	kg
sheet rolling, aluminiu	sheet rolling, aluminium (GLO, market for sheet rolling, aluminium)	0,242075471698113	kg
BOM entries	printed wiring board, surface mounted, unspecified, Pb free (GLO, market for printed wiring board, surface mounted, unspecified, Pb free)	0,000754716981132075	kg
heat, natural gas	heat, district or industrial, natural gas (GLO, market group for heat, district or industrial, natural gas)	0,421698113207547	MJ
wire drawing, copper	wire drawing, copper (GLO, market for wire drawing, copper)	0,134905660377358	kg
heat	heat, central or small-scale, other than natural gas (GLO, market group for heat, central or small-scale, other than natural gas)	0,409245283018868	MJ
sheet rolling steel	sheet rolling, steel (GLO, market for sheet rolling, steel)	0,797169811320755	kg
BOM entries	steel, chromium steel 18/8, hot rolled (GLO, market for steel, chromium steel 18/8, hot rolled)	0,121433962264151	kg
BOM entries	resistor, auxilliaries and energy use (GLO, market for resistor, auxilliaries and energy use)	0,00322641509433962	kg
electricity	electricity, low voltage (GLO, market group for electricity, low voltage)	0,000151547169811321	kWh
BOM entries	selective coat, aluminium sheet, nickel pigmented aluminium oxide (GLO, market for selective coat, aluminium sheet, nickel pigmented aluminium oxide)	0,000104698113207547	m2
BOM entries	aluminium scrap, new (GLO, aluminium scrap, new, Recycled Content cut-off)	-0,0484150943396226	kg
BOM entries	aluminium oxide, non-metallurgical (RoW, market for aluminium oxide, non-metallurgical)	0,00278670328215989	kg
BOM entries	aluminium oxide, non-metallurgical (IAI Area, EU27 & EFTA, market for aluminium oxide, non-metallurgical)	0,000471787283877841	kg
BOM entries	nylon 6 (RER, market for nylon 6)	0,00157499186394196	kg

Insert | Remove | 11 More

Destination	Output	Coefficient	Unit
Output 9	iron scrap, unsorted (GLO, market for iron scrap, unsorted)	0,159418867924528	kg
Packaging	electric motor, electric passenger car	1	kg
Output 9	waste plastic, industrial electronics (CH, market for waste plastic, industrial electronics)	2,80803953908841E-06	kg
Output 9	waste plastic, industrial electronics (RoW, market for waste plastic, industrial electronics)	0,00018587120574393	kg

Figure 35 Motor Assembly Process Inventory (1/2)



Source	Input	Coefficient	Unit
BOM entries	permanent magnet, for electric motor (GLO, market for permanent magnet, for electric motor)	0,0373584905660377	kg
BOM entries	copper, cathode (GLO, market for copper, cathode)	0,134905660377358	kg
sheet rolling, aluminiu	sheet rolling, aluminium (GLO, market for sheet rolling, aluminium)	0,242075471698113	kg
BOM entries	printed wiring board, surface mounted, unspecified, Pb free (GLO, market for printed wiring board, surface mounted, unspecified, Pb free)	0,000754716981132075	kg
heat, natural gas	heat, district or industrial, natural gas (GLO, market group for heat, district or industrial, natural gas)	0,421698113207547	MJ
wire drawing, copper	wire drawing, copper (GLO, market for wire drawing, copper)	0,134905660377358	kg
heat	heat, central or small-scale, other than natural gas (GLO, market group for heat, central or small-scale, other than natural gas)	0,409245283018868	MJ
sheet rolling steel	sheet rolling, steel (GLO, market for sheet rolling, steel)	0,797169811320755	kg
BOM entries	steel, chromium steel 18/8, hot rolled (GLO, market for steel, chromium steel 18/8, hot rolled)	0,121433962264151	kg
BOM entries	resistor, auxilliaries and energy use (GLO, market for resistor, auxilliaries and energy use)	0,00322641509433962	kg
electricity	electricity, low voltage (GLO, market group for electricity, low voltage)	0,000151547169811321	kWh
BOM entries	selective coat, aluminium sheet, nickel pigmented aluminium oxide (GLO, market for selective coat, aluminium sheet, nickel pigmented aluminium oxide)	0,000104698113207547	m2
BOM entries	aluminium scrap, new (GLO, aluminium scrap, new, Recycled Content cut-off)	-0,0484150943396226	kg
BOM entries	aluminium oxide, non-metallurgical (RoW, market for aluminium oxide, non-metallurgical)	0,00278670328215989	kg
BOM entries	aluminium oxide, non-metallurgical (IAI Area, EU27 & EFTA, market for aluminium oxide, non-metallurgical)	0,000471787283877841	kg
BOM entries	nylon 6 (RER, market for nylon 6)	0,00157499186394196	kg
BOM entries	nylon 6 (RoW, market for nylon 6)	0,00318915907945426	kg
BOM entries	polyester resin, unsaturated (RER, market for polyester resin, unsaturated)	0,000264484888963099	kg
BOM entries	polyester resin, unsaturated (RoW, market for polyester resin, unsaturated)	0,00181098680915011	kg
BOM entries	brass (CH, market for brass)	1,79150943396226E-05	kg
BOM entries	brass (RoW, market for brass)	0,00356510377358491	kg

Destination	Output	Coefficient	Unit
Output 9	iron scrap, unsorted (GLO, market for iron scrap, unsorted)	0,159418867924528	kg
Packaging	electric motor, electric passenger car	1	kg
Output 9	waste plastic, industrial electronics (CH, market for waste plastic, industrial electronics)	2,80803953908841E-06	kg
Output 9	waste plastic, industrial electronics (RoW, market for waste plastic, industrial electronics)	0,00018587120574393	kg

Figure 36 Motor Assembly Process Inventory (2/2)

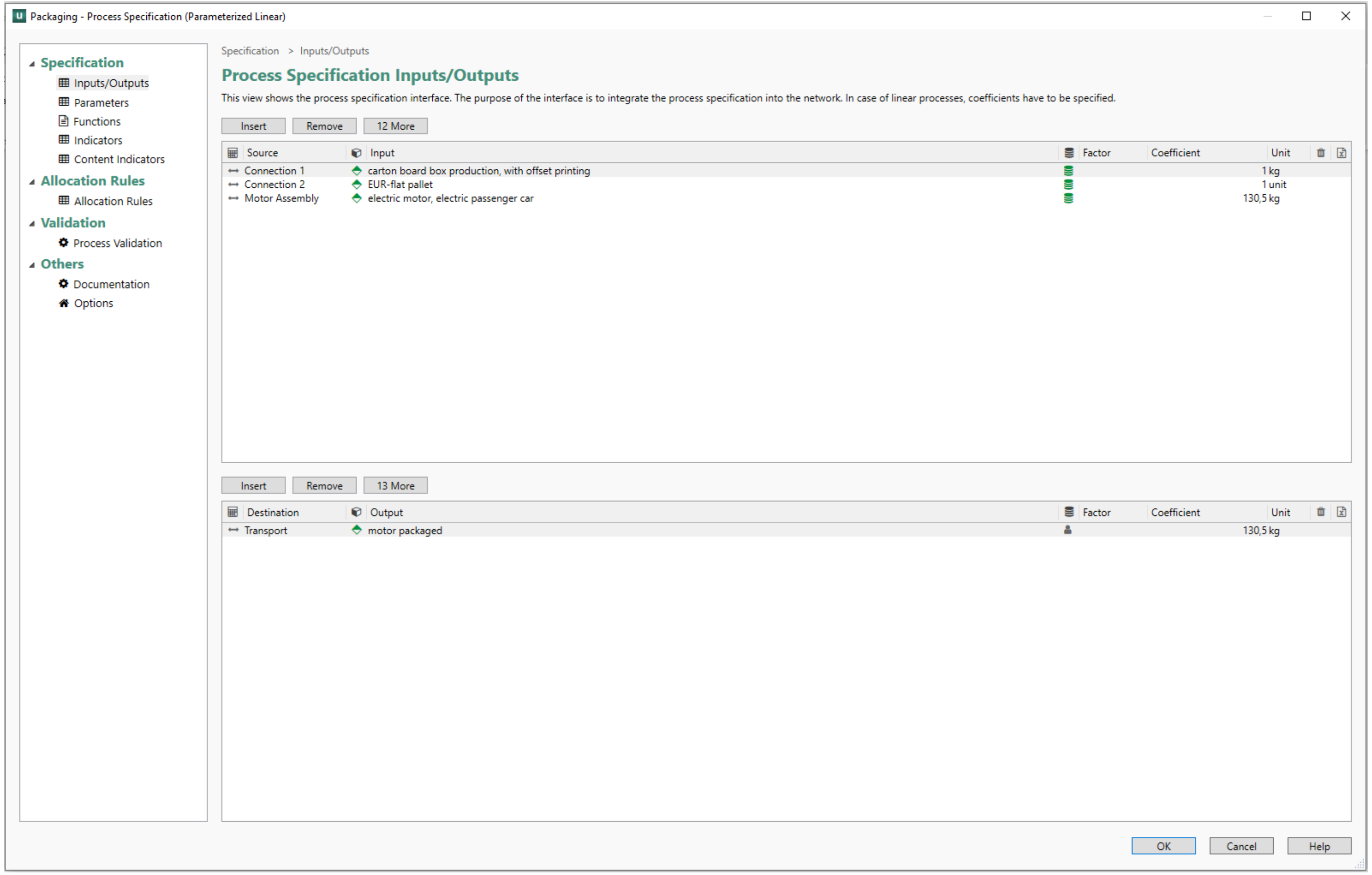


Figure 37 Packaging Process Specification

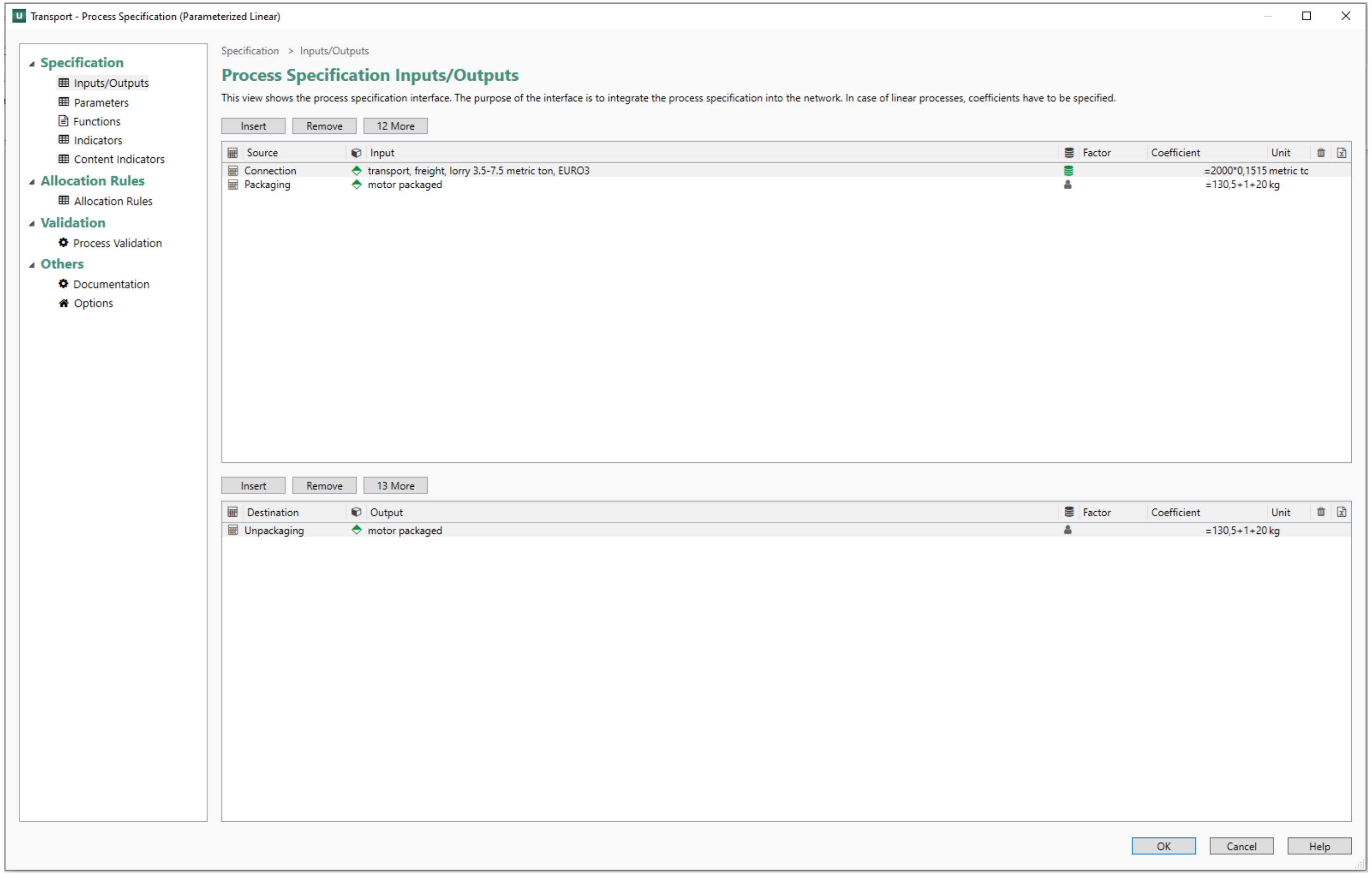


Figure 38 Transport Process Specifications

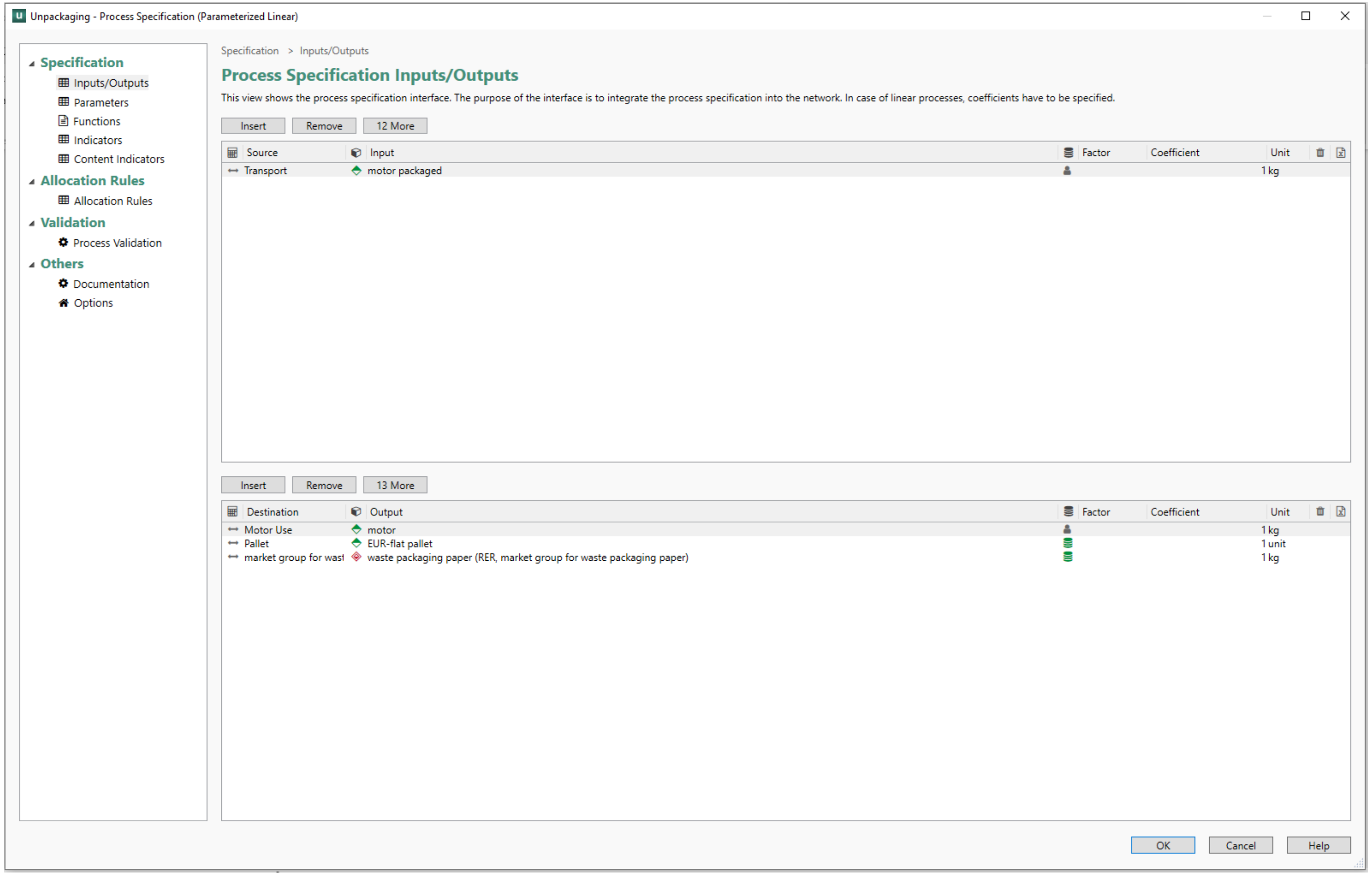


Figure 39 Unpackaging Process Specification

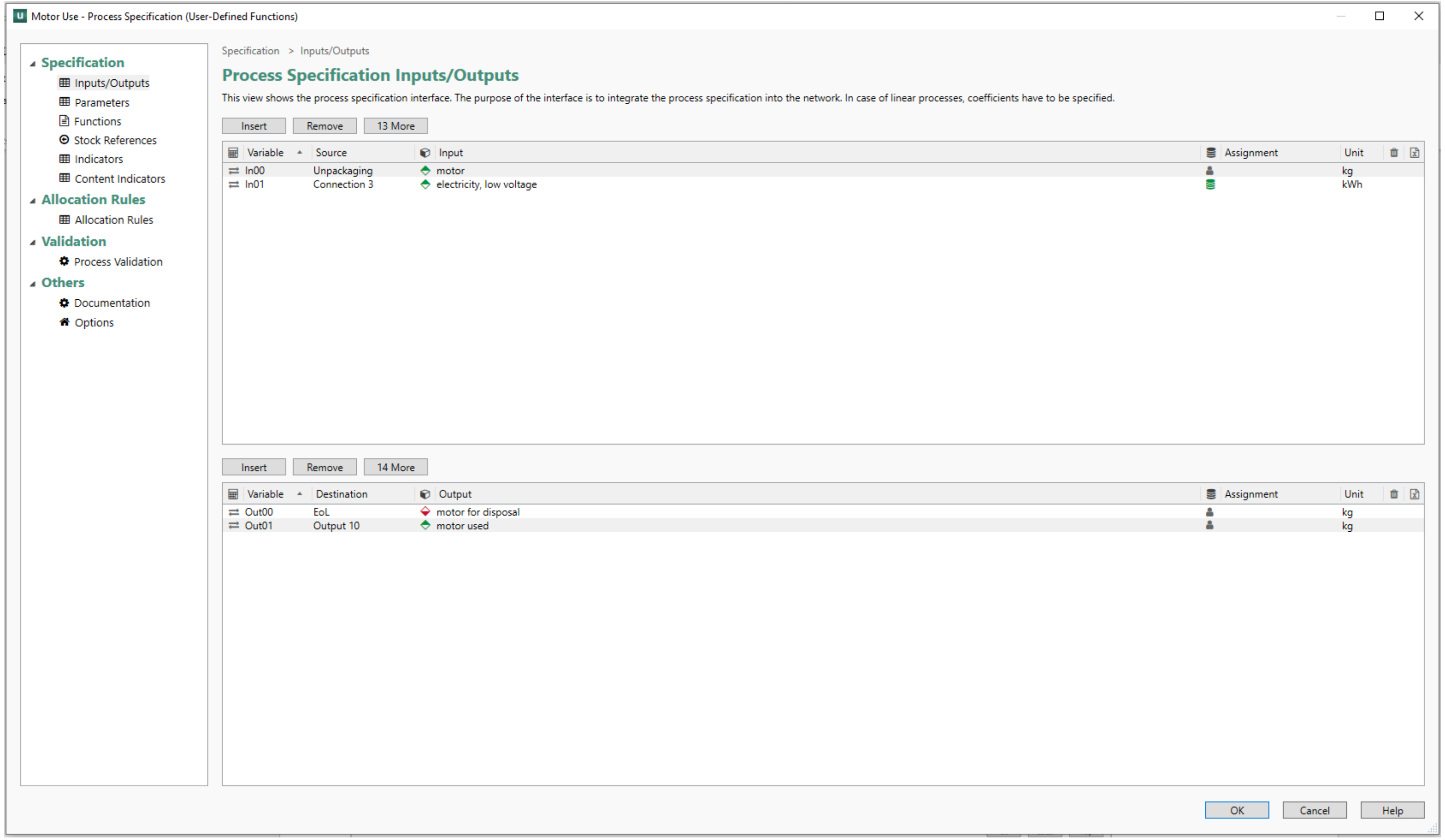


Figure 40 Motor Use Process Specification

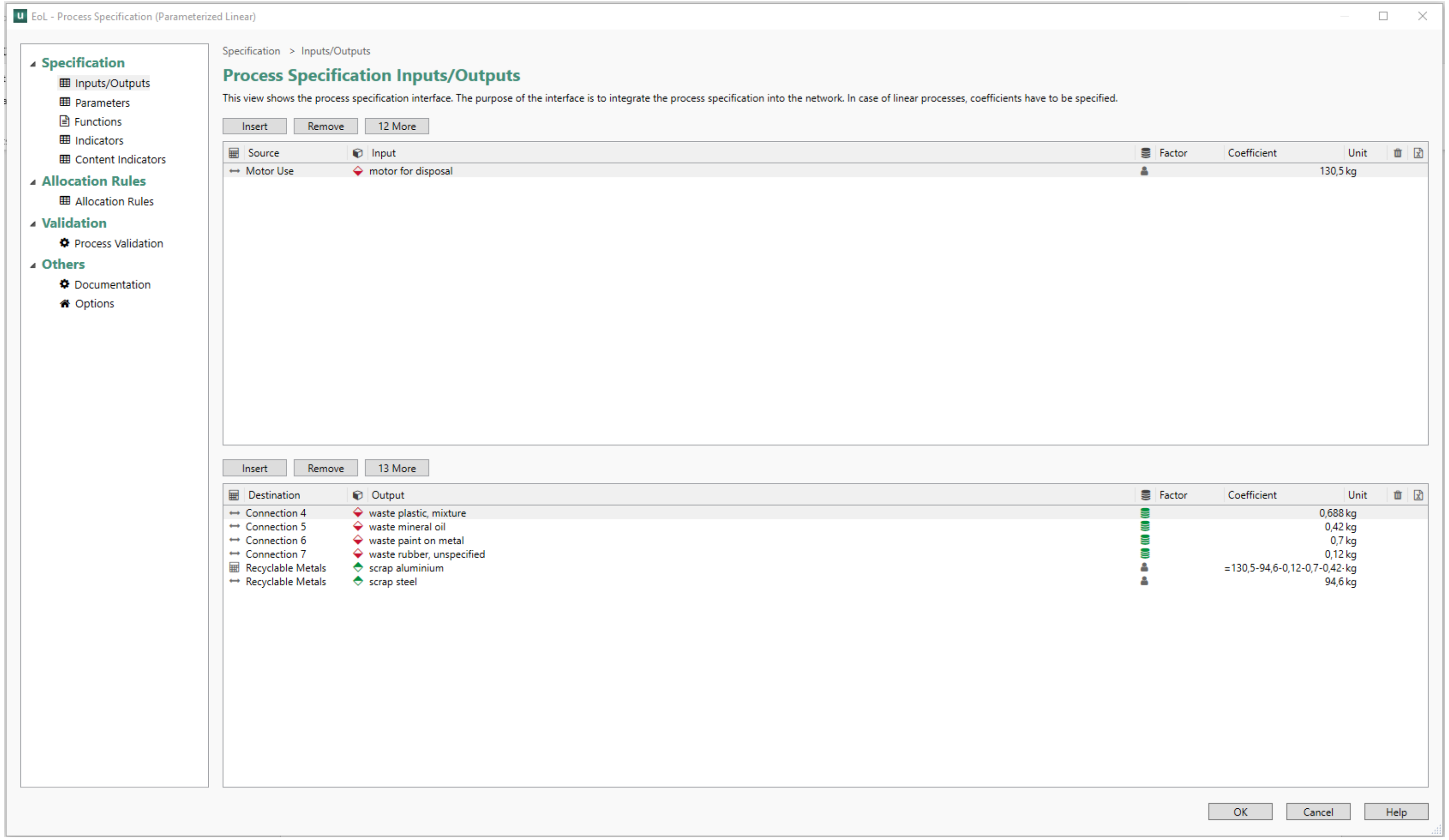


Figure 41 EOL Process Specification

Table 8 Full Electric Motor EPD Result Export

EPD - EN 15804

The ecoinvent EN15804 system model provides all Life Cycle Inventory (LCI) indicators required in EPDs, additional to the EF 3.0 LCIA indicators. The indicators describe resource use, waste categories and output flows, and provide information on biogenic carbon content.

Item	Contribution	Value	
motor used			
Environmental Product Declaration	Total	0.000	
Environmental impacts	Total	0.000	
Climate change - Total	Disposal	1.766	kg CO2-Eq
	Raw Materials	7.927	kg CO2-Eq
	Manufacture	1.079	kg CO2-Eq
	Distribution	1.031	kg CO2-Eq
	Use Phase	32586.403	kg CO2-Eq
	Total	32598.207	kg CO2-Eq
Climate change - Selection	Total	32598.207	kg CO2-Eq
Biogenic	Disposal	1.714	kg CO2-Eq
	Raw Materials	-0.295	kg CO2-Eq
	Manufacture	0.042	kg CO2-Eq
	Distribution	0.005	kg CO2-Eq
	Use Phase	3382.017	kg CO2-Eq
	Total	3383.484	kg CO2-Eq
Land use and land use change	Raw Materials	0.017	kg CO2-Eq
	Manufacture	0.002	kg CO2-Eq

	Disposal	0.000	kg CO2-Eq
	Distribution	0.001	kg CO2-Eq
	Use Phase	68.131	kg CO2-Eq
	Total	68.151	kg CO2-Eq
Fossil	Raw Materials	8.204	kg CO2-Eq
	Manufacture	1.035	kg CO2-Eq
	Disposal	0.052	kg CO2-Eq
	Distribution	1.025	kg CO2-Eq
	Use Phase	29136.256	kg CO2-Eq
	Total	29146.572	kg CO2-Eq
Human health	Total	0.000	
Carcinogenic effects	Raw Materials	0.000	CTUh
	Manufacture	0.000	CTUh
	Disposal	0.000	CTUh
	Distribution	0.000	CTUh
	Use Phase	0.000	CTUh
	Total	0.000	CTUh
Non-carcinogenic effects	Raw Materials	0.000	CTUh
	Manufacture	0.000	CTUh
	Disposal	0.000	CTUh
	Distribution	0.000	CTUh
	Use Phase	0.000	CTUh
	Total	0.000	CTUh
Respiratory effects, inorganics	Raw Materials	0.000	Disease incidences
	Manufacture	0.000	Disease incidences

	Disposal	0.000	Disease in-cidences
	Distribution	0.000	Disease in-cidences
	Use Phase	0.001	Disease in-cidences
	Total	0.001	Disease in-cidences
Ozone layer depletion	Raw Materials	0.000	kg CFC-11-Eq
	Manufacture	0.000	kg CFC-11-Eq
	Disposal	0.000	kg CFC-11-Eq
	Distribution	0.000	kg CFC-11-Eq
	Use Phase	0.001	kg CFC-11-Eq
	Total	0.001	kg CFC-11-Eq
Photochemical ozone creation	Raw Materials	0.040	kg NMVOC-Eq
	Manufacture	0.004	kg NMVOC-Eq
	Disposal	0.001	kg NMVOC-Eq
	Distribution	0.007	kg NMVOC-Eq
	Use Phase	68.736	kg NMVOC-Eq
	Total	68.788	kg NMVOC-Eq
Ionising radiation	Raw Materials	1.024	kg U235-Eq
	Manufacture	0.111	kg U235-Eq
	Disposal	0.002	kg U235-Eq
	Distribution	0.085	kg U235-Eq
	Use Phase	16787.311	kg U235-Eq
	Total	16788.534	kg U235-Eq
Ecosystem quality	Total	0.000	
Freshwater ecotoxicity	Raw Materials	1049.164	CTUe
	Manufacture	50.496	CTUe

	Disposal	55.558	CTUe
	Distribution	14.013	CTUe
	Use Phase	421792.818	CTUe
	Total	422962.048	CTUe
Freshwater eutrophication	Raw Materials	0.009	kg P-Eq
	Manufacture	0.001	kg P-Eq
	Disposal	0.000	kg P-Eq
	Distribution	0.000	kg P-Eq
	Use Phase	31.764	kg P-Eq
	Total	31.774	kg P-Eq
Marine eutrophication	Raw Materials	0.041	kg N-Eq
	Manufacture	0.001	kg N-Eq
	Disposal	0.001	kg N-Eq
	Distribution	0.002	kg N-Eq
	Use Phase	28.836	kg N-Eq
	Total	28.882	kg N-Eq
Terrestrial eutrophication	Raw Materials	0.133	mol N-Eq
	Manufacture	0.012	mol N-Eq
	Disposal	0.002	mol N-Eq
	Distribution	0.026	mol N-Eq
	Use Phase	251.140	mol N-Eq
	Total	251.312	mol N-Eq
Freshwater and terrestrial acidification	Raw Materials	0.121	mol H+-Eq
	Manufacture	0.008	mol H+-Eq
	Disposal	0.000	mol H+-Eq
	Distribution	0.006	mol H+-Eq
	Use Phase	166.462	mol H+-Eq
	Total	166.598	mol H+-Eq

Resources		Total	0.000	
	Fossils	Disposal	0.002	MJ
		Raw Materials	86.598	MJ
		Manufacture	12.192	MJ
		Distribution	15.094	MJ
		Use Phase	620106.656	MJ
		Total	620220.543	MJ
	Minerals and metals	Disposal	0.000	kg Sb-Eq
		Raw Materials	0.002	kg Sb-Eq
		Manufacture	0.000	kg Sb-Eq
		Distribution	0.000	kg Sb-Eq
		Use Phase	0.272	kg Sb-Eq
		Total	0.274	kg Sb-Eq
	Land use	Disposal	0.001	points
		Raw Materials	94.637	points
		Manufacture	3.289	points
		Distribution	7.434	points
		Use Phase	112127.049	points
		Total	112232.410	points
	Water Scarcity	Raw Materials	3.391	m3 world-Eq
		Manufacture	0.508	m3 world-Eq
		Disposal	0.041	m3 world-Eq
		Distribution	0.093	m3 world-Eq
		Use Phase	16945.305	m3 world-Eq
		Total	16949.338	m3 world-Eq
Resource use		Total	0.000	
	Cumulative Energy Demand, Non-Renewable Sources (CEDNR)	Disposal	0.002	MJ
		Raw Materials	86.618	MJ

	Manufacture	12.193	MJ
	Distribution	15.095	MJ
	Use Phase	620118.060	MJ
	Total	620231.968	MJ
Cumulative Energy Demand, Renewable Sources (CEDR)	Disposal	0.000	MJ
	Raw Materials	16.186	MJ
	Manufacture	1.237	MJ
	Distribution	0.322	MJ
	Use Phase	126245.189	MJ
	Total	126262.935	MJ
Primary Energy Non-Renewable - Total (PENRT)	Total	620231.968	MJ
Primary Energy Non-Renewable - Selection	Total	620231.968	MJ
Primary Energy Non-Renewable, used as energy carrier (PENRE)	Total	620231.968	MJ
Primary Energy Non-Renewable, used as raw materials (PENRM)	Total	0.000	MJ
Primary Energy Renewable - Total (PERT)	Total	126262.935	MJ
Primary Energy Renewable - Selection	Total	126262.935	MJ
Primary Energy Renewable, used as energy carrier (PERE)	Total	126262.935	MJ
Primary Energy Renewable, used as raw materials (PERM)	Total	0.000	MJ
Use of secondary materials (SM)	Raw Materials	0.395	kg
	Manufacture	0.028	kg
	Disposal	0.000	kg
	Distribution	0.008	kg
	Use Phase	63.829	kg
	Total	64.260	kg
Use of renewable secondary fuels (RSF)	Raw Materials	0.001	MJ
	Manufacture	0.081	MJ

	Disposal	0.000	MJ
	Distribution	0.000	MJ
	Use Phase	0.518	MJ
	Total	0.600	MJ
Use of fresh water (FW)	Disposal	-0.056	m3
	Raw Materials	0.257	m3
	Manufacture	-0.159	m3
	Distribution	0.002	m3
	Use Phase	533.648	m3
	Total	533.694	m3
Waste to disposal	Total	0.000	
Non-hazardous waste disposed (NHWD)	Raw Materials	33.010	kg
	Manufacture	2.733	kg
	Disposal	0.003	kg
	Distribution	0.437	kg
	Use Phase	140839.586	kg
	Total	140875.768	kg
Hazardous waste disposed (HWD)	Raw Materials	2.363	kg
	Manufacture	0.142	kg
	Disposal	0.001	kg
	Distribution	0.024	kg
	Use Phase	2226.125	kg
	Total	2228.655	kg
Radioactive waste disposed (RWD) - Total	Total	4.516	kg
Radioactive waste disposed (RWD) - Selection	Total	4.516	kg
Medium- and Low-level radioactive waste disposed (MLRWD & LLRWD)	Raw Materials	0.001	kg
	Manufacture	0.000	kg

	Disposal	0.000	kg
	Distribution	0.000	kg
	Use Phase	3.565	kg
	Total	3.567	kg
High-level radioactive waste disposed (HLRWD)	Raw Materials	0.000	kg
	Manufacture	0.000	kg
	Disposal	0.000	kg
	Distribution	0.000	kg
	Use Phase	0.949	kg
	Total	0.949	kg
Other output flows	Total	0.000	
Materials for recycling (MFR)	Raw Materials	0.001	kg
	Manufacture	0.162	kg
	Disposal	0.000	kg
	Distribution	0.000	kg
	Use Phase	10.186	kg
	Total	10.348	kg
Materials for energy recovery (MER)	Raw Materials	0.000	kg
	Manufacture	0.000	kg
	Disposal	0.000	kg
	Distribution	0.000	kg
	Use Phase	0.005	kg
	Total	0.005	kg
Exported energy (EE) - Total	Total	5156.832	MJ
Exported energy (EE) - Selection	Total	5156.832	MJ
Exported energy, electric (EEE)	Raw Materials	0.044	MJ
	Manufacture	0.009	MJ
	Disposal	0.013	MJ

	Distribution	0.004	MJ
	Use Phase	1205.340	MJ
	Total	1205.411	MJ
Exported energy, thermal (EET)	Raw Materials	0.324	MJ
	Manufacture	0.038	MJ
	Disposal	0.040	MJ
	Distribution	0.017	MJ
	Use Phase	3951.002	MJ
	Total	3951.421	MJ
Recovered energy (RE)	Raw Materials	0.068	MJ
	Manufacture	0.025	MJ
	Disposal	0.000	MJ
	Distribution	0.032	MJ
	Use Phase	2593.255	MJ
	Total	2593.380	MJ
Biogenic carbon content, total	Total	0.000	kg C
Biogenic carbon content in accompanying packaging	Total	0.000	kg C
Biogenic carbon content in product	Total	0.000	kg C