Hochschule für Angewandte Wissenschaften Hamburg
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Master Thesis

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Modelling and Simulation CO2-Emissions of a Product (From Cradle-to-Grave) early in Design

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Modelling and Simulation CO2-Emissions of a Product (From Cradle-to-Grave) early in Design

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To my parents:

It is with tears of joy and sadness that I write these sentences. The tears of joy come from
the wonderful life I have that couldn't be possible without all your sacrifices.
I know you sacrificed a lot.

The tears of sadness come from the alike wonderful life that you couldn't have, including
living all its good and bad experiences.
I know you suffered a lot, and you still do.

I promise you that I will do everything I can to make you live the rest of your life in
happiness and peace of mind.

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Hamza Bassam

Title of the Thesis

Modelling and Simulation the CO_2-Emissions of a Product (from Cradle to Grave) early in Design

Keywords

Life Cycle Assessment, Model Based Systems Engineering, Systems Modeling Language, Product Life Cycle, Cradle-to-Grave

Abstract

As the global temperature increases continually, the demand for methodologies that support the development of sustainable systems becomes more and more important. Under these circumstances, industries are forced to become sustainable in order to compete successfully against ecologically acting market participants. This work supports these industries interested in developing complex sustainable systems. It is also beneficial for both the Life Cycle Assessment (LCA) and Model-Based Systems Engineering (MBSE) communities. This work develops an MBSE methodology that supports the modelling and Simulation of the environmental aspect of a product from cradle-to-grave in early design stages, when changes are easy and incurred costs are low. It extends the V-Model to consider all life cycle stages and assigns a V for each stage. The left wing of the V, which represents early design stages, is separated with regard to the Requirements, Functions, Logic and Physics (RFLP) approach. The LCA stages are allocated to each level of the RFLP approach. This work demonstrates the methodology using a SysML model of the robot Engineering Living Systems in Automation (ELSA). The model encompasses all life cycle stages that are representative for cradle-to-grave. The results show that MBSE can support in managing the complexity, better understanding the problem, ease the communication of information and analysis throughout the life cycle of a product. The SysML Model provides a way to navigate through the different life cycle stages and hierarchies to study the system. One can go from a top-level perspective and further narrow the scope in order to identify the critical elements. Once a critical element is identified, the traceability relationships offer a chain, where in each step of it a possibility for changing the design is offered. This offers a way to analyze the life cycle of a product in early design stages, when incurred costs are low and changes are easy. Since the main focus of this work is to develop a methodology that shows WHAT to do, HOW to do it and demonstrate the HOWs using a tool. Due to the time constraint of a master thesis, the scope was compromised from one life cycle stage to another in order to include all stages that are representative for cradle-to-grave. Therefore, future work could validate the methodology in order to assess the effort needed to implement it and the benefit from it. Furthermore, the circular economy strategies could be integrated in future research in order to close the cycle from cradle-to-cradle.

Hamza Bassam

Thema der Arbeit

Modellierung und Simulation der CO_2-Emissionen eines Produkts (von der Wiege bis zur Bahre) bereits in frühen Entwicklungsphasen

Stichworte

Ökobilanz, Modellbasiertes Systems Engineering, SysML, Produktlebenszyklus, Von der Wiege bis zur Bahre.

Kurzzusammenfassung

Mit dem kontinuierlichen Anstieg der globalen Temperatur wird die Nachfrage nach Methoden, die die Entwicklung nachhaltiger Systeme unterstützen, immer wichtiger. Unter diesen Umständen sind Industrien gezwungen, nachhaltig zu werden, um im Wettbewerb mit ökologisch handelnden Marktteilnehmern bestehen zu können. Diese Arbeit unterstützt diese Industrien, die an der Entwicklung komplexer nachhaltiger Systeme interessiert sind. Außerdem ist sie sowohl für die Life Cycle Assessment (LCA)- als auch für das Modell-basierte Systems Engineering (MBSE)-Gemeinschaft von Nutzen. In dieser Arbeit wird eine MBSE-Methodik entwickelt, die die Modellierung und Simulation des Umweltaspekts eines Produkts von der Wiege bis zur Bahre in frühen Entwicklungsphasen unterstützt, wenn Designänderungen einfach und die anfallenden Kosten gering sind. Die Methodik erweitert das V-Modell, um alle Lebenszyklusphasen zu berücksichtigen und weist jeder Phase ein V zu. Der linke Flügel des Vs wird im Hinblick auf den Ansatz der Requirements, Functions, Logic und Physics (RFLP) aufgeteilt, dem die Phasen der LCA zugeordnet werden. Diese Arbeit demonstriert die Methodik anhand eines SysML-Modells, das alle Lebenszyklusphasen umfasst, die von der Wiege bis zur Bahre repräsentativ sind. Die Ergebnisse zeigen, dass MBSE dabei helfen kann, die Komplexität zu bewältigen, das Problem besser zu verstehen, die Kommunikation von Informationen sowie die Analyse im gesamten Produktlebenszyklus zu erleichtern. Das SysML-Modell bietet eine Möglichkeit, durch die verschiedenen Lebenszyklusphasen und Hierarchien zu navigieren, um das System zu untersuchen. Man kann von einer Top-Level-Perspektive ausgehen und den Bereich weiter eingrenzen, um die kritischen Elemente zu identifizieren. Sobald ein kritisches Element identifiziert ist, bieten die Traceability-Beziehungen eine Kette, bei der in jedem Schritt eine Möglichkeit zur Änderung des Entwurfs angeboten wird. Auf diese Weise kann der Produktlebenszyklus in frühen Entwicklungsphasen analysiert werden, wenn die anfallenden Kosten gering und Änderungen einfach sind. Das Hauptaugenmerk dieser Arbeit liegt auf der Entwicklung einer Methodik, die zeigt, WAS zu tun ist, WIE es zu tun ist und die das WIE mit Hilfe eines Werkzeugs demonstriert. Aufgrund der zeitlichen Beschränkung einer Masterarbeit wurde der Umfang von einem Lebenszyklusstadium zum anderen eingeschränkt, um alle Stadien, die von der Wiege bis zur Bahre repräsentativ sind, zu berücksichtigen. Daher könnte die Methodik in künftigen

Arbeiten validiert werden, um den für ihre Umsetzung erforderlichen Aufwand und den damit verbundenen Nutzen zu bewerten. Darüber hinaus könnten die Strategien der Kreislaufwirtschaft in die künftige Forschung integriert werden, um den Kreislauf von der Wiege bis zur Wiege zu schließen.

List of Abbreviations

Abbreviation	Meaning
ac	Activity Diagram
AF	Architectural Framework
bdd	Block Definition Diagram
BOM	Bill of Materials
CAD	Computer Aided Design
CE	Circular Economy
COP	Conference of the Parties
DELS	Discret Event Logistic Systems
EBOM	Engineering Bill of Materials
ELSA	Engineering Living Systems in Autonomy
EP	Ecodesign-Pilot
EU	European Union
ERPS	Entreprise Resource Planning
FAF	Framework for Architectural Framework
ibd	Internal Block Diagram
INCOSE	International Council on Systems Engineering
NCOSE	National Council on Systems Engineering
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MBOM	Mechanical Bill of Materials
MBSE	Model-Based Systems Engineering
NCOSE	National Council on Systems Engineering
NIST	National Institute of Standards and Technologies
OMG	Object Management Group
par	Parametric Diagram
PDM	Product Data Management
pkg	Package Diagram
req	Requirement Diagram

RFLP	Requirements (R), Functions (F), Logical solution elements (L), and Physical parts (P)
SE	Systems Engineering
seq	Sequence Diagram
SETAC	Society of Environmental Toxicology and Chemistry
SOI	System of Interest
SOS	System of Systems
stm	State Machine Diagram
SysML	System Modeling Language
uc	Use Case Diagram
UML	Unified Modeling Language

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Chapter 1

Introduction

This chapter presents the motivation and the problem behind this work. Then, the research questions and hypotheses are presented. Finally, the research strategy and the organization of this work are described.

1.1 Motivation and Problem Definition

As the global temperature increases continually, the demand for methodologies that support the development of sustainable systems becomes more and more important. The Paris Agreement resulting from the Conference of the Parties (COP) 21 was adopted in December 2015 by 196 countries (UNFCC, 2021). It is a legally binding international treaty on climate change aiming to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels.

The Intergovernmental Panel on Climate Change (IPCC) predicts reaching a global temperature of 1.5 °C by 2040 if we proceed with the business-as-usual strategy (Allen et al., 2018). At 1.5 °C, risks increase regarding health, livelihoods, food security, water supply, human security and economic growth. Exceeding such temperatures will make the climate of the earth inhabitable for most of the living species. Once such temperature is reached, Clark et al. estimates that the reduction of global temperature by 1 °C could take up to 10,000 years (Clark et al., 2016). This is one of the arguments used to support the hypothesis that humans are heading towards their extinction.

Worldwide, several policies are being implemented in order to fight against climate change. In the European Union (EU), for example, the European Commission defines strategies and laws that will force the members of the EU to achieve the set-up goals in order to combat climate change. As an example, the European Climate Law enshrines the 2050 climate-neutrality objective into EU law (EU-Commission, 2022b). This law is supported by several guidelines on corporate sustainability obligations, such as: the climate action plan (EU-Commission, 2022a), directive on corporate sustainability (EU-Commission, 2022c), the EU emissions trading system (EU-Commission, 2022d) etc.

Under these circumstances, industries are forced to become sustainable in order to compete successfully against ecologically acting market participants. In this context, this work aims to develop a Model-Based Systems Engineering (MBSE) methodology for modelling and simulating the CO_2-Emissions. The MBSE methodology analyzes the lifecycle of a product from cradle-to-grave in early design stages.

MBSE is a multidisciplinary approach for developing complex systems to function as they are intended (Walden and Shortell, 2015). It has seen a great widespread in the development of such systems (Li et al., 2022). Moreover, it delivers a significant return on investment (Rogers III and Mitchell, 2021). MBSE uses a graphical modelling language, such as Systems Modelling Language (SysML), to support its activities. SysML is a general-purpose graphical modelling language developed by the Object Management Group (OMG) (OMG, 2017). The modelling language supports analysis, design, verification and validation of complex systems, including hardware, software, electric/electronic and services.

The early design stages are the most crucial for the whole life cycle of a product. Eigner et al. argue that 80% of the shape of the product is determined in early design stages (Eigner et al., 2014b, p. 379). Figure 1.1 uses the V-Model to emphasize the importance of an analysis in early design stages. The V-Model is a systematic procedure for the development of complex systems (VDI/VDE 2206, 2004). The left wing describes how a system is decomposed from a top-down perspective, starting from requirement engineering to discipline specific development. The right wing integrates the system in a bottom-up manner. The V-Model is described in detail in section 2.2.3.

Figure 1.1 shows the rate of defects induced and found. It also provides nominal estimated cost of defect removal at each development stage. One can notice that late defect discovery leads to escalating repair costs. About 70% of defects are induced on the left side of the V-Model, which represents early design stages. In the meantime, it is the stage with the lowest costs for reparation, but also the one with the lowest rate of error detection. The rest of the defects is introduced on the right wing of the V-Model. This is also the stage, where most of the defects are identified, but reparation costs vary from 5 to 1000 times of the nominal estimated cost, depending on how late the defects are detected. Therefore, it is important to invest time and efforts in early design stage, when design-changes are the cheapest and the easiest.

An analysis of the whole life cycle of a product is mandatory in order to have a good estimate of its environmental impacts of a product (Matthews et al., 2015, p. 15). The interest of studying environmental impacts of consumer products has taken a great interest in the last years. In particular, comparative studies have sparked several controversies. In these studies, the environmental impacts of several product alternatives are assessed to identify the optimal solution. A good example is represented by the light bulb market. On the one hand, these of fluorescent type have a longer life span and consume less energy than the traditional incandescent types. On the other hand, they require more material and contain heavy metals. Other classic examples are baby diapers (paper versus cotton)

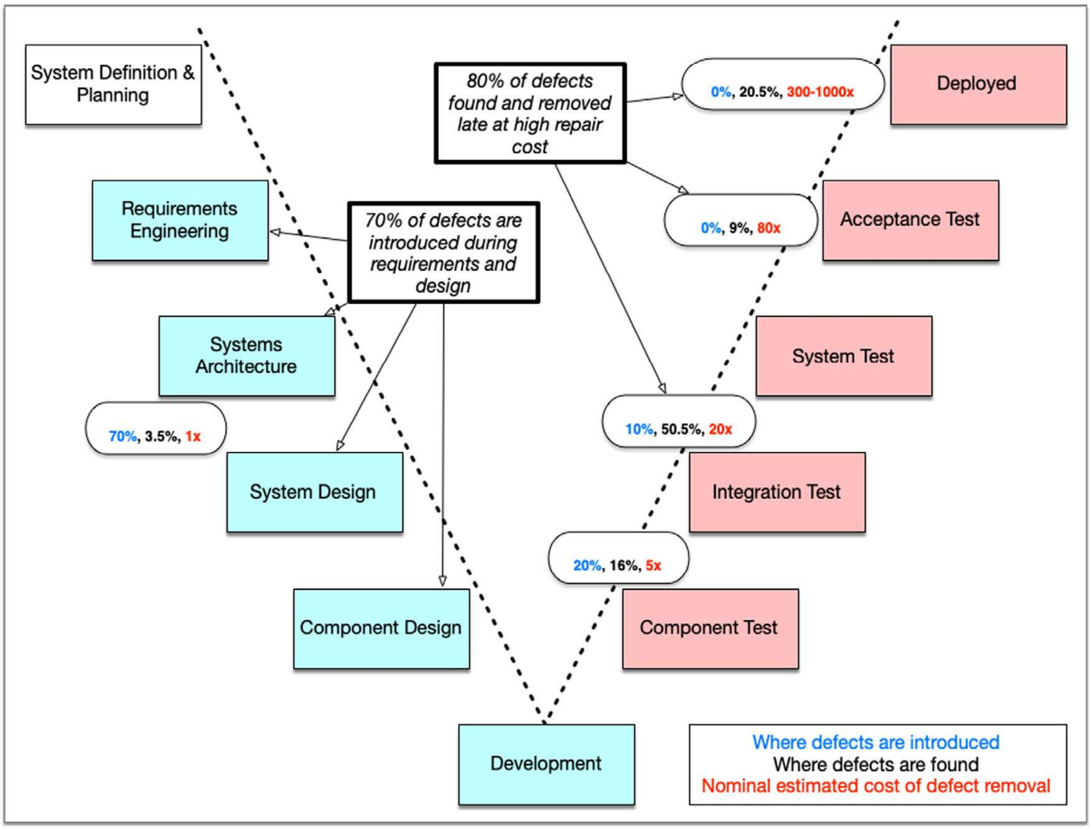


Figure 1.1: Late defect discovery drives escalating repair costs (Rogers III and Mitchell, 2021)

and milk packaging (glass versus plastic versus carton). It has been recognized that, for many of these products, one cannot assess only one life cycle stage to provide a statement on the sustainability of the product, but rather requires a holistic view on the life cycle of the product.

Sustainability considers three aspects: economical, environmental and social. In this thesis, the focus is narrowed on the environmental facet. Meaning, the term sustainability only involves the environmental side in this work. Sustainability is addressed in more detail in section 2.1. Furthermore, The models presented in this work were generated using Cameo Systems Modeler version 19.0 Sp2 with SysML 1.5. Elements of the model are highlighted using camel case to distinguish them from normal text.

1.2 Research Questions and Hypotheses

This project aims to support industries in developing sustainable systems with the lowest cost possible. Based on the initial literature review, the following assumptions were made:

1. Early design stages are the most crucial in the life cycle of a product, maybe even
2. Improving the design of the product in early design stages can reduce costs and increase sustainability as well as product quality
3. This quality and sustainability of the product is assumed to increase customer satisfaction and thus the success of the product

Two key concepts are important for developing sustainable products: the life cycle thinking (Matthews et al., 2015, p. 15) and the analysis in early design stages (Eigner et al., 2014b, p. 379). The life cycle thinking perspective is necessary for a reliable assessment of the environmental impacts of a product. However, the analysis of the whole life cycle of a product increases the complexity of the system, so that it becomes a System of Systems (SOS). INCOSE defines SOS as *"a System of Interest (SOI) whose elements are managerially and/or operationally independent systems. These interoperating collections of constituent systems usually produce results unachievable by the individual systems alone"* (Walden and Shortell, 2015, p. 8). In each life cycle stage, we have separate systems that can operate independently of each other. However, for a specific product, these systems have to work together in order to produce the system of interest. This is an example of an SOS. Therefore, analyzing the life cycle of a product is considered to be a complex problem that needs sophisticated methods to address it. MBSE has seen in recent years a great adoption in studying such complex systems (Li et al., 2022). Therefore, it is considered as the most adequate method in this thesis.

Early design stages are responsible for 80% of the decisions regarding the life cycle of a product (Eigner et al., 2014b, p. 21), and 70% of defects induced in a project (Rogers III and Mitchell, 2021). It is also the stage where the costs for design changes are the easiest and the cheapest. Therefore, this research focuses on supporting decision-making in early design stages in order to lower the costs for the development as much as possible. This is especially important for industries. From an environmental perspective, it is also crucial to have a proactive analysis in order to analyze the environmental impacts before harming the environment.

To summarize, developing a sustainable system requires considering the whole life cycle of the product. Hence, increasing the complexity of the system, which results in the need of a sophisticated method, such as MBSE. Furthermore, the analysis should be performed in early design stages in order to support decision-making when incurred costs are low and changes are easy. This motivation led to the initial goal of this thesis, which is the development of an MBSE methodology that allows the assessment of the environmental impacts through the life cycle of a product in early design stages.

Due to the time constraints of a master thesis, the focus is narrowed down to two perspectives. First, the assessment in this work concentrates only on quantifying the CO_2-Emissions of a product. The goal of this work is to develop a methodology. The latter shall define WHAT needs to be done, HOW to do it and demonstrate the HOWs using tools (Martin, 2020). Therefore, it is assumed that showing how the CO_2-Emissions can be assessed is sufficient to demonstrate how to quantify several parameters. The approach used to assess CO_2-Emissions is the same for the other parameters. Assessing other parameters would require applying the same approach but using different data. Secondly, this thesis considers only the life cycle stages from cradle-to-grave. The necessary nine Circular Economy (CE) strategies, or the so-called R-Strategies, for closing the cycle from cradle-to-cradle could be studied in future research (Potting et al., 2017).

Thereby, the central goal of this thesis changes to the development of an MBSE methodology that supports the assessment of CO_2-Emissions of a product from cradle-to-grave in early design stages. This leads us to the main research question:

To what extent can MBSE support the assessment of CO_2-Emissions from cradle-to-grave in early design stages?

Based on literature, I consider the following assumption:

MBSE can support in managing the complexity, better understanding the problem. Furthermore, it can facilitate communication of information and analysis throughout the life cycle of a product.

In order to answer the main question, the following sub-questions are set:

1. How to model the life cycle of a product from cradle-to-grave?
2. How to assess the CO_2-Emissions of a product from cradle-to-grave?
3. How can the approach from the previous question be integrated into an MBSE methodology?
4. How meaningful are the results?

Blessing and Chakrabarti advises in their Design Research Methodology (DRM) formulating Success Criteria and Measurable Success Criteria could be used as measures against which the outcome of the research could be evaluated (Blessing and Chakrabarti, 2009, p. 26). DRM is described in more detail in the following section. This work considers the success criteria "increase sustainability" and "profit".

"Increase sustainability" is measurable during the project. For example, when assessing CO_2-Emissions, one calculates the total emissions of a product; if the methodology can support in reducing the CO_2-Emissions, then, it helps in improving the sustainability of the product. The lower the CO_2-Emissions are, the more sustainable a product is. Normally, one should assess several environmental parameters to assess the sustainability of a product. In this thesis, the focus is narrowed on the CO_2-Emissions. Additionally, the following measurable success criteria are considered in order to evaluate the credibility of the developed methodology.

1. Completeness: Is the methodology applicable for all life cycle stages from cradle-to-grave?
2. Correctness: Does the methodology provide a correct assessment of the environmental perspective of a product?
3. Recognition: Can the assessment provided by the methodology be globally recognized?

Profit is, on the other side, not measurable during the project, but rather after the product is launched. In order to evaluate the developed methodology and the success criterion "profit", the following measurable success criteria are defined:

- Applicability: Can the MBSE approach be applied in early design stages?

- Simplicity: Is the methodology easy to implement?
- Effort: How much effort is needed to apply the methodology?

1.3 Research Strategy and Organization

This master thesis is based on the Design Research Methodology (DRM) by Blessing and Chakrabarti, which makes design research more productive and efficient (Blessing and Chakrabarti, 2009, p. 305). DRM defines an approach as well as a set of methods and guidelines that serve as a basic structure to support the conduct of design research. On the one hand, DRM supports the modelling, as well as the validation of models and theories of the subject of interest. On the other hand, it aims to develop and validate tools based on these models and theories in order to improve design practice.

DRM is a goal-directed yet flexible approach. Besides the possible iterations, parallel execution of phases is also possible. Iterations occur both when comprehension has improved and to further advance understanding (Blessing and Chakrabarti, 2009, p. 14). Stages are executed in parallel for a more efficient process, known as concurrent or simultaneous engineering. In addition, each of the phases can represent the starting point of the method deployment. Moreover, not all phases have to be executed within the scope of a project.

DRM can be divided into four stages: research clarification, descriptive study I, prescriptive study and descriptive study II (see Fig. 1.2). The figure illustrates the stages of DRM, the basic means used in each stage and the main outcomes.

In the research clarification stage, researchers perform a first literature analysis in order to find evidence or at least indications that support their assumptions (Blessing and Chakrabarti, 2009, p. 14). Based on these findings, a realistic and worthwhile research goal is defined. Additionally, researchers describe the actual situation, as well as the desired one, in order to make the assumptions underlying each of the descriptions explicit. Following this, researchers formulate criteria that could be used as measures against which the outcome of the research could be evaluated.

In their work, the authors distinguish between two types of criteria: success criteria and the measurable success criteria (Blessing and Chakrabarti, 2009, p. 26). Success criteria are coupled with the main goal that the research project or program seeks to contribute to. These criteria typically make the goal of the research and its anticipated future contribution to practice clear. Since numerous factors affect success, the definition of success is still a subject of research. Therefore, there are no agreed upon criteria to measure success. To solve this problem, the authors suggest using measurable success criteria. As the name indicates, these criteria are measurable during the project and linked to the success criteria. They can be applied to evaluate the outcomes of the research, given the resources available within the project. The measurable success criteria should be chosen to be as close as possible to the success criteria. In this way, there is a high probability that the success criteria will also be met when the measurable success criteria are.

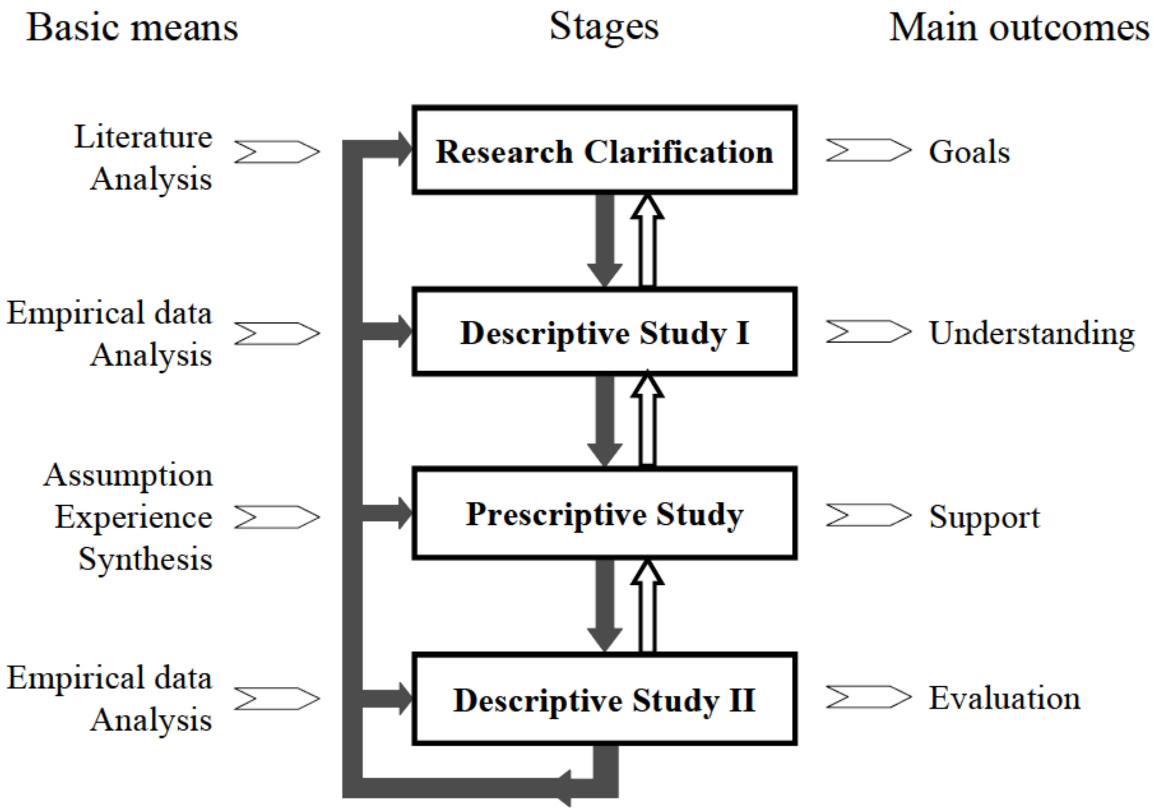


Figure 1.2: Framework of the design research methodology (Blessing and Chakrabarti, 2009, p. 14)

After defining a clear goal of study, in the Descriptive Study I, researchers review the literature for more influencing factors to elaborate the initial description of the existing situation (Blessing and Chakrabarti, 2009, p. 15). The intention is to make the description detailed enough to determine which factor(s) should be addressed to improve task clarification as effectively and efficiently as possible. The evidence from the literature can be complemented by observations or interviews in order to better understand the existing situation, before moving on to the next stage and start developing support to address these factors.

In the Prescriptive Study stage, researchers use their increased understanding of the existing situation to correct and elaborate on their initial description of the desired situation (Blessing and Chakrabarti, 2009, p. 15). This description represents their vision on how addressing one or more factors in the existing situation would lead to the realization of the desired, improved situation. They now have enough confidence to start the systematic development of a support to reach the desired situation. They use their understanding of the various interconnected influencing factors obtained in the Descriptive Study I stage; the well-developed description of the desired situation; as well as their experience. The researchers develop a solution to reach their goal, focusing on the criteria that will be used in order to evaluate the concept and verify the assumptions. First test can be performed to verify that the developed solution solves the problem correctly.

Researchers then proceed to the Descriptive Study II stage in order to investigate the impacts of the support and its ability to produce the desired situation (Blessing and Chakrabarti, 2009, p. 16). Here, tests can be performed to evaluate the solution against the criteria defined in the descriptive study I. From the evaluation, the findings are discussed and suggestions for further research are made.

Figure 1.3 illustrates the DRM as applied in this work. Chapter 1 represents the research clarification stage. In this stage, a first literature review is performed. As a result, the research goal of this master thesis is defined. Also, the motivation and organization of this work are provided. Chapter 2 introduces the background needed to understand this thesis.

Chapter 3 represents the descriptive study I. In this stage, a complementary literature review is performed in order to identify the state-of-the-art methodologies for assessing the environmental perspective of a product using MBSE. Afterwards, the literature is summarized and evaluated against certain defined criteria with the goal of identifying the research gap. Moreover, requirements on the methodology are specified and the expected benefits from studying this research gap are elaborated.

In the prescriptive study, the MBSE methodology is developed based on the requirements defined in the previous stages (see chapter 4). Chapter 5 presents the systems of interest studied in this work. In the descriptive study II, the developed methodology is implemented by developing a model based on SysML (see chapter 6). Chapter 7 interprets the results from the simulation of the model. After that, the model is verified against the requirements of the LCA standard and discussed. Chapter 8 summarizes the findings, concludes this work and provides suggestions for future research.

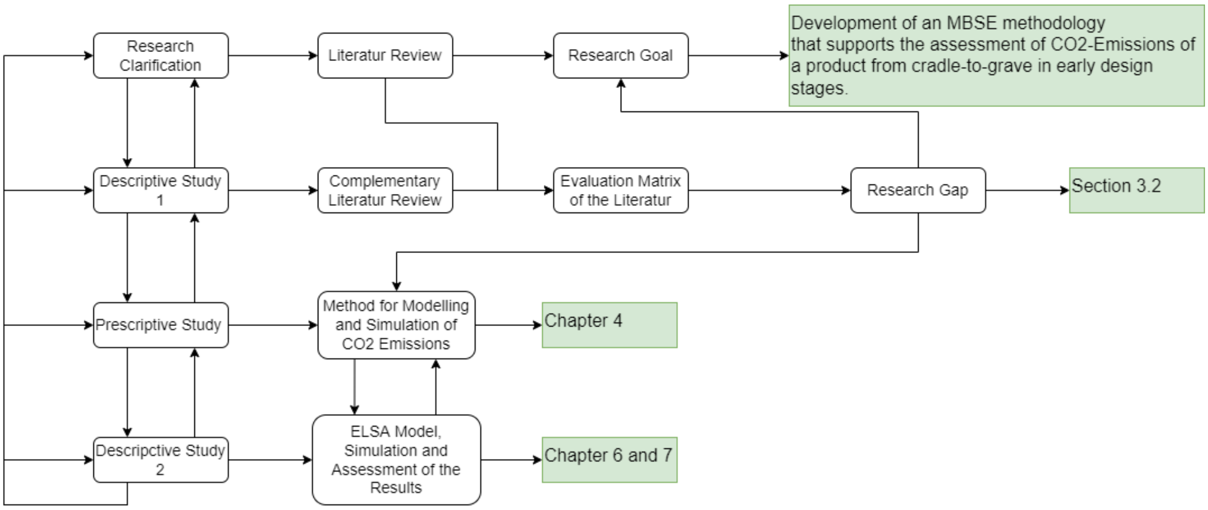


Figure 1.3: The design research methodology used in this work

Chapter 2

Background on Sustainability and Model-Based Systems Engineering (MBSE)

This chapter focuses on the background needed to understand this thesis. Firstly, the concept of sustainability is introduced. Secondly, the chapter centers the focus on the ecological perspective of sustainability based on the ISO 14044 standard. Lastly, both the MBSE methodology from Holt and Perry and modelling techniques used in this work are briefly presented.

2.1 Introducing Concepts of Sustainable Development

This section presents initially the concepts of sustainable development on a broad context. Afterwards, the scope is narrowed to the environmental aspect of sustainability using the International Organization for Standardisation (ISO) 14044 standard, or the so-called Life Cycle Assessment (LCA). Finally, the development steps of an LCA and its most relevant topics are briefly explained. Most of the information in this section is based on the ISO 14044 standard (ISO 14044, 2021). The book from Matthews et al. was used to enlighten the ambiguities of this standard (Matthews et al., 2015).

The history of sustainability can be traced back to the 18th century (Grober, 2007). Particularly in the three last decades, the term “Sustainable Development” has made a rapid rise, when it comes to solving the world’s environmental and social problems. However, the Brundtland Commission, which launched the concept globally in 1987, was not the brainchild of the modern environmental movement. Its blueprint can be traced back to professional forestry terminology, where the major doctrine was “sustained yield”, translated from the German term ’nachhaltiger Ertrag’.

The origin of the concept of sustainability comes from German ’Kameralists’ of early European Enlightenment (Grober, 2007). Cameralism was a German science of administration in the 18th and early 19th centuries that was concerned with the management of the state’s finances. Influenced by the works of the English author John Evelyn and the French statesman Jean Baptist Colbert, the Kameralists began planning their dynastic woodlands “nachhaltig”. Their goal was to pass on their royal woodlands undiminished to future generations. The head of the Royal Mining Office in Germany, Hanns Carl von Carlowitz, invented the term “sustainability” in 1713 while addressing a predicted shortage of timber.

Butlin defines sustainable development as one, which ensures meeting the needs of the present without compromising the ability of future generations to meet their own (Butlin, 1989). These ’needs’ are not only those of survival, but of economic, social and environmental nature. These are the three pillars of sustainability, also called the “triple bottom line”. They include (Munier, 2005):

- economic growth
- societal progress, which makes achieving social equity and equal chances easier, hinders social discrimination and facilitates access to safe housing, education, healthcare and employment opportunities
- environmental preservation, which ensures that resources are renewable and replaceable, so that they can be put to use by future generations as well

Sustainable development is defined as the implementation of the guiding principles of sustainability in the design of products (Eigner et al., 2014b, p. 371). Sustainability should be considered in planning, conception, production, as well as the use of the product (with aspects of possible new forms of utility) and management in cycles (with regard to recycling, reuse and recovery). Requirements of sustainability focus on the product responsibility, in particular the design of a reasonable lifetime of the product, real-time sensing and assessment of current product status. Multi-generational product planning and the incorporation of product-related new services, have also gained a remarkable traction in recent years. These requirements must be included in early design stages and further developed along the lifecycle of the product.

This work focuses solely on the environmental dimension of sustainability. To study the environmental perspective, the LCA standard was used for the following reasons:

1. Based on the literature review (Reap et al., 2008), (Fet et al., 2013), (Culler, 2010), (Azevedo et al., 2009) , LCA is the most extensive and pre-eminent tool for estimating environmental effects
2. LCA is a globally accepted and recognized standard (ISO 14044, 2021), (Matthews et al., 2015, p. 80). This is due to the characteristics of an ISO standard, how it is developed, the community behind it, its rigor and credibility. This will be addressed in details in section 2.1.1

Performing a comparative study of the existing environmental impacts assessment methods, before choosing one, goes beyond the scope of a master thesis. However, this could be carried out in future work.

2.1.1 The ISO Life Cycle Assessment (LCA) Standard

A standard is a set of agreed-upon principles or procedures that can be used to ensure consistency in a particular activity or process (Matthews et al., 2015, p. 80). It can be set up to level up the playing field in a particular market by ensuring that all businesses run similarly, for example, using the same management systems. The ISO standards are backed by extensive studies and their development process encompasses the following components:

1. It addresses a market demand
2. It uses the opinion of experts in the field as its basis
3. A multi-stakeholder team works on its development
4. it is approved by consensus.

The ISO standard is globally accepted due to the thoroughness behind its development process (Guinee et al., 2011). An ISO standard is developed by a technical committee of worldwide specialists. The technical committee drafts, edits and revises the actual standard based on feedback until consensus (75% agreement) is established. An organization aiming for global acceptability and recognition often aims to comply with the numerous ISO standards. For example, firms in the automotive supply chain seek "ISO 9000 compliance" to demonstrate that their quality systems match the standard defined by ISO and thus are allowed to do business in the worldwide market. Standards from other organizations may have a similar development process, but they may differ in terms of ratification requirements, review duration and numerous other factors.

LCA must be standardized to ensure consistency between comparative studies (Matthews et al., 2015, p. 81). Without a clear set of requirements and/or guidelines, any party could conduct an LCA in accordance with their own opinions of how research should be conducted and what methods are deemed appropriate. Without a standard, it is possible to conduct an LCA on the same product and have 10 different results from 10 separate parties. To ensure consistency, the LCA Standard has been developed. However, its laws and norms aren't as rigid as one might expect. Although all ten parties adhere to the standard, one may still get ten different solutions. One could argue that in an area like LCA, it is beneficial to have different perspectives and techniques, rather than having a prescriptive standard that limits the advancement of methods or findings. LCA is also not a single model solution to our complex energy and environmental problems. It should be supported with appropriate models e.g., : risk analysis, environmental impacts assessment, environmental management, benefit-cost analysis, etc. in order to ensure the decision-making process.

From 1970 to 1990, the development of LCA saw a wide range of techniques, terminologies and results throughout the decades (Matthews et al., 2015, p. 80). There was a distinct shortage of LCA discussion and exchange in the worldwide scientific community. It was during the 1970s and 1980s that LCAs were conducted in a variety of ways and without a consistent theoretical framework. LCA was frequently used by companies to support their claims on the market. Nevertheless, LCA was unable to become a more widely acknowledged and applied analytical tool since the results differed substantially, despite the objectives of the study were identical. The ISO became interested in standardization during the 1990s and early 2000s. The working groups from the Society of Environmental Toxicology and Chemistry (SETAC) concentrated on developing and harmonizing methods, whereas ISO took on the formal role of standardizing methods and procedures. Listed below are helpful standards covering LCA:

1. ISO 14040:2021: Environmental management - Life cycle assessment - Principles and framework (ISO 14040, 2021)
2. ISO 14044:2021: Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044, 2021)
3. ISO 14049:2012: Environmental management — Life cycle assessment — Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis (ISO 14049, 2012)

These three underlying standards will be referred to in this work as the ISO LCA standard (Matthews et al., 2015, p. 82). The notation “14040:2021” means that the ISO LCA Standard is in the “ISO 14000” family of standards. The current version, as of the time of writing this work, was most recently updated in 2021. The first version of the ISO LCA standard was published in 1997. ISO LCA Standard formalizes the quantitative modelling and accounting needs to implement life cycle thinking to support decisions. ISO 14040:2021 represents the current principles and framework of the Standard and is written for a managerial audience. ISO 14044:2021 gives the requirements and guidelines as for a practitioner. Whereas ISO 14049:2021 provides illustrative examples on how to apply ISO 14044.

A key result of ISO’s standardization work has been the definition of a general methodological framework (see Fig. 2.1) (Matthews et al., 2015, p. 83). The figure shows the four stages of the ISO LCA standard: goal and scope definition, inventory analysis, impacts assessment and interpretation. The goal and scope state the intent of the study. They make it clear why and to what extent a study is being conducted. In the inventory analysis stage, the data and the documents needed are collected (e.g., energy use and emissions of greenhouse gases) to meet the stated goal and scope. In the impacts assessment stage, a transition is carried out from tracking life cycle inventory results like greenhouse gas emissions to environmental impacts, such as climate change. Finally, the interpretation concludes by analyzing and putting into perspective the findings of the study and making suggestions in order to minimize their negative effects. The results from the LCA study can be directly used in product development and improvement, strategic planning, public policy making, etc.

The double arrows indicate that the four stages are iterative, i.e., the purpose and scope may need to be adjusted if inventory data collection proves difficult (Matthews et al., 2015). In the course of analysis, every study will be changed in some manner. This is not a sign of weakness or failure, but rather a defined method for furthering one’s understanding of the subject matter.

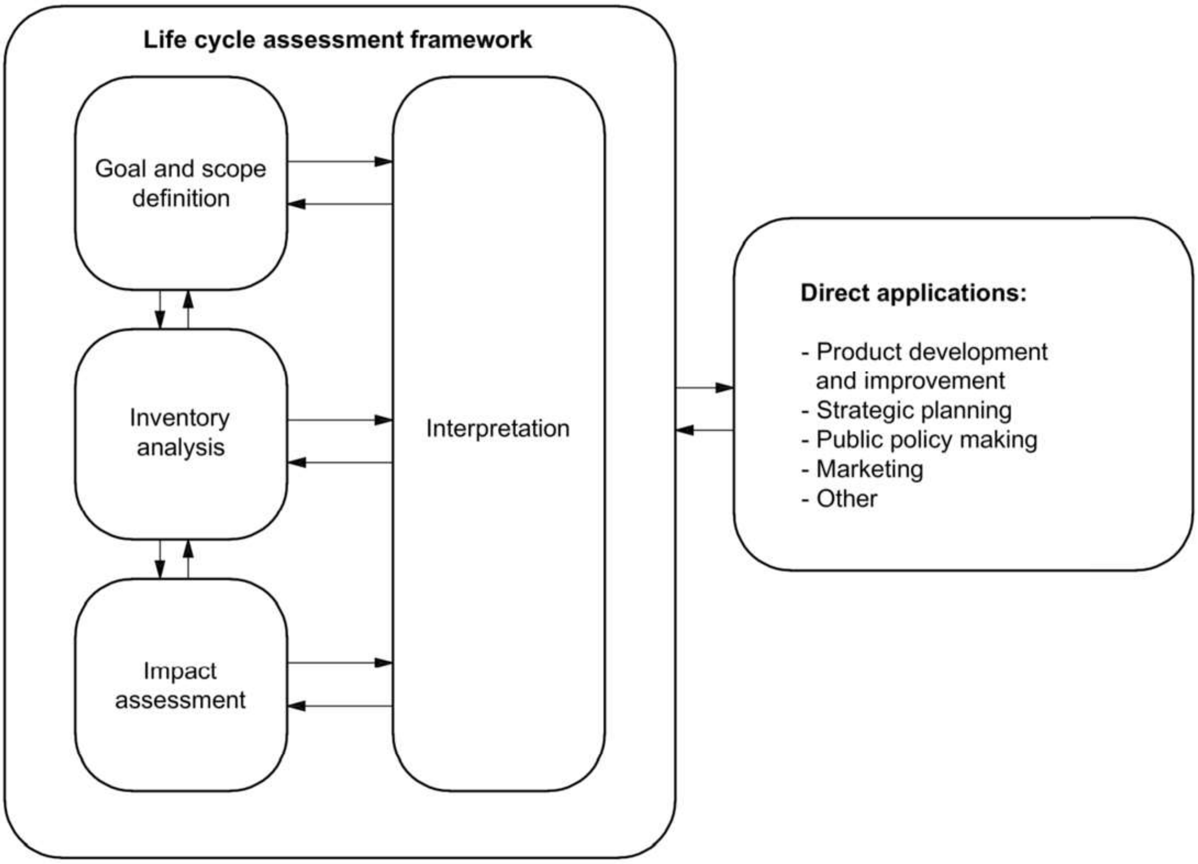


Figure 2.1: Overview of ISO LCA Framework (Matthews et al., 2015, p. 83)

The term Life Cycle Inventory (LCI) is used to describe a study that does not include the impact assessment stage, as noted by ISO (Matthews et al., 2015, p. 100). In other words, its end conclusions are calculations of the total input and output without any consideration of the impact. This work performs an LCI study with the goal of integrating LCI methodology with MBSE to quantify the CO_2-Emissions of a product across its lifecycle. The goal is not to assess the environmental impacts of the system of interest. Therefore, the interpretation stage is omitted.

2.1.1.1 Goal and Scope Definition

This section introduces the goal and scope definition steps from LCA. First, goal definition stage is presented, afterwards, the scope definition and its relevant concepts are explained.

Goal Definition

The requirements for goal definition can be found in Fig. 9.5. ISO requires that the goal definition shall include unambiguous statements about four items: 1) the intended application; 2) The reasons for carrying out the study; 3) The intended audience; 4) Whether the results will be used in comparative assertions and released publicly.

The goal of an LCA must be clearly stated. As an example, the following statements were used to define the goal of an LCA study that compares artificial and natural Christmas trees bought in the U.S.:

"The findings of the study are intended to be used as a basis for educated external communication and marketing aimed at the American Christmas tree consumer" (Americas, 2010)

"The goal of this LCA is to understand the environmental impacts of both the most common artificial Christmas tree and the most common natural Christmas tree and to compare between their environmental impacts compare. To enable this comparison, a cradle-to-grave LCA was conducted of the most commonly sold artificial and the most commonly sold natural Christmas tree in the United States." (Americas, 2010)

"This comparative study is expected to be released to the public by the ACTA to refute myths and misconceptions about the relative difference in environmental impacts by real and artificial trees." (Americas, 2010)

From these statements, one can understand all four of the ISO-required items of the goal statement. The intended application is external marketing. The reasons are to refute misconceptions. The audience is American tree consumers. Finally, the study was noted to be planned for public release.

Scope Definition

ISO requires 14 parameters to be qualitatively and quantitatively described for an LCA study to define its scope (see Tab. 2.1). The requirements for scope definition can be found in Fig. 9.5. In the following, the parameters 1-4 are explained in detail due to its important relevance in this work. The seventh parameter is addressed in section 2.1.1.4. As for the rest of the parameters, they are covered sufficiently in the LCA ISO Standard (ISO 14044, 2021).

Table 2.1: The 14 parameters of the LCA scope definition (ISO 14044, 2021)

Parameters of the scope definition	
Product system	Data requirements
Functions of the product system	Assumptions
Functional unit	Value choices and optional elements
System boundary	limitations
Allocation procedures	data quality requirements
LCIA Methodology and types of impacts	type of critical review
Interpretation to be used	Type and format of the report required for the study

Product System and System Boundary

In order to understand the product system, it is important to first understand some relevant terms. The ISO LCA standard defines a product as any type of good or service (ISO 14044, 2021). It can be a physical object, software, or service. Processes describe activities that transform input into output. A unit process is the smallest element analyzed during the life cycle inventory analysis to which input and output data are assigned in order to quantify the flows, as shown in Fig. 2.2. Flows can be separated into elementary and intermediate flow. Elementary flow represents natural material or energy entering or leaving the system being studied. It has not been subject to any human transformation. It is illustrated in Fig. 2.2 as emission(s) and input from nature. Intermediate flow describes product, material, or energy flow occurring between unit processes of the product system being studied. It is shown in Fig. 2.2 as input(s) from technosphere and product(s).

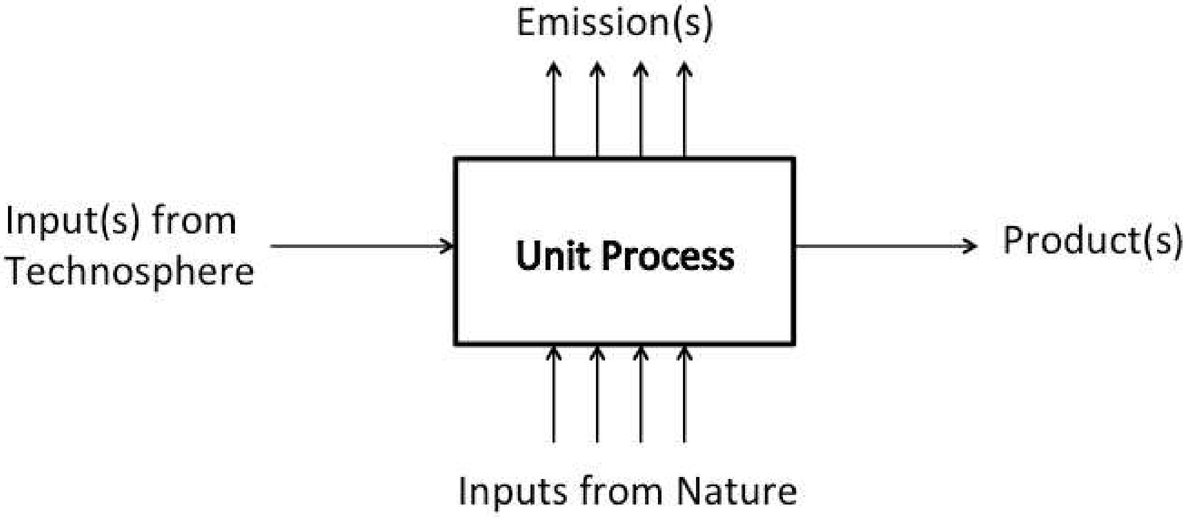


Figure 2.2: Generalized unit process diagram (Matthews et al., 2015, p. 103)

ISO 14044 defines a product system as the collection of unit processes and their flows, performing one or more defined functions and which represent the product's life cycle (ISO 14044, 2021). This definition contains two main concepts. First, the collection of unit processes perform one, or more functions. This part will be elaborated later in this section when addressing "Function of the product system". Second, the collection of unit processes build the life cycle of the product. Fig. 2.3 shows an example of a product system. The product system contains five unit processes: energy supply, transport, production, use and end of life. Each of these unit processes has input from or/and output flows to other unit processes. They are marked with the different colors.

The system boundary defines, according to the study goals, the start, the end and the interfacing flows of the product system. Based on the previous example of a product system, Fig. 2.4 shows an example of a system boundary. The boundary is illustrated using a rectangle with dashed lines. The elements inside of the rectangle are part of the scope and the elements outside of it are out of the scope. The ISO LCA standard requires the defi-

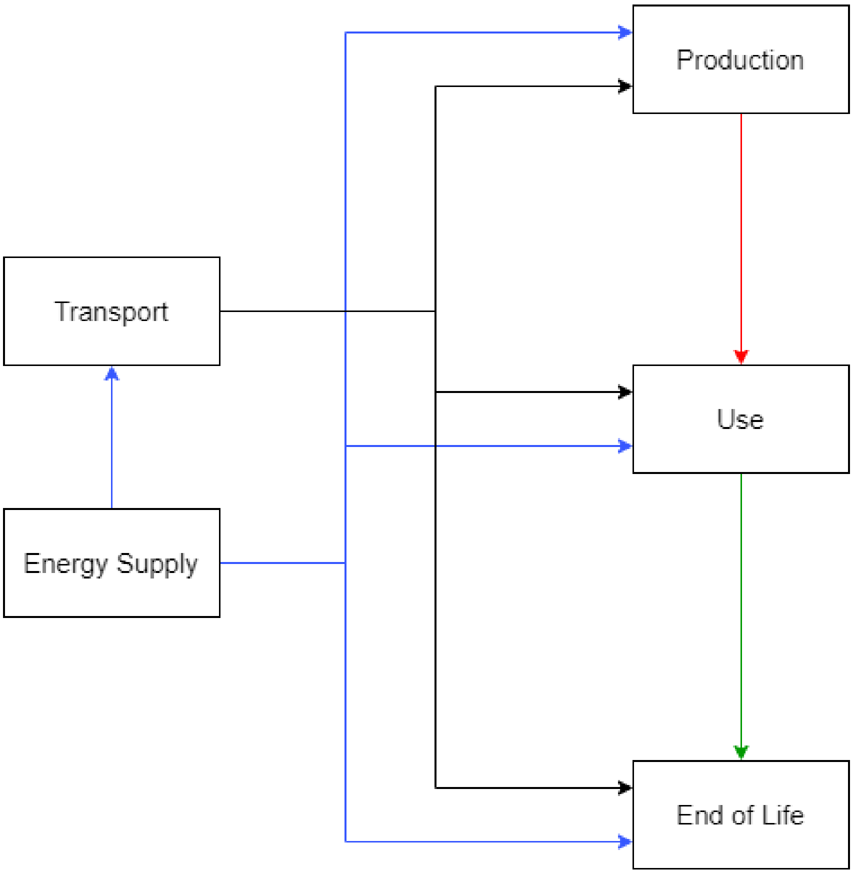


Figure 2.3: An example of a product system, adapted from (Matthews et al., 2015, p. 90)

nition of the system, as well as, the in- and output flows entering and leaving the system boundary.

Defining the system boundary is a crucial and often not a simple task. Let's assume that we want to perform an LCA on an aircraft. Lufthansa claims that it took around six million parts to build Boeing 747-8 (KnisleyWeldingInc., 2019). We can obviously not include all the six million parts and their life cycles in the LCA. Therefore, one has to select the right boundary that includes all relevant factors and sacrifice some level of detail, according to the study goal. Beyond the visualization and description of the system boundary, the ISO LCA standard requires the justification of the chosen boundaries. Justification, also, helps the audience understand the difficulties encountered and trade-offs made in the study.

Functions of the Product

The ISO LCA standard requires a discussion of the function of the product system in the context of what does the system do? (Matthews et al., 2015, p. 87) A product system is defined in the ISO LCA standard as a collection of unit process that performs one or more defined functions (ISO 14049, 2012). The purpose of describing the function is to dispel any misunderstandings or assumptions that might arise from focusing solely on the product system. Elaborating with the Christmas tree example, its function would be to bring joy to the holiday season, for example. When a product has multiple functions, the ISO LCA standard requires to specify the relevant

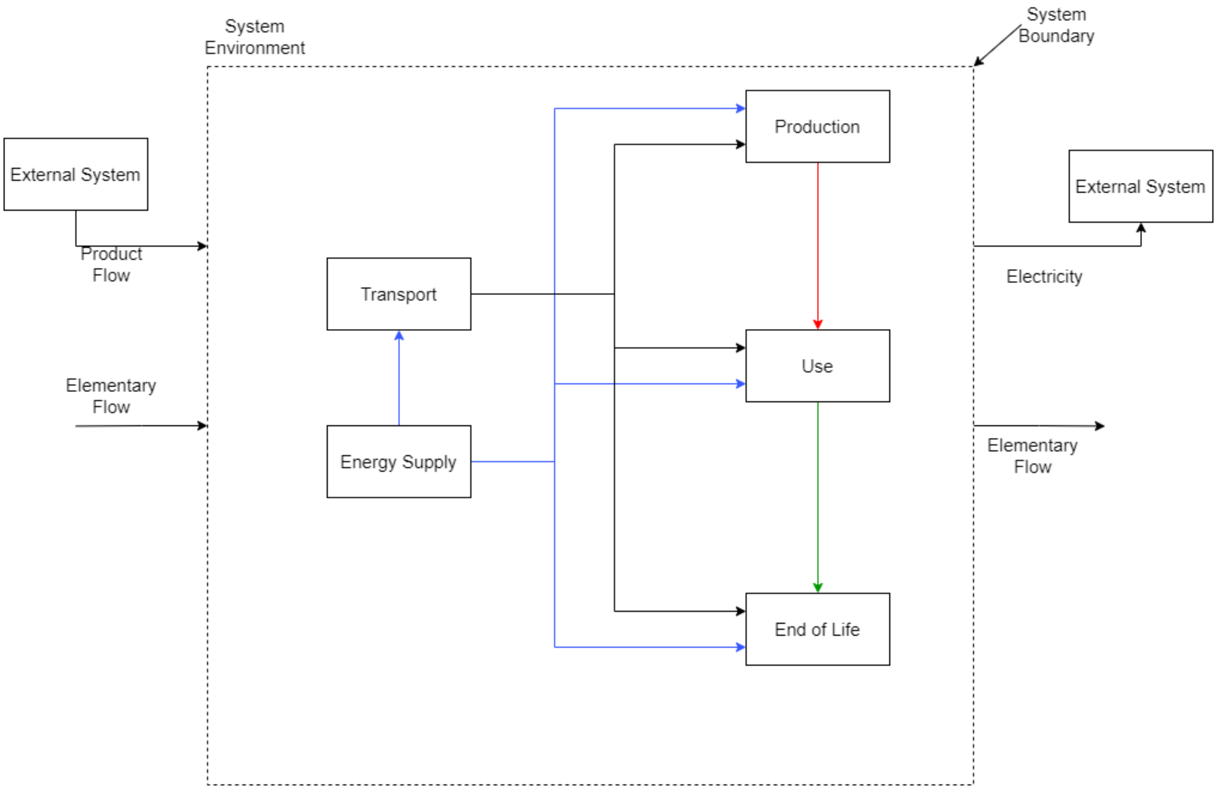


Figure 2.4: An example of the boundary of a product system, adapted from (Matthews et al., 2015, p. 90)

function(s) for the particular LCA study.

Functional Unit

The ISO LCA standard defines the functional unit as a quantitative measure that describes the performance of a product system. The purpose of the functional unit is to provide a reference to which in- and output data are normalized. This ambiguity is addressed in more detail in (ISO 14049, 2012), as shown exemplary in Fig. 2.5. The product used in the example is wall paint. It has the following functions: surface protection, coloring, etc. The relevant function for the LCA study was chosen to be the colouring of a wall with a paint of type A. The functional unit is the colouring of 20 m^2 of a wall with a paint of type A, an opacity of 98% and a durability of 5 years. One can notice that the example provides a functional unit that bridges the function as well as the input and output. Also, the functional unit explicitly states the units used. The results of the study will be normalized by the chosen functional unit.

Once the functional unit is specified, the necessary amount of the product to fulfill the function shall be quantified. This is referred to as the reference flow. To identify the reference flow, it is helpful to first know the performance of the product, then specify the reference flow, as shown in Fig. 2.5. The performance of the wall paint A is the colouring of 8.7 m^2 per liter. To colour 20 m^2 (from the functional unit), we need 2.3 liter of paint A. This is the reference flow for this example.

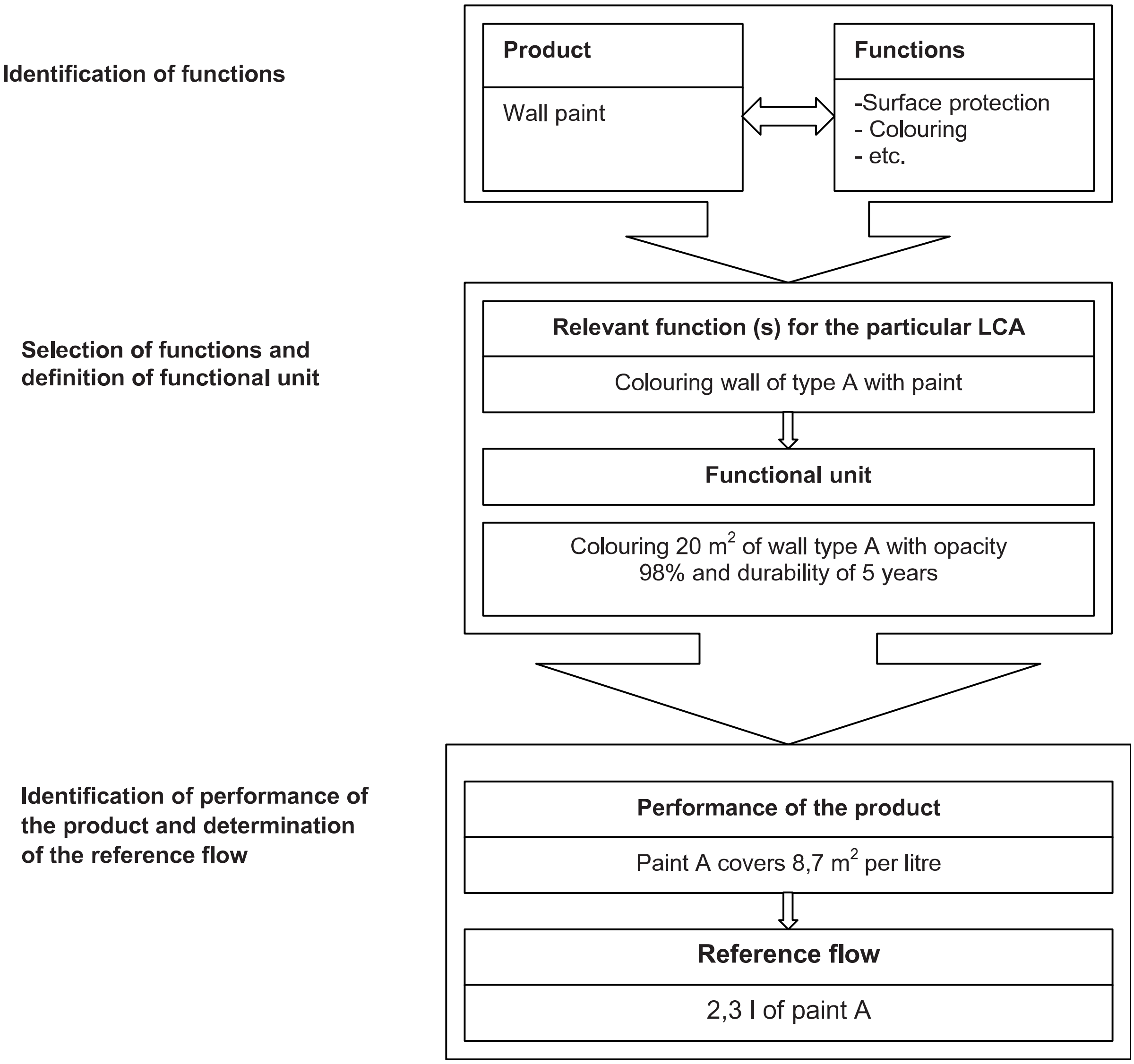


Figure 2.5: Example for developing functions, functional units and reference flows (ISO 14049, 2012)

2.1.1.2 Life Cycle Inventory Analysis (LCI)

The definition of the goal and scope of a study specifies the context for conducting the life cycle inventory analysis stage of an LCA. ISO 14044 advises the procedure shown in Fig. 2.6 when performing an inventory analysis. The procedure is explained in great detail in (Matthews et al., 2015, p. 101) and (ISO 14044, 2021). In the following, the life cycle inventory analysis is briefly presented (Matthews et al., 2015, p. 101):

1. Goal and scope definition: define the context of the study. This step was described in section 2.1.1.1

2. Preparing for data collection: the goal and scope definition from the previous step serves as a guide for the data that need to be collected. The product system and the system boundary specify which unit processes are included and which are not. Each unit process shall be described in terms of what are the relevant input and output for the study. If data

for a specific unit process is not available or inaccessible, then the product system, system boundary, or goal may need to be modified (Matthews et al., 2015, p. 102)

3. Data collection: the ISO LCA standard requires the data for each unit process in the system boundary to be measured, calculated, or estimated. Here, ISO distinguishes between primary and secondary data collection. Primary data, considered the “gold standard”, is when one collects the data on its own for one’s specific processes, e.g., through direct measurement. Secondary data is data that has been collected by another party, e.g., life cycle databases, literature sources, past work, etc. ISO LCA standard has numerous requirements concerning data collection. They can be found in (ISO 14044, 2021, p. 103)

4. Data validation: the collected data must be checked for its conformance to the required data quality. This may involve establishing mass balances, energy balances, etc. (ISO 14044, 2021, p. 108)

5. Data allocation: this step is relevant for processes that have different output and multi-functional products. The goal of the allocation stage is to assign specific quantities of input and output to the various products of a process. This is achieved through a quantitative process based on mathematical relations between products. This step was kept out of the scope because the system of interest is not considered to be multi-functional. More information on data allocation can be found in (Matthews et al., 2015, p. 109)

6. Relating data to unit process: In this step, the validated data is scaled to one unit process, as shown exemplary in Fig. 2.7. The figure illustrates the scaling of raw LCI data to one unit process and one functional unit for injection molded plastic parts. The rows contain the flows relevant for the process and the columns contain the raw LCI data, LCI flow per pound of part and LCI Flow per functional unit need (0.13 pound). One can notice in the second column that the raw LCA data was divided per 1,000 pounds to scale it to one unit process (Matthews et al., 2015, p. 110)

7. Relating data to functional unit: this step is similar to the previous one. The only difference is that here the data is scaled to one functional unit. In Figure 2.7 the functional unit is referred to as 0.13 pound. Therefore, the data from the previous step was scaled up to 0.13 pounds. All unit processes will eventually have to be scaled to one functional unit (Matthews et al., 2015, p. 110)

8. Data aggregation: When all unit processes have been scaled to functional unit, then data from all the unit processes needs to be summed to one unit process. This represents the result of the LCI analysis (Matthews et al., 2015, p. 111)

9. Refining the system boundary: LCA is an iterative process. The boundary is most likely to be subject to various refinement due to missing data, added process, deleted process, etc. (ISO 14044, 2021)

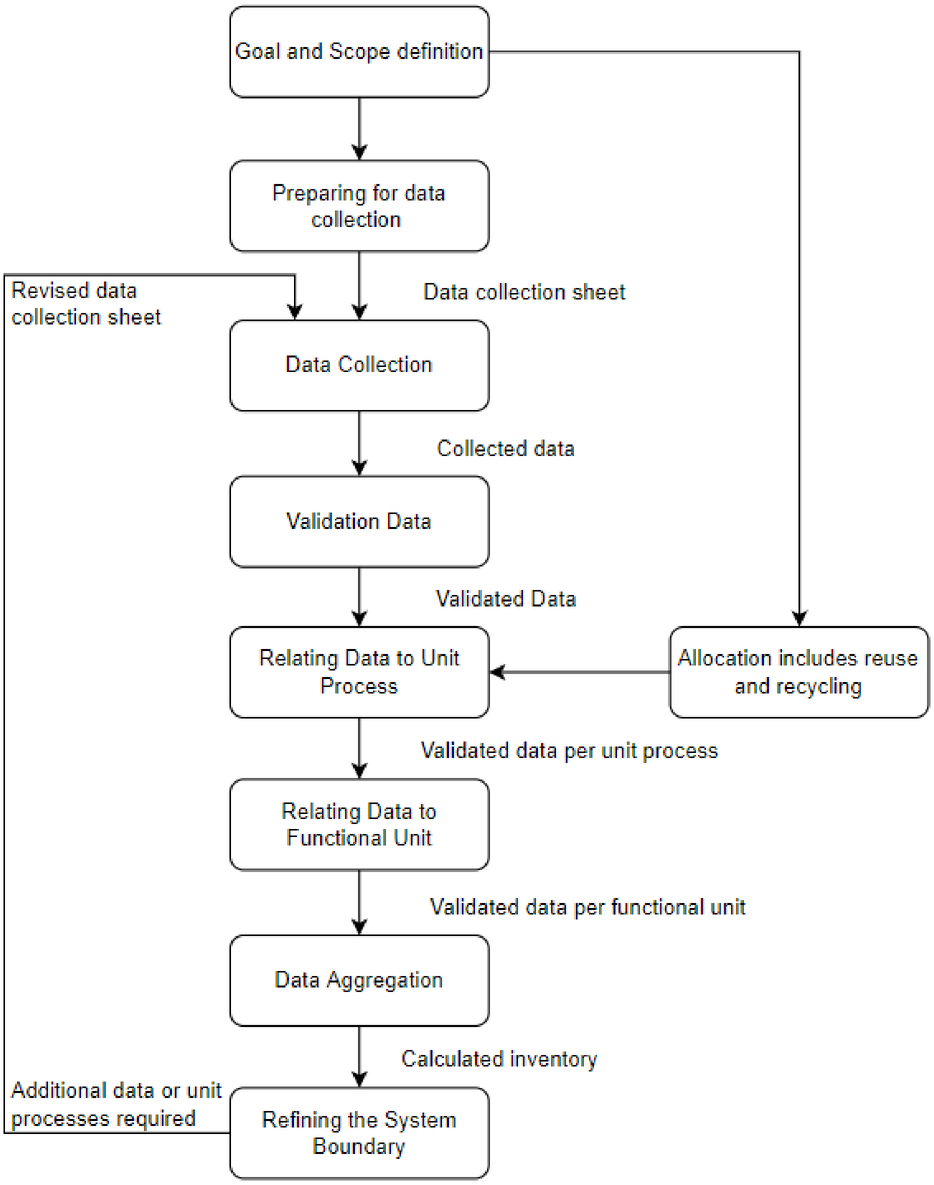


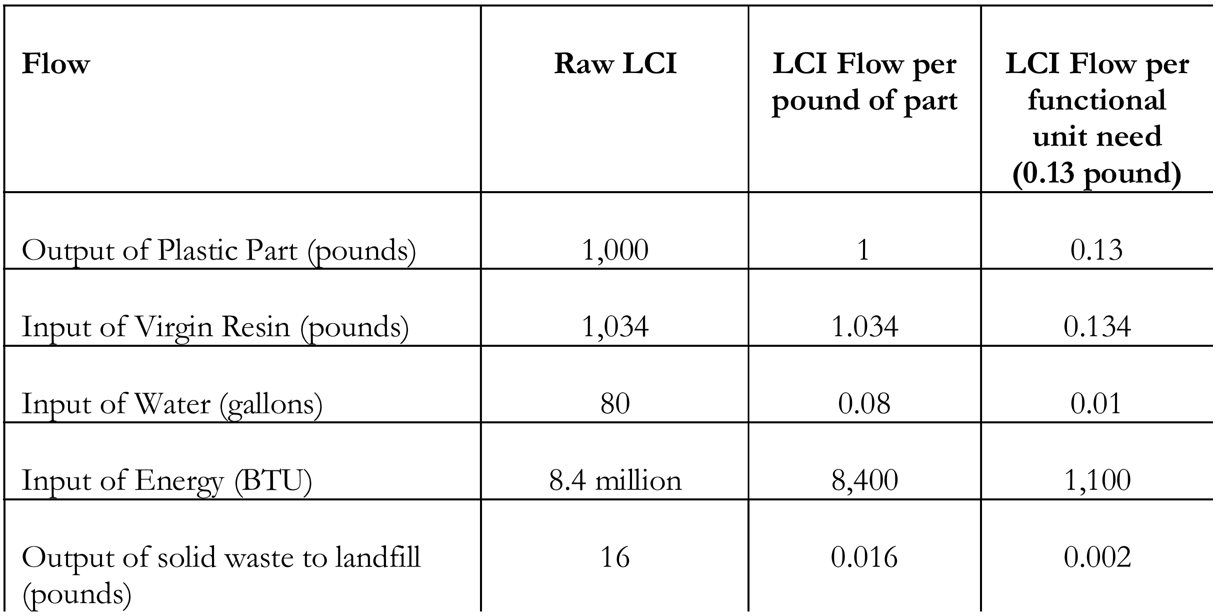
Figure 2.6: Simplified procedures for inventory analysis (ISO 14044, 2021)

2.1.1.3 Life Cycle impacts Assessment (LCIA)

In this part of the standard, the results from life cycle inventory analysis are translated to impacts in order to assess their significance. These impacts may be on ecosystems, humans and resources. More detail regarding this stage can be found in (Matthews et al., 2015, p. 366) and (ISO 14044, 2021). This part of the LCA was left out of the scope for the following reasons:

1. The goal of the study is to demonstrate a methodology that integrates the LCA process with MBSE and not to assess the environmental impacts of the system of interest. Assessing the environmental impacts of the system of interest will require expanding system scope, which will exceed the time provided to conceive a master thesis

2. The scope of the study has been compromised in order to include all life cycle stages that are different in their characteristics in the MBSE methodology. Therefore, impacts



Flow	Raw LCI	LCI Flow per pound of part	LCI Flow per functional unit need (0.13 pound)
Output of Plastic Part (pounds)	1,000	1	0.13
Input of Virgin Resin (pounds)	1,034	1.034	0.134
Input of Water (gallons)	80	0.08	0.01
Input of Energy (BTU)	8.4 million	8,400	1,100
Output of solid waste to landfill (pounds)	16	0.016	0.002

Figure 2.7: Relating raw LCI data to unit process and functional unit (Matthews et al., 2015, p. 110)

assessment, with the actual scope, will not lead to meaningful results

3. Life cycle impacts assessment is basically nothing more than performing mathematical calculation to relate LCI results to environmental impact. This can be achieved easily using the parametric diagram

4. The required data for the defined scope of the study will need additional time and effort that would extend beyond the scope of a master thesis

2.1.1.4 Life Cycle Interpretation

The life cycle interpretation stage is the final stage of an LCA or LCI study. It consists of studying the results of the goal and scope, inventory analysis and impacts assessment, to draw conclusions and recommendations that can be reported. The ISO LCA standard defines three essential steps, when performing life cycle interpretation, as depicted in Fig 2.8:

1. The output from the previous stages: goal and scope definition, inventory analysis and impacts assessment, are fed as an input to the interpretation stage to identify the significant issues of the study

2. An evaluation is performed using: completeness check, sensitivity check, consistency check, etc.

3. Conclusions are drawn as well as limitations and recommendations are presented

The output of the interpretation stage can be used directly in the form of product development and optimization, strategic planning, public policy, marketing, etc.

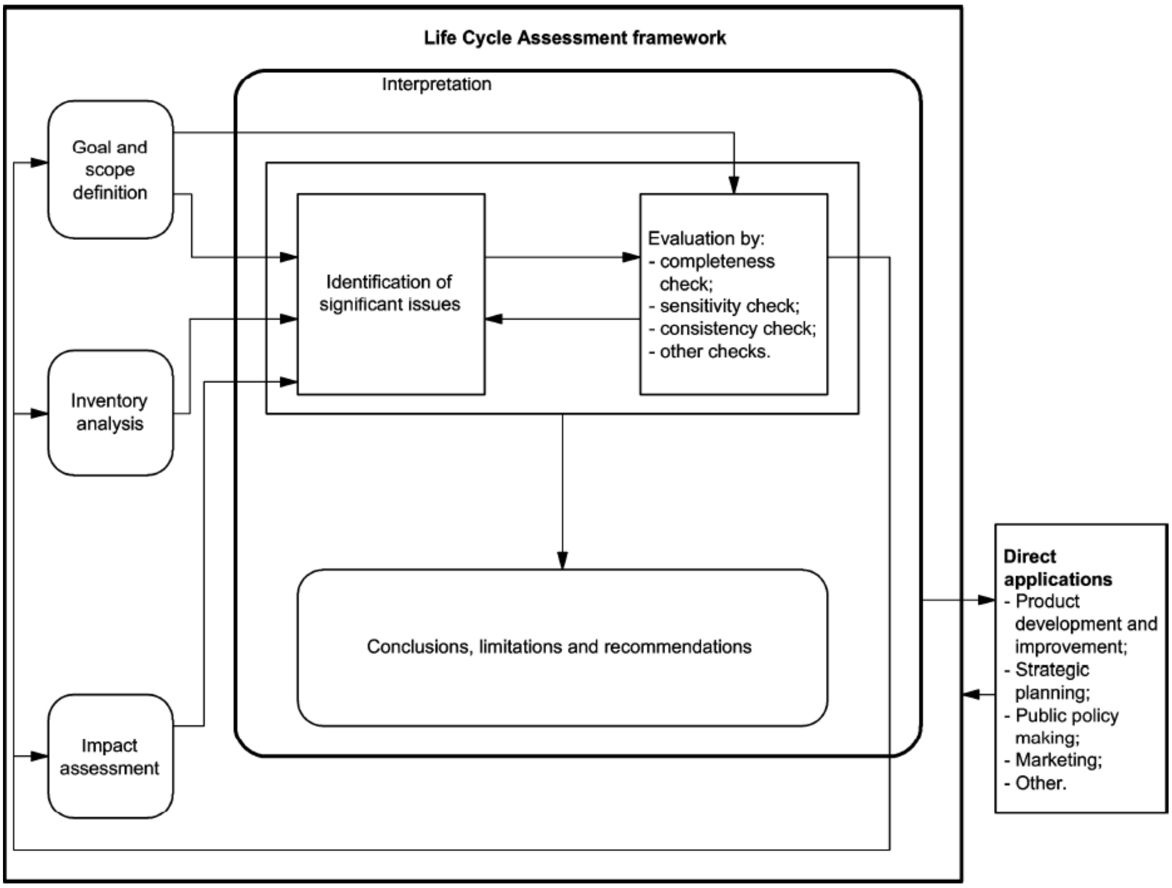


Figure 4 — Relationships between elements within the interpretation phase with the other phases of LCA

Figure 2.8: The life cycle interpretation procedure (ISO 14044, 2021)

2.1.2 Overview of the Life Cycle Stages of a Product

Just as the genesis of a butterfly has a cycle that goes from egg to larva to caterpillar to chrysalis to butterfly; Any product or a system also has a life cycle. The ISO 15288 describes a life cycle as an abstract functional model that depicts the conceptualization of a need for the system, its realization, utilization, evolution and disposal (ISO 15288, 2008). A system progresses through its life cycle as the result of actions, performed and managed by people in organizations. These actions are executed within the product development process. The detail in the life cycle model is expressed in terms of these processes, their outcomes, relationships and sequence. This ISO 15288 standard defines a set of processes, termed the system life cycle processes, that can be used in order to define the life cycle of a system (ISO 15288, 2008, p. 12).

The life cycle of a product depends on its purpose, use and current circumstances. Each stage serves a specific function and is taken into account when developing and implementing the system life cycle. In general, ISO 15288 defines five important stages in the life cycle of a product: conception, development, production, use/maintenance and disposal/recycling (ISO 15288, 2008). Each of these top-level life cycle stages can be broken down into more stages. As an example, the production stage can be further broken into material extraction, material processing, manufacturing and transportation. These stages may differ in their number and annotations from an organization to another, depending on the scope of their product. The stages represent main milestones and progress of the system as it moves through its life cycle. It is important for organizations to recognize and manage the inherent uncertainties and risks connected with costs, schedule and functionality of each life cycle stage (ISO 15288, 2008).

Three major views on the product life cycle have emerged recently in the field of sustainability: cradle-to-gate, cradle-to-grave and cradle-to-cradle, as shown exemplary in Fig. 2.9. The life cycle of a man-made product goes from obtaining all the needed material and equipment to produce it, through manufacturing it, using it and deciding what to do with it when it has once fulfilled the purpose it was produced for. This is shown exemplary in Fig. 2.9 as raw material extraction, materials manufacture, product manufacture, use stage and end-of-life. Cradle signifies the birth of the product. Some LCA studies consider the concept stage as the birth of the product, as it represents the first idea of the product. Gate represents the point where the product leaves the production factory. This is mostly used in studies that focus on the process of production. Grave is the stage after the product is not used anymore, e.g., disposal in landfill. A cradle-to-cradle perspective refers to the complete recycling of the products.

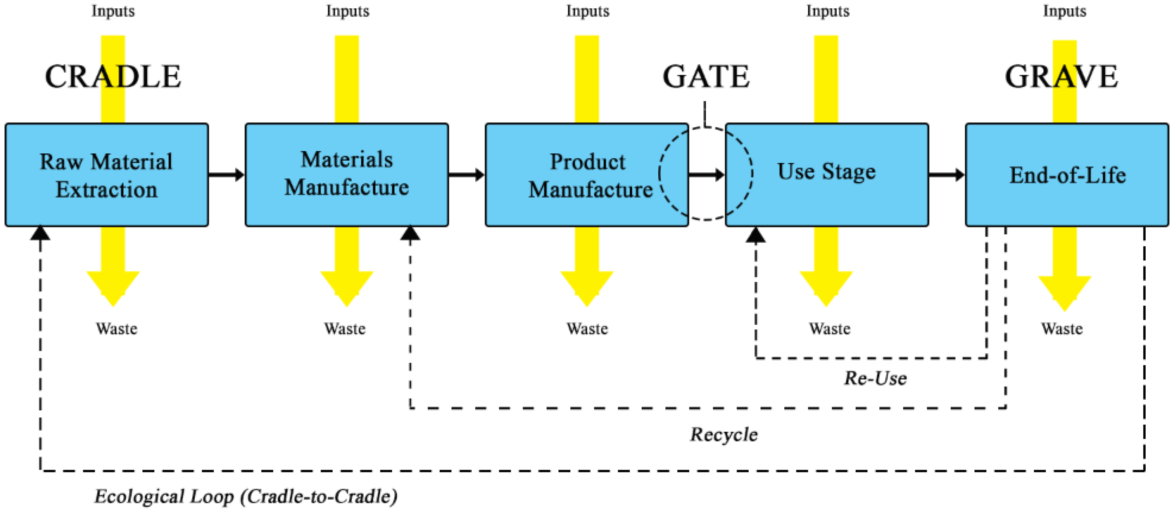


Figure 2.9: Difference between the life cycle views: cradle-to-gate, cradle-to-grave and cradle-to-cradle (Wikimedia, 2022)

The ISO LCA standard advises the consideration of certain life cycle stages, but it does not define a mandatory life cycle model. Figure 2.10 summarizes the advised life cycle stages from ISO 14041. The figure contains a set of input and output of interest, as well as, a set of processes defined within the system boundary that represent the life cycle stages. Color indications are used to group the life cycle stages according to the previously introduced generic life cycle stages, as shown in the legend. One can notice that ISO 14041 lays the focus on three generic life cycle stages: production, use/maintenance and disposal/recycling. These being the most resource consuming stages. It even includes the manufacturing of ancillary materials and capital equipment. Moreover, it advises considering all life cycle stages related to the impacts assessment.

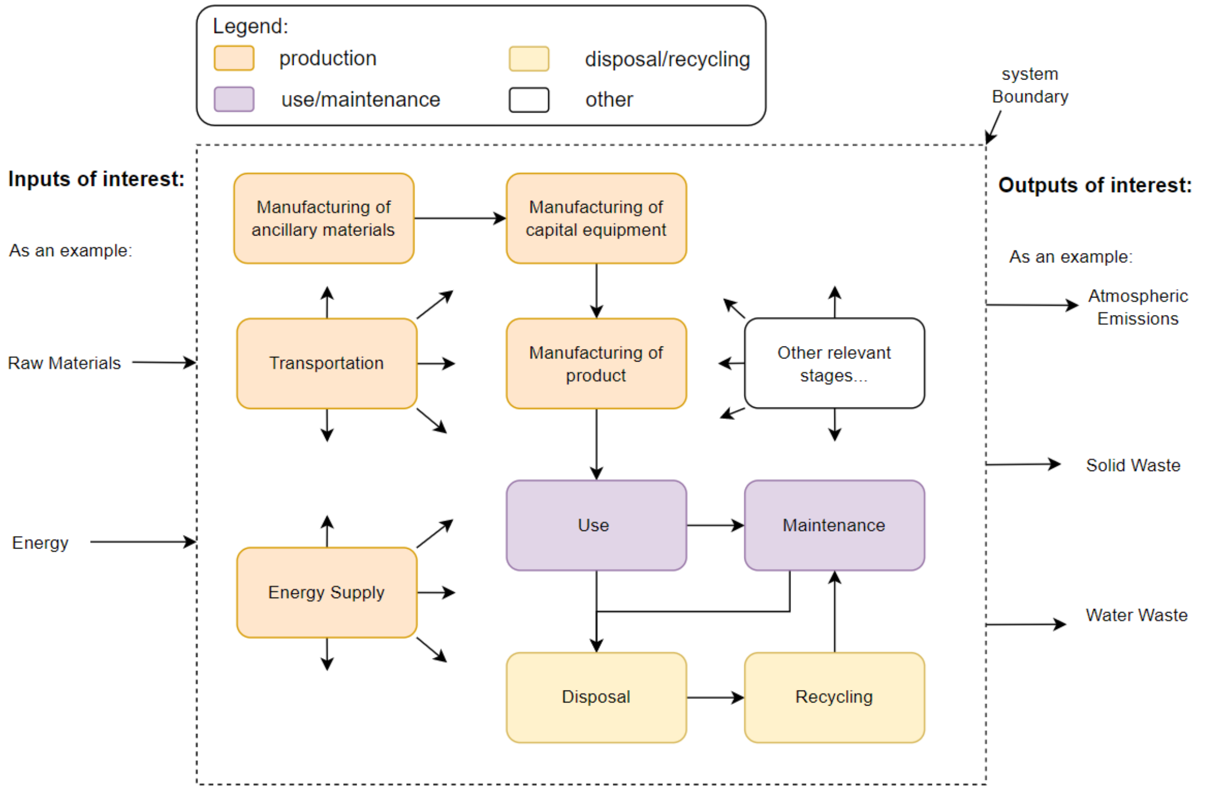


Figure 2.10: The advised life cycle stages from ISO 14041 (ISO 14041, 1998)

Based on the ISO 14041 recommendations, there is no one life cycle model that should be used when performing an LCA, but rather that the system boundary must be aligned with the goal and scope of the study. When one assesses the environmental impacts of a product, then all relevant life cycle stages related to environmental impacts should be included in the analysis. This could mean including the machines that produced the product, the life cycle of those machines and the life cycle of the machines, that in turn, produced those machines, etc. However, at some point a line shall be drawn. Therefore, choosing the system boundary is not a simple task. The issue with the system boundary is especially important when performing a comparative study. In the latter, one can only compare between products that fulfill the same function(s) and have the same system boundary, otherwise a comparison would be futile. The choice of the system boundary and the focus of analysis is often the reason of several controversies in the LCA studies.

A good example of such controversies would be answering the question “what harms the environment the most, paper or plastic?” A complex discourse in thoughts and findings was triggered in response to this simple question that one could ask oneself at a supermarket or a coffee shop (Matthews et al., 2015, p. 20). The fact that paper is a “natural” product rather than a chemical-based one, like plastic, may lead us to believe that we already know the proper solution. This result was yielded by studies that compared the production process between paper and plastic. When it comes to answering these straightforward questions, statistics and analysis should be used instead of anecdotal evidence. This was demonstrated when Hocking compared between paper cups with polystyrene cups. The author focused on energy consumption and estimated that washing a glass cup 15 times consumed as much energy as producing 15 paper cups. The break-even use levels were also calculated for ceramic and plastic cups (Hocking, 1991).

The reaction sparked a wave of critics and additional research. There is no single agreed-upon response to the simple question of “paper vs. plastic” at the time of this research (Matthews et al., 2015, p. 20). Although, the best data and procedures are accessible now, every study still answers the question with “it depends.” For a field striving to gain momentum in the scientific community, this is a depressing result. Plant-processing and the disposal of the product are two examples of elements that play an important role in this case. As far as customers are concerned, the most essential lesson is that they should demand that the material they purchase be created and disposed in an environmentally friendly factory.

2.2 Introducing the Concepts of MBSE

Fagen et al. traces the concept of Systems Engineering (SE) within the Bell Lab, the former research laboratory of the telephone company AT&T, back to 1900 (Fagen et al., 1975). Examples of early application of SE have been observed in the Second World War. The first teaching efforts of SE were made in 1950 at MIT. The increase of system complexity through the integration of hardware, electrics/electronics and software necessitated a new approach to system development. As a response to this growing need, the National Council on Systems Engineering (NCOSE) was established in 1990 in the United States. Thereafter, SE propagated all over the world. As a consequence, the International Council on Systems Engineering (INCOSE), was founded in 1995. It is the world’s leading authority on systems engineering and has more than 70 chapters worldwide (Holt, 2021, p. 3).

In order to understand MBSE, it is important to have a good definition of the meaning of SE. INCOSE defines systems engineering as a multidisciplinary approach for developing systems that work as intended (Walden and Shortell, 2015, p. 11). This short sentence means that SE is a multidisciplinary approach that encompasses all areas of engineering, including mechanical, electrical/electronic, software, service and so on. Moreover, SE is applied throughout the product life cycle, starting from the stakeholder needs to the retirement of the system. Unaffected by which current stage one is working on, all stages of the life cycle must be considered (Holt, 2021, p. 3).

MBSE is the practice of SE using models. Initially, SE has been performed using manual transcription of concepts and documentation. This approach yielded thousands of document pages, which made it difficult to understand the complexity and increased the probability of mistakes to be made. To solve this problem, the model-driven design workgroup decided to adapt the Unified modelling Language (UML) for use in SE applications in 2001, which marked the beginning of the Systems modelling Language (SysML). UML and SysML are both general-purpose modelling languages designed to provide a standard way to visualize system design. The first one is used in the field of software engineering and the latter in systems engineering (OMG, 2015), (OMG, 2017). Today's SE is evolving from document-based to model-based (Holt, 2021, p. 50).

This section provides a background on MBSE. First, the relevant concepts of SysML are introduced. Afterwards, the implementation of MBSE using SysML is elaborated through the MBSE in a Slide from John Holt (Holt, 2021, p. 21). Finally, the modelling approaches used in this work are presented.

2.2.1 Introducing the Systems modelling Language (SysML)

SysML is a general-purpose graphical modelling language that supports the analysis, design, verification and validation of complex systems, including hardware, software, electric/electronic and services. An MBSE approach can be used in conjunction with SysML in order to create a consistent and cohesive model of the system. SysML allows the modelling of the following characteristics of systems, components and other entities (Friedenthal et al., 2014, p. 29):

- Composition, interconnectivity and classification of the structure
- Function-based, message-based and state-based behavior
- Allocations of behavior, structure and constraints
- Requirement traceability between different life cycle stages and model elements

Figure 2.11 illustrates the nine SysML diagrams. SysML diagrams can be grouped into three categories: structural, behavioral and requirement. As SysML is based on UML, Fig. 2.11 highlights the new diagram types of UML with yellow color. The white colored diagram types are similar to UML. The diagram types and their relationship to UML can be described as follows (Friedenthal et al., 2014, p. 21):

1. Package diagram (pkg) shows how the components of a model are organized into packages (same as UML package diagram)
2. Requirement diagram (req) supports requirement traceability through definition of relationships between text-based requirements and other design elements and test cases (not in UML)

3. Activity diagram (ac) depicts, as an example, the actions of a system in relation to what input, output and control are available to them at any given time (modification of UML activity diagram)
4. Sequence diagram (seq) represents the flow of information between two or more systems (same as UML sequence diagram)
5. State machine diagram (stm) shows the behavior of an entity in terms of its transitions between states that are triggered by events (same as UML state machine diagram)
6. Use case diagram (uc) illustrates functionality in terms of the ways, in which an external entity (i.e., an actor) utilizes the system to achieve a set of goals (same as UML use case diagram)
7. Block definition diagram (bdd) depicts the composition and classification of structural elements known as blocks (modification of UML class diagram)
8. Internal block diagram (ibd) shows the connections and interfaces within the various constituent components of a block (modification of UML composite structure diagram)
9. Parametric diagram (par) is used for engineering analysis, where constraints are represented on property values such as F = [m × a] (not in UML)

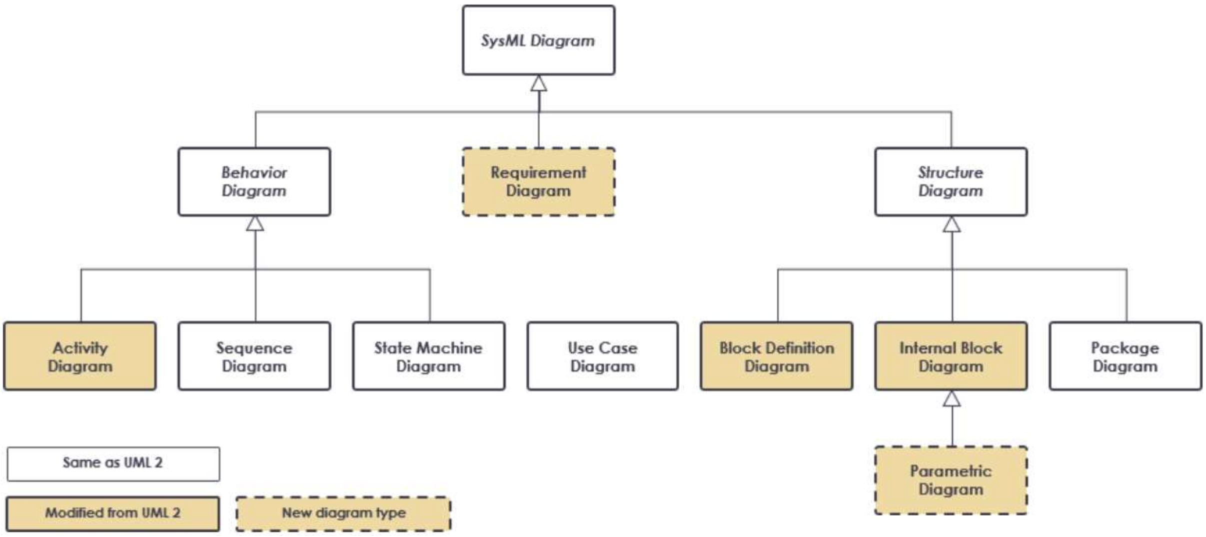


Figure 2.11: Overview of SysML Diagrams (Friedenthal et al., 2014, p. 29)

SysML provides the possibility to customize the modelling language according to our needs using stereotypes. Stereotypes are model elements that are based on one or several metaclasses in a reference metamodel. SysML is by itself an extension of the UML metamodel, which is essentially used for software engineering, to encompass the needs of modelling systems engineering activities. Stereotypes are defined in the profile diagram (Friedenthal et al., 2014, p. 369). Examples of SysML modelling tools that support the use of profile diagram are: Cameo Systems Modeler, Papyrus, etc.

The properties, constraints and requirements of a system are all represented in a SysML system model. It has a semantic foundation that defines the types of model elements and the relationships that can be used in the system model. The model elements of a system are stored in a model repository and can be represented graphically. Sophisticated SysML-tools such as Cameo can simulate these SysML models (Friedenthal et al., 2014, p. 523).

This section provided a brief overview on SysML. More information on SysML can be found in (Friedenthal et al., 2014) and (OMG, 2017). The following section presents the context of MBSE and its implementation using SysML.

2.2.2 Implementing MBSE using SysML

The MBSE approach used in this thesis is based on the work from Holt and Perry. The authors' approach has three main constituents: ontology, framework and views. The framework represents the scope of the model through viewpoints and ontology. Whereas ontology defines the produced artifacts during MBSE activities and their relationships. The viewpoints use a subset of the ontology to specify the information that must be visualized through the views. This approach has been specifically chosen due to its rigor in ensuring consistency. The rigor of the methodology makes one think about what to model and why to model it before modelling it. This is especially important, when working on a broad scope, such as modelling the product life cycle. Otherwise, it is easy to get lost in the countless number of possible diagrams that can be generated. Moreover, this approach is based on standards and best practices from the industry, e.g., ISO 152888 (Holt and Perry, 2008, p. 45).

The "MBSE in a Slide" from Holt pictured in Fig. 2.12 summarizes the concepts of MBSE using an ontology based on SysML (Haskins et al., 2006, p. 45). An ontology diagram is intuitive in its nature and it can be read as follows:

1. The ontology diagram is composed of blocks and connectors
2. A connector connects the blocks with each other. It contains words to express the semantic between the connected blocks and an arrow to show the direction of reading
3. Reading an ontology diagram can be started at any block. The meaning of the diagram stays the same, if the diagram conforms to SysML specification
4. When following the direction of the connector, the semantic between the blocks can be read in the active form, otherwise, it must be read in the passive form
5. The numbers next to the blocks represent the multiplicity of the block. Otherwise, the multiplicity is by default one.
6. The black colored diamond represents a composition relationship. It shows that an element is part of another and it owns it.
7. The white colored diamond represents an aggregation relationship. It shows that an element is part of another, but it doesn't own it.

8. the rest of the rules can be found in the SysML specification (Haskins et al., 2006, p. 45)

Applying the previous rules, the following is a breakdown of how Fig. 2.12 should be interpreted. The MBSE concepts can be divided into five subcategories: compliance, approach, system, visualization and implementation. The approach section encompasses: the process set, the framework, the viewpoint and the ontology. The process set explains how to make use of the framework while also adhering to industry best practices and compliance with the standard (ISO 15288, 2008). Consequently, the framework also complies with the standard. It consists of a single ontology and a number of different viewpoints. Each viewpoint is based on a subset of the ontology and serve as a template for the views. The different views are consistent with one another, resulting in a model that abstracts many systems from a single one. Diagrams are used to represent the various views and they are all consistent with one another. These diagrams are part of the notation, in this case SysML, which is implemented by the tool (Holt, 2021, p. 45).

This section presented the concepts of the MBSE approach used in this study. The following subsections elaborate on the concepts: ontology, framework and views that form the basic pillars of the MBSE approach.

2.2.2.1 The MBSE Ontology

An ontology defines the artifacts produced within the MBSE activities and the relationships between them. As the ontology forms the basis of an MBSE model, Holt identifies it as the single most important construct within MBSE (Holt, 2021, p. 84) for the following reasons (Holt, 2021, p. 84):

1. The ontology visualizes the relationships and the definitions of the key concepts of the domain-specific language. This is essential for an effective systems engineering
2. The ontology forms the basis for the structure and content of viewpoints. The viewpoints use artifacts from the ontology to specify the information that should be visualized. Whereas, the views use the viewpoints as a template to ensure consistency and rigor between the views. The collection of all the views forms the model of the system of interest
3. Ontology and SysML are necessary to ensure model consistency in both the spoken and domain-specific languages. The relationship between all the ontological elements provides all the needed consistency rules to validate that the model is built right. This consistency must be reflected in all the views that form the model. Otherwise, the model would be a random collection of diagrams

For these reasons, the ontology plays an essential part of MBSE and one that it is crucial to get right. Section 9.1 presents the ontology used in this work.

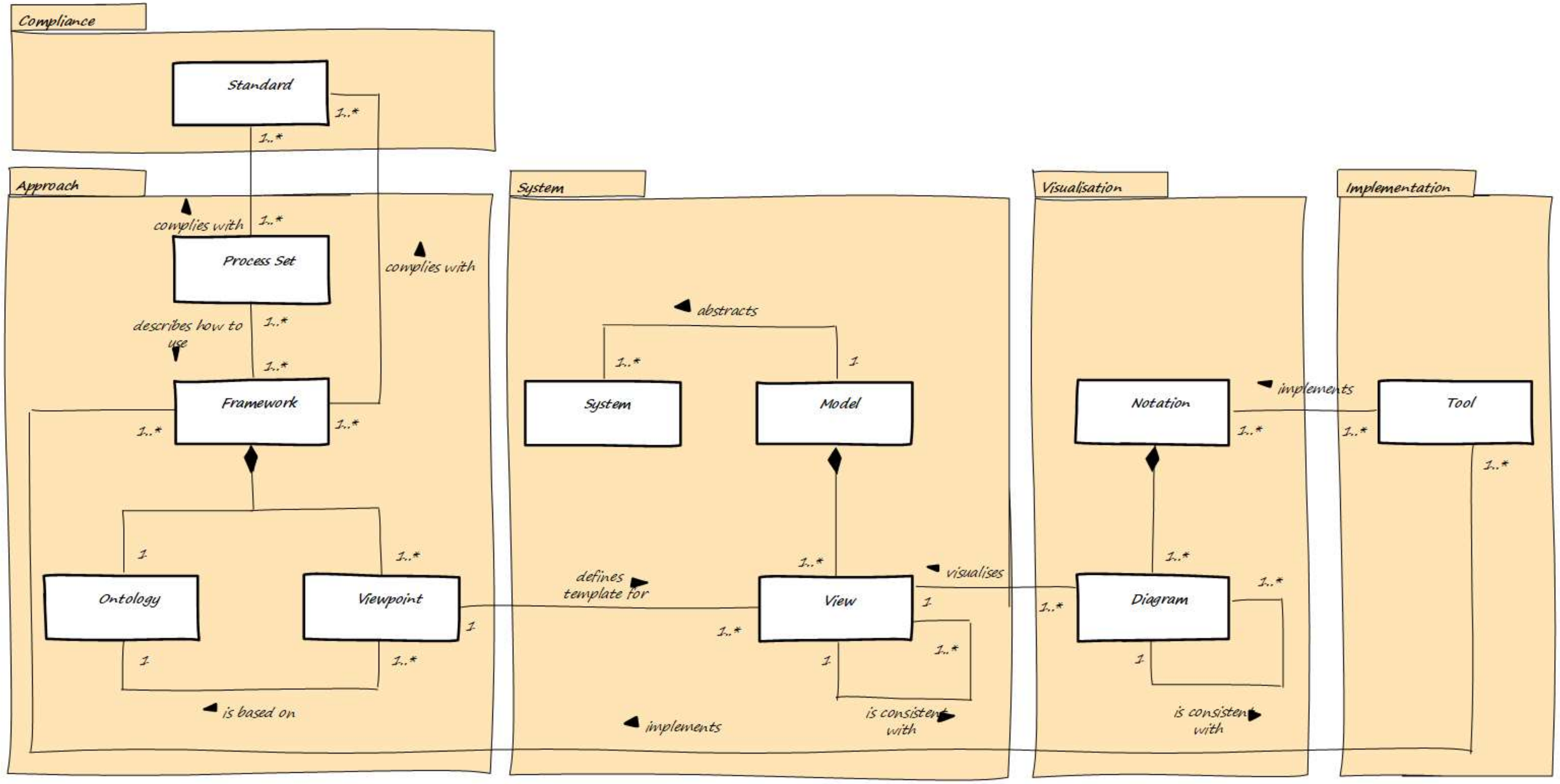


Figure 2.12: MBSE in a Slide (Holt and Perry, 2008, p. 45)

2.2.2.2 The Framework

The MBSE framework describes the scope of it's approach using the ontology and viewpoints. Whereas the ontology defines the produced artifacts during MBSE activities as well as their relationships and the viewpoints use a subset of this ontology to specify which information must be visualized. Defining the MBSE framework is, according to Holt and Perry, critical for the following practical considerations (Holt and Perry, 2008, p. 20):

1. The coverage of the MBSE ontology is ensured through the sum of the viewpoints, whereas each viewpoint covers a subset of the ontology
2. The rigor of the model is achieved through the realization of all the views, that are generated from the template of the viewpoint. Depending on the criticality of the project, it can be decided whether to produce all the views for the highest level of rigor or some of the views for less
3. The approach defines how the views are created based on the viewpoints
4. The MBSE framework is flexible in its application. It defines a certain number of viewpoints. However, depending on the project, one can choose to add or delete some of these to adapt the scale of the framework
5. The views are flexible in their realizations. Depending on the used tool, one can choose between different ways of visualizing these. As an example, Cameo Systems Modeler provides SysML diagrams, dependency tables (in form of a matrix to specify the relationship between the model artifacts), relation maps (to illustrate the traceability across the model) among other things
6. The MBSE framework is based on different standards, e.g., ISO 15288. It can also be integrated with other processes and methodologies
7. An automated MBSE approach built on top of sophisticated systems engineering tools can be made possible by the MBSE Framework. Many of the process artifacts can be generated automatically when using such an approach, which saves costs, time and effort

2.2.2.3 The Views

The third main concept is the View. It is worth emphasizing on the difference between a viewpoint and a view. Fig. 2.12 illustrates the relationship between the View and the other MBSE concepts. The MBSE framework is made up of one or more viewpoints and each one defines a template for the views. Therefore, each view must conform to its associated viewpoint. The viewpoint corresponds directly to a subset of the ontology, which yields the model consistency. A view represents an actual artifact, usually visualized by a diagram, which is produced as part of a project. In summary, each viewpoint is defined as part of the MBSE framework and provides the template for one or more views, which are created as part of the MBSE activities on a project. A Viewpoint is a definition and a View is the realization of its defining Viewpoint.

This chapter has introduced the three main concepts of ontology, framework and views that dictate the MBSE approach. The concepts were first brought back together in the form of the MBSE meta-model, then each concept has been expanded and discussed. The following section presents the MBSE modelling methods used in this work.

2.2.3 The RFLP (Requirements engineering, Functional design, Logical design and Physical design) Design Methodology

This section introduces the MBSE modelling methods used as the basis of this work. First, the RFLP is presented as a top-level method. The acronym RFLP stands for the four level of the methodology: Requirements engineering, Functional design, Logical design and Physical design (Kleiner and Kramer, 2013). Afterwards, the modelling method of each level is introduced. Finally, the RFLP method in Discrete Event Logistic Systems (DELS) is presented. DELS is a meta-model that represents production and logistic systems (Sprock et al., 2020, p. 1).

RFLP is a top-down integrated product development methodology to support the design of mechatronic and cyber physical systems. It describes the procedure of systematic product development from system analysis, through system development, up to system integration. Moreover, it spans the left-side of the V-model based on VDI Guideline 2206 "Development methodology for mechatronic systems" (VDI/VDE 2206, 2004), as shown in Fig. 2.13.

Figure 2.13 illustrates the product development procedure of mechatronic systems. The V-Model is horizontally divided into three main stages: system analysis, system development and system integration. In system analysis, first, the requirements of the product being developed are defined. Then, the functional analysis is performed. Afterwards, the logical architecture is design. Lastly, the physical components are specified. The system development stage creates product development data (including e.g., 3D Computer Aided Design (CAD) models, behavior models). In the system integration stage, the developed components are simulated, tested, integrated in the system and subjected to continuous verification and validation (Kleiner and Kramer, 2013).

Requirements Engineering

Requirement definition is the starting point of every product development. It reflects more or less the abstract idea behind the product in the form of stakeholder needs. The stakeholder needs are then translated into technical requirements. These represent the top-level requirements that shall be fulfilled to validate the product at the end of the development process (Eigner et al., 2012). Quality function deployment is one of the methods that can support the translation of non-technical stakeholder needs into technical requirements (Bergquist and Abeysekera, 1996).

Once the top-level requirements are defined, a context analysis is performed to identify the system boundaries, external interfaces of the system and interacting systems or actors. Afterwards, use cases are defined in the context of "how the stakeholders will use the system?" and refined using activities. The developed use cases and activities will serve as an input for the development of the functional architecture (Lamm and Weilkiens, 2014). This step is marked in Fig. 2.13

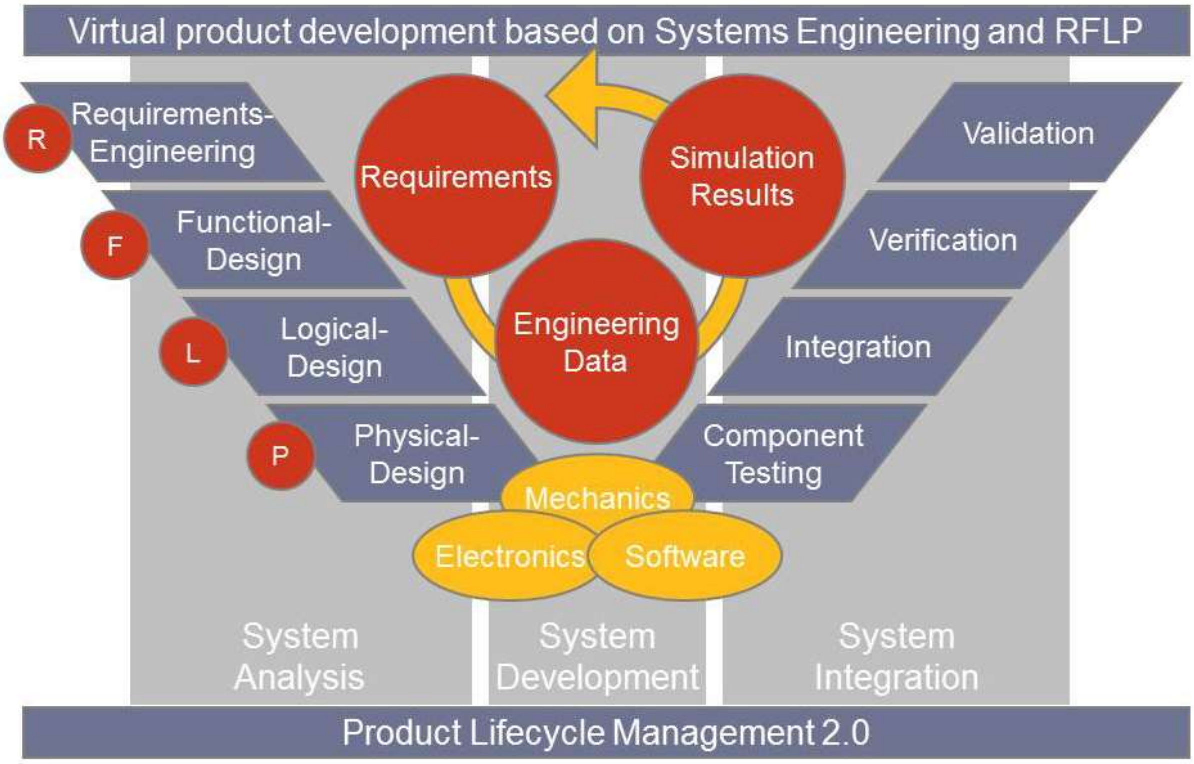


Figure 2.13: Virtual product development based on Systems Engineering and RFLP (Kleiner and Kramer, 2013)

with R. Depending on the project and tasks assignments, the tasks for requirement engineering do not end at this point, but they could span to the verification and validation of the end product.

Functional Design

Functional design allows the development of an interdisciplinary functional solution for a technical system. It is marked in Fig. 2.13 with the letter F. This is critical in the system analysis stage because it brings together all disciplines, due to the fact that functions are solution- and discipline independent. The functional solution focuses solely on the functions that are needed to fulfill stakeholder needs. The resulting functional architecture becomes one of the most stable types of structure in the design process because of its independence from specific solutions. This gives a room for creativity to explore the design space of alternative technical solutions (Eigner et al., 2012).

The functional design can be supported through the Functional Architecture for Systems (FAS) method (Lamm and Weilkiens, 2014). Lamm and Weilkiens developed the FAS method in an attempt to close the gap between the requirements and the physical architecture. The method does not fully close the gap, rather it minimizes it to the logical level. The scope of the method is based on high abstraction level of architectural tasks that use functional decomposition with moderate granularity. This approach incorporates SE techniques such as context identification and use case analysis. Once, the context and use case analysis is performed, the method establishes a transition from requirements like “The system shall provide xyz” to functional architecture by describing use cases and the flow of their activities. A plug-in for the automatic generation of the functional architecture can be found in (GfSE, 2012b). Further information on the FAS method and model examples for the implementation of the plug-in can be found in (GfSE, 2012a).

Logical Design

Logical design is the specification of logical components that realize the functional elements of the functional architecture. Supported by semi-formal language like SysML and a simulation tool as Cameo System Modeler, one can model and simulate the logical structure and behavior of the system. Consequently, virtual tests are performed as the first stage of system integration in a virtual world. They allow the verification of the system under development against requirements and test scenarios (Eigner et al., 2012). The logical design is marked with L in Fig. 2.13.

Physical Design

Based on the logical architecture, each discipline can begin with its discipline-specific detail design. This results in physical elements of the system, such as hardware components or software code (Eigner et al., 2012). This stage is marked with P in Fig. 2.13.

2.2.4 RFLP in Discrete-Event Logistic Systems (DELS)

In this work, DELS references the ontology developed by Sprock et al. to model supply chain and production systems (Sprock et al., 2020). The ontology is based on the product, process and resource (PPR) models, widely used in the manufacturing sector, as shown in Fig. 2.14. The PPR model has been extended with Facility and Task to become (PPRFT). The facility represents the system structure and organization and the task captures the unit of work and organization. The PPRFT model describes a facility that contains a network of resources, where resources can be active or passive. Active resources transform the state of passive resources through a process, e.g., a raw material processing machine. Whereas passive resources are transformed through a process using an active resource, e.g., raw material. Products are the result of each process. A process might require capabilities of more than one resource. Processes can change location, age, or condition of products. Finally, a process is authorized by a task. The model library and applied use cases regarding DELS can be found in (Sprock, 2017). The library contains several projects that have been performed in cooperation with INCOSE, OMG and the National Institute of Standards and Technologies (NIST).

Professor Leon McGinnis from Georgia Tech university mentioned in two presentations an integrated DELS-based MBSE and RFLP design methodology (Mcginnis, 2018), (Mcginnis et al., 2019), as shown in Fig. 2.15. Similar to the RFLP methodology, Fig. 2.15 is separated into: requirements, functional, logical and physical levels:

- R-Level answers the question “What must be produced?” It contains the Engineering Bill of Materials (EBOM) and the production ramp. EBOM is a type of Bill of Materials

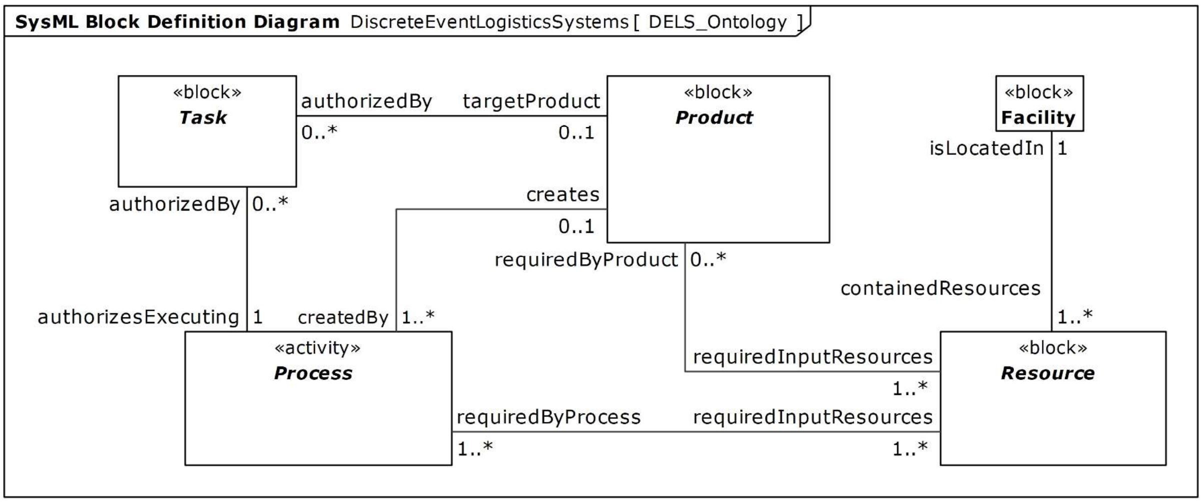


Figure 2.14: The extended product, process, resource, facility and Task (Sprock et al., 2020, p. 18)

(BOM) that represents the product as designed by engineers. A BOM provides information about the raw materials and quantities of sub-assemblies, subcomponents and parts to manufacture an end product. The production ramp describes an increase in production ahead of anticipated increases in product demand

- F-Level answers the question “How is it produced?” It is composed of Manufacturing BOM (MBOM), process model, task model and process control model. From the EBOM, the manufacturing parts are extracted and fed as an input to the MBOM. MBOM reflects the list of items needed to produce the end-product. Every part of the MBOM needs a process to produce it, which creates the process model. Every process in turn requires an authorization, which yields the task model. Finally, every task involves an authorization by a controler, which generates the process control model

- L-Level answers the question “How is production organized and controlled?” It encompasses the resource model and the control architecture. Every process from the F-Level requires a capable resource type to execute it, which yields the resource model. Control zones from the resource model and control process organization from the process control model are used as an input to the control architecture

- P-Level answers the question “What are the resources and interfaces?” It contains the facility model and the controller model. The Facility model is generated as an instance of specific resource numbers and arrangement from the resource model. The plant model from the resource model and the implementation plan from the control architecture serve as an input to the controller model

This chapter provided the background needed to understand this work. The following chapter provides a literature review and evaluation of the state-of-the-art methodologies in modelling the environmental impacts using MBSE. Afterwards, the research gap is identified. Based on the research latter, requirements on the modelling methodology are derived and the expected benefit from this study is presented.

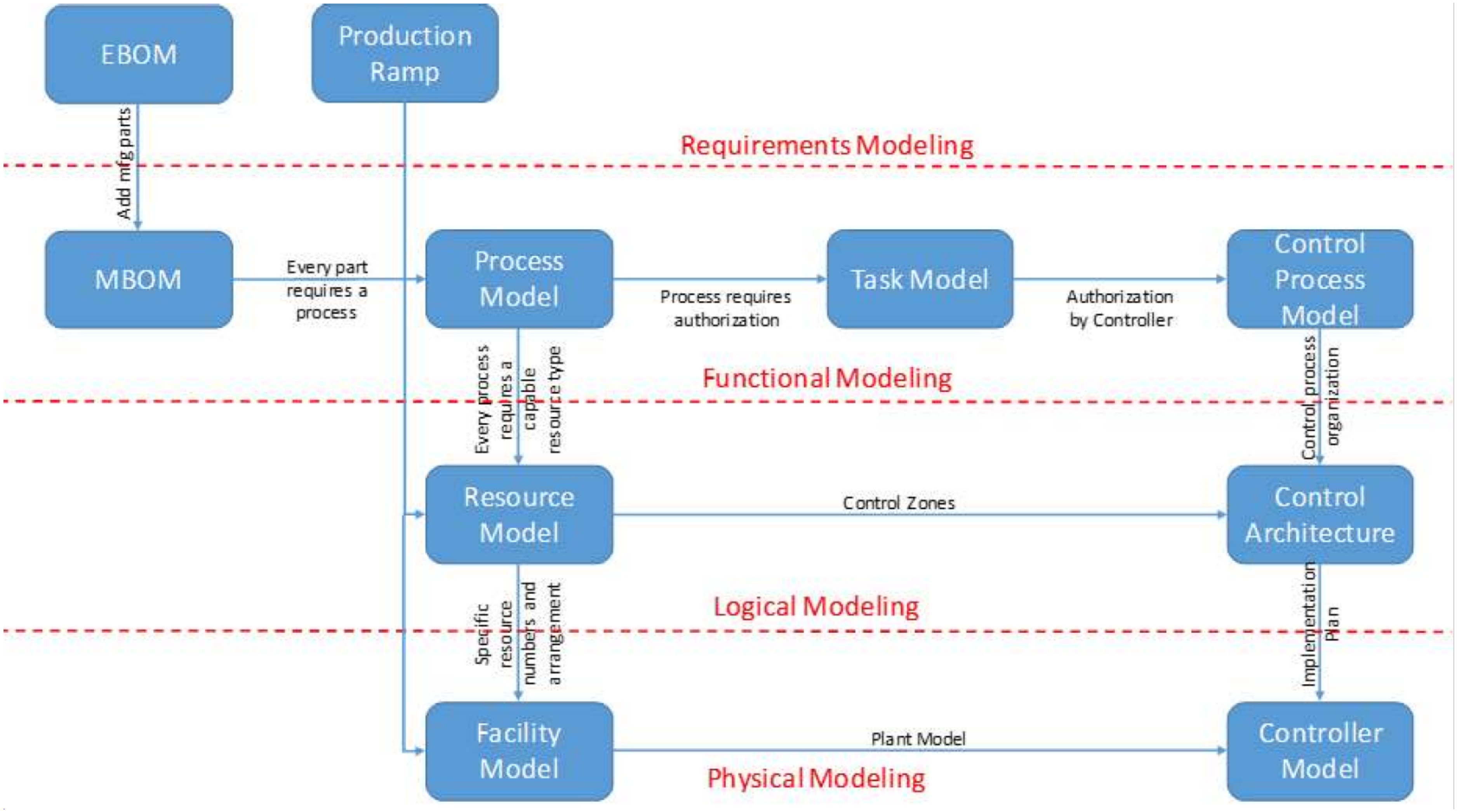


Figure 2.15: The integrated DELS ontology and RFLP methodology (Mcginnis et al., 2019)

Chapter 3

Evaluation and Summary of the Literature Review

This chapter starts with analyzing the state-of-the-art methodologies for assessing the environmental impacts using MBSE. After that, modelling approaches for each life cycle stage are presented. The results of the literature are then summarized and the gap in the literature is highlighted. From the gap in the literature, requirements on the methodology of this work are formulated and the benefits in studying this gap are elaborated.

3.1 Analysis of the State-of-the-Art Methodologies in modelling the Environmental impacts Using MBSE

This section analyzes the state-of-the-art methodologies in modelling the environmental impacts using MBSE. First, articles covering the integration of environmental impacts with MBSE methodology are presented. Afterwards, modelling techniques of environmental impacts using SysML during extraction, manufacturing, use and disposal stages are introduced. Those life cycle stages were the only ones covered by the literature review.

Integrating Environmental impacts with MBSE Methodology

Fet et al. highlighted the commonality between the SE and LCA methods (Fet et al., 2013), as shown in Tab. 3.1. The first step from the LCA-method is similar to the first two steps in the SE-methodology: identify needs and define requirements. The second stage of LCA is comparable to performance specification from SE. The last two steps of LCA are equivalent to analyze and optimize from SE. The last two steps in the SE-method is identical to the application of the LCA-results into a design process.

Zanetti et al. argued that LCA should be included within the development stage of a system to ensure that emissions during manufacturing, operations and end-of-life are minimized at their source (Zanetti et al., 2016). The authors introduced the W-Model as a way to proactively think about sustainability and achieve an optimal balance between economic and environmental

Table 3.1: Commonality between SE and LCA methodology steps (Fet et al., 2013)

SE	LCA
1. Identify needs	1. Goal and scope definition
2. Define requirements	2. Inventory Analysis
3. Specify performance	
4. Analyze and optimize	3. impacts assessment
	4. Interpretation
5. Design and solve	5. Application of LCA-results
6. Verify and test	

requirements. The W-Model is similar to V-Model, however, in its divergence, it allows for parallel processing of development activities, as shown in Fig. 3.1. The method encompasses the following five stages (Zanetti et al., 2016):

1. Operational requirements, operations, maintenance and end-of-life strategies: The primary goal of this stage is to define the system or the high-level requirements of the product. As part of the subsequent processes, acceptance testing and end-of-life strategies are formulated. The main focus of this stage is the establishment of the pre-defined conditions, as defined by the customer, that require testing and verification

2. System-level requirements, certification testing and life cycle analysis: This stage refines the aforementioned requirements, focusing on what is required by the system to validate these requirements. As early as possible in the development process, alternatives can be discovered through the use of requirement analysis. Certification testing and system-level LCA allow for further clarification and refinement of the customer requirements. These tests document discrepancies between predicted and actual outcomes

3. Preliminary design, sub-system integration/testing and life cycle analysis: Systems and operational requirements established in the first two stages are further refined. The primary goal of this stage is to create a conceptual design model based on the aforementioned specifications. Moreover, testing activities are planned to verify that the system works as expected. Between stages two and three, reiteration may be necessary to ensure clarity, focus and refinement. System testing and life cycle analysis are carried out on a subsystem level to verify the methods of system integration

4. Detailed design, component testing and life cycle analysis: The requirements and alternatives should be thoroughly analyzed by the end of stage four. The primary responsibilities of this stage include the detailed design of the system, product and production and testing processes. As part of inventory analysis, testing and life cycle analysis are performed on a component level. Distribution strategies and architectures for components, sub systems and systems are also part of component testing

5. Implementation: Requirements and specifications are translated into a physical process by a project team. This stage requires the use of closed-loop production processes

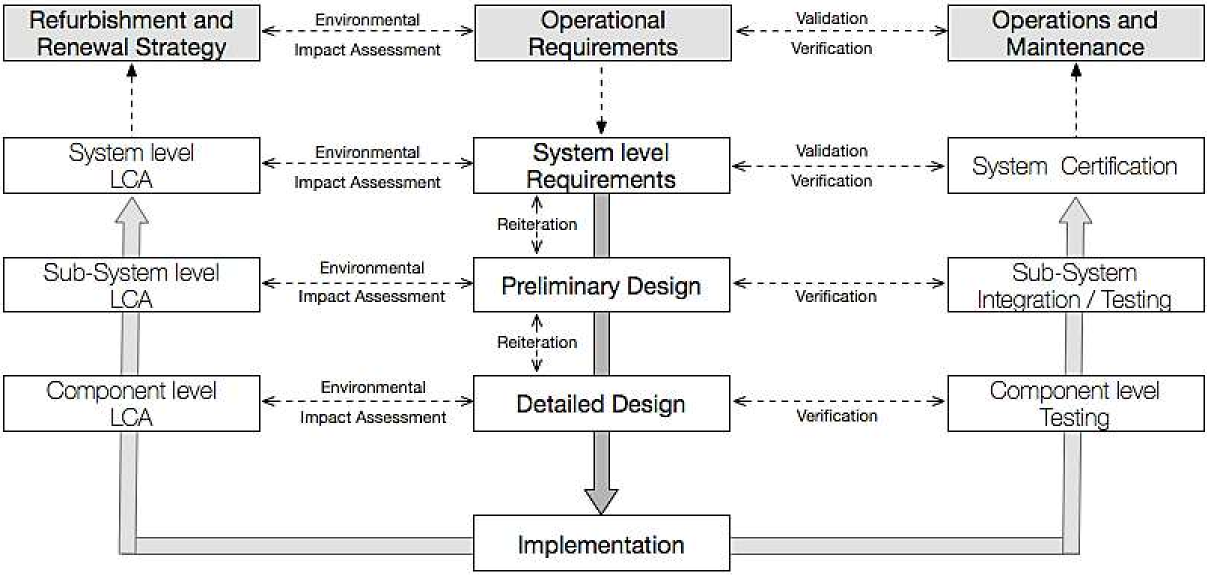


Figure 3.1: W-Methodology according to (Zanetti et al., 2016)

Steimer et al., also, modified the V-Model in order to develop a model-based design process for early stages of manufacturing system planning, as shown in Fig. 3.2. The V-Model is divided into two parts: the cross-disciplinary early system design and the discipline-specific design. The approach allows for iterations within and between the two parts (Steimer et al., 2017).

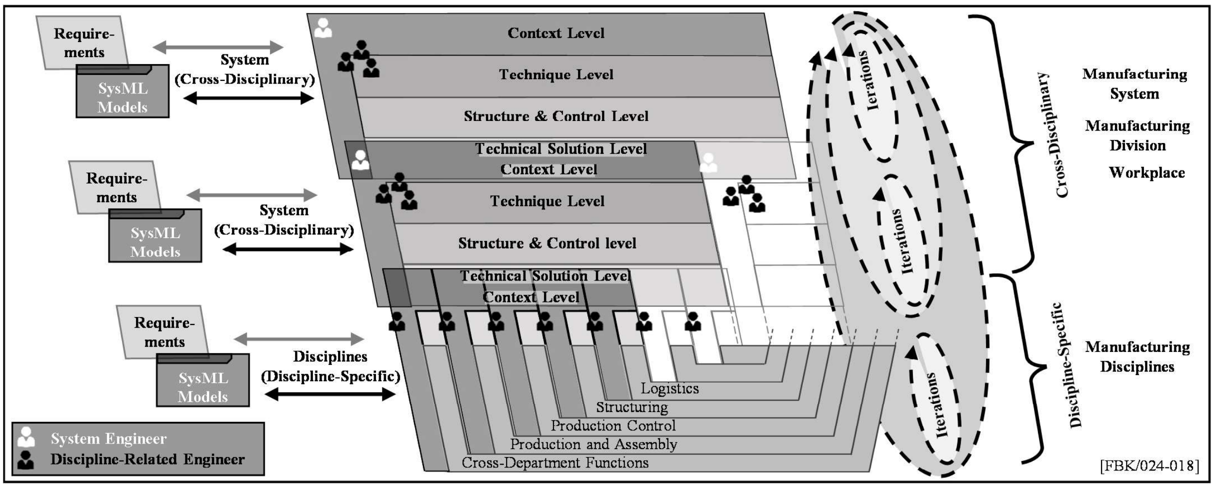


Figure 3.2: Iterative V-Model of an MBSE approach for manufacturing system planning (Steimer et al., 2017)

Bougain and Gerhard integrated the environmental impacts of a mechatronic product in an MBSE method using SysML. The method has three different goals (Bougain and Gerhard, 2017):

1. An adequate eco-design strategy is proposed for design engineers to assist in making the right (verified) decisions during product development projects as soon as possible
2. Integrating the environmental impacts Green House Gas Potential (GHGP) and Cumulative Energy Demand (CED) from four lifecycle stages: Extraction stage, Manufacturing stage, Use stage and End-of-Life stage

3. Enable reporting about the product and its sustainability at an early stage

In their method, Bougain and Gerhard illustrated the requirements derived from Ecodesign-Pilot (EP) method of each stage in a separate requirements diagram (Wimmer et al., 2002). Each strategy from a particular stage of the life cycle has a name and a weight (from 0 to 2), as shown in Fig. 3.3. The figure illustrates an eco-design strategy and two of its measures in the form of requirements. The importance of the strategy is measured by a scale ranging from 0 (indifferent) to 2 (important). This means that importance 0 will have no effect; importance 1 will have an average effect; importance 2 is strongly recommended. The most intensive stage is assigned importance value 2, while the second most intensive stage is assigned importance value 1. Only EP strategies have an importance value, whereas eco-design measures have the following eight properties: Designation, Priority (P)= R*F (from 0 to 40), Relevance (R), Fulfillment (F), Idea for realization, Costs, Feasibility and Action. With such a representation, the best eco-design path is shown to the design engineer. In another work, the authors used a Case-Base Reasoning (CBR) approach for continuous optimization of the system of interest (Bougain et al., 2017)

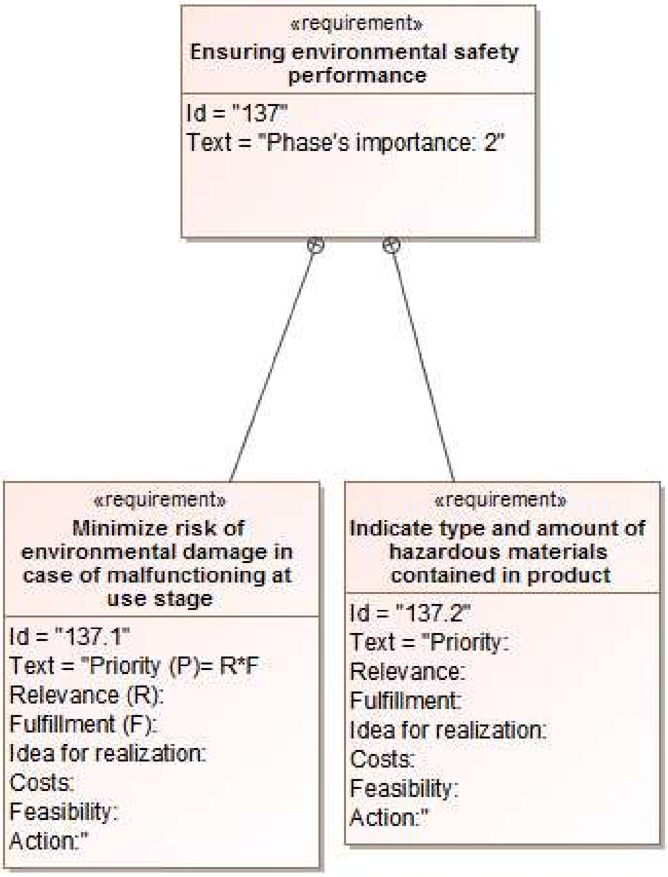


Figure 3.3: An eco-design strategy and two of its measures according to (Bougain and Gerhard, 2017)

Eigner et al. introduced System Lifecycle Management (SysLM) as a key concept for the definition of engineering design processes (Eigner et al., 2014a). SysLM is an integrated, information-driven concept for improving the performance of a product system throughout its entire life cycle. It does so by utilizing a central-shared information system that aids engineers in effectively managing the complexity of the product system from the initial definition of requirements to the final stages of disposal. Eigner et al. argue that MBSE plays an essential role in the SysLM concept. In their work, they presented a new approach to a comprehensive system description based on an extended V-Model (VDI/VDE 2206, 2021). This new version of the V-Model is similar to the one previously introduced in section 2.2.3. It extends the previous V-Model by incorporating cyper-physical systems, services and spans along the life cycle of the product. The developed methodology allows for functional system description in a multidisciplinary system development that takes environmental sustainability into account. This is achieved through the following 5 steps (Eigner et al., 2014a):

1. The authors relied on the the RFLP approach (described in section 2.2.3) to trace the most environmentally harmful components of the system
2. Once the component is identified, a model of the behavior of the component is specified using use case and activity diagrams
3. Afterwards, a context of analysis is set up to incorporate the affected functions and their relationships through constraints and properties
4. Then, the results of the analysis are verified and tested against the requirements
5. Finally, the results are visualized and concrete recommendations are presented to support decision-making

The modelling of environmental impacts using SysML was addressed in three works from the Georgia Institute of Technology, supervised by Prof. Bras and Prof. Paredis (Yen, 2011), (Azevedo et al., 2009), (Culler, 2010). Yen and Azevedo et al. used MBSE with SysML to study complex urban transportation systems and adopted almost the similar approach (Yen, 2011), (Azevedo et al., 2009). The approach consists of the following six steps:

1. Definition of the desired system boundaries and environment
2. Definition of the hierarchical model structure that encompasses all necessary scales
3. Identification of relevant system constraints and associated object variables
4. Automatic generation of parametric diagrams based on model structure and constraints using analysis tools
5. Mapping of SysML object variables to corresponding variables in the analysis tool
6. Execution of system parametrics to calculate results at each level of the system hierarchy
7. Definition of other system viewpoints and analyzes as needed

Table 3.2: Summary of modelling layers and their levels according to (Culler, 2010)

Stakeholder Modelling	Material Flow Modelling	Energy Flow Modelling		
Network	Manufactured Product	Network Energy		
Facility	Mass Flow	Facility Energy		
Process	Mass	Total Process Energy		
		Total Machine Energy		Total Material Energy
		Electrical Power	Combustive Power	Specific Energy for Processing Individual Materials

Culler used SysML to capture the network structure of the stakeholders involved in the life cycle of electronics waste as it is transformed to mass and energy transfer. In his work, he defined the model in terms of three modelling layers: stakeholder modelling, material flow modelling and energy flow modelling. Each of these layers contains three levels, as summarized in Tab. 3.2 (Culler, 2010).

1. Stakeholder modelling: First the boundary of the system is specified. Culler considered three levels: the process level, the facility level and the network level.
    (a) Beginning at the bottom, the process level corresponds to the lowest level of mass and energy transfer. An example of a process is a hammer mill, where mass in some form enters the hammer mill and mass of a different form exits the mill. If the power requirements of the machine are known along with the operating time, then the energy consumed by the machine can be calculated
    (b) Facility level represents the factory. Assuming the operating hours of the facility equals the operating hours of the machines. Then, the sum of the operating hours of the machines equals the operating hours of the Facility
    (c) Network level describes a number of facilities that are grouped together. The network level serves to capture the interactions between facilities. An example of a network might include the manufacturer of a computer monitor, the user of the computer monitor and the disposer of the computer monitor. The difference between the facility level and the network level is that the network level does not aggregate the flows between facilities, but rather represents them. In other words, it is assumed that there is no level higher than the network level and that there is only one network. This makes sense from a real world perspective, because facilities are the ones that exchange mass and energy, not networks
2. Material Flow modelling: The three levels are: Mass, Mass Flow and Manufactured Product (End product). The reason for adding the layers of detail to material flow is so that the interactions between processes and facilities in a network have a higher fidelity. For example, if one facility sends steel screws to another, then the screws can be described as a manufactured part in the transaction rather than just an exchange of mass. Also, because the layers are related in a formal way, transitioning from one layer to the next is relatively simple by either adding or removing information

3. Energy Flow modelling: the author argues that in order to accurately calculate the energy of a process, the flow of mass must be taken into consideration. The energy consumption can either be determined from a specific energy basis (energy consumed per mass processed) or machine specifications in terms of electrical power and/or combustion power combined with processing speed, the number of machines required and the time required for processing. At the process layer, energy is directly calculated from mass flow. The energy consumed at the facility level is the sum of the energy consumed by the process inside of the facility. Finally, at the network level, energy is exchanged between energy producing and consuming facilities

Moreover, Culler argues that modular modelling makes it possible for different persons to benefit from the work of each other. The knowledge gained from designing and modelling processes and facilities within this framework can then be used by other modelers in future work on the same project. As an example, once a hammer mill process is specified, it can be used by other persons.

Bras argues that LCA boundary selection issues can be alleviated by using MBSE with SysML (Bras, 2009). When viewpoints of the model are included, the boundaries and scope of the model are defined in a formal manner, which reduces uncertainty. A history of SysML iterations can be kept to show the evolution of an LCA model and further reduce questions about the design process if these boundaries are refined during the design process. In addition, SysML provides a unique method for mapping existing LCA tools to a system-of-systems model. Moreover, the author sees a possible significant contribution of the PLM community to the field of sustainability. Nevertheless, integration of environmental issues and tools in existing PLM operating procedures is still lacking and represents a significant challenge. Although the number of PLM tools available is increasing, very few have achieved widespread acceptance for a variety of reasons, including lack of transparency, cost, learning curve, etc.

Modelling the Environmental Impacts of the Extraction Stage

Bougain and Gerhard used GHGP and CED values of the material and the mass to calculate environmental impact. Once a design engineer specifies a material, the corresponding values are retrieved from eco-databases and added as a property value for each part of the system. These values are later on newly calculated when a CAD model is available. Then, a Product Data Management (PDM) system that links CAD and SysML model overwrite the previously estimated values (Bougain and Gerhard, 2017).

Modelling the Environmental Impacts of the Manufacturing Stage

Bougain and Gerhard assessed the environmental impacts during the manufacturing stage by adding an estimated manufacturing process and work time for each part of the system (Bougain and Gerhard, 2017). The necessary data can either be retrieved from eco-databases or measured directly in the machine. The SysML model is then linked to the Entreprise Resource Planning System (ERPS) to update the values, when a manufacturing plan is developed and available in an Enterprise Resource Planning System (ERPS) (Bougain et al., 2017). Furthermore, Sprock et al. defined an ontology for DELS to model production and supply chain systems (Sprock et al., 2020). This approach was explained in section 2.2.4.

Modelling the Environmental Impacts of the Use Stage

Eigner et al. as well as Bougain and Gerhard modeled proactively the environmental impacts in the use stage in almost the same manner (Eigner et al., 2014a), (Bougain and Gerhard, 2017). In both works, a use case model was adopted to model the possible use scenarios of the product. The environmental impacts of each use case was calculated from the frequency of the usage and the energy consumption of each use case. The only difference is that Eigner et al. used existing energy data. Whereas, to calculate the energy consumption of the use case, Bougain and Gerhard refined the use cases using activities and assigned the energy consumption value to each activity. The sum of the energy consumption of the activities yields the energy consumption of the use case. The mathematical calculation was performed in the parametric diagram. The result of the analysis was used to identify the most significant issues in the system and support design decision-making. Meanwhile, Matar et al. used an MBSE approach to evaluate the sustainability of civil infrastructure. In their approach, the authors defined all the relevant sustainability parameters in a block and allocated them to the corresponding component. Afterwards, constraints and parametric diagram were used to calculate the environment impacts (Matar et al., 2014).

Modelling the Environmental Impacts of the Disposal Stage

Bougain and Gerhard used the same principle in the End-of-Life stage as in the extraction stage. The material designation and weight of the component are used to search a database for GHGP and CED values. First, the engineer is able to write down what materials he plans to use and how much weight each one will carry, but when a CAD model is linked, the data is retrieved for it automatically (Bougain and Gerhard, 2017).

The literature review is summarized and discussed in the following section.

3.2 Summary of the Literature Review and Requirements on the Methodology

In this section, the results from the literature review are summarized in Tab. 3.3. Afterwards, the results are discussed and the research gap is identified.

The rows from Tab. 3.3 show the publications found during the literature review and the columns categorize the articles using the following criteria:

- Life cycle stages: This criteria is used in order to identify the stages that were and were not addressed in the research. This will allow identifying the gap in the research
- SE or MBSE methodology: The goal of this work is to develop an MBSE methodology with the goal of assessing the environmental impacts of the systems. Any work from SE can also inspire in developing the method behind the MBSE methodology
- Proactive and reactive simulation time: These criteria are used to discover the modelling and simulation techniques and, especially, how to assess the environmental impacts in early design stages

In total, 12 articles were included in the scope. Fet et al. and Zanetti et al. have both developed a method for integrating SE with LCA, however, their method addressed only the product development and not the product life cycle from cradle-to-grave (Fet et al., 2013), (Zanetti et al., 2016). Yen and Azevedo used an MBSE methodology to assess the environmental impacts in complex urban transportation systems, but their approach was merely reactive rather than proactive (Yen, 2011), (Azevedo, 2010). Meanwhile, Eigner et al. provided an approach to proactively identify the significant issues in a system using the RFLP approach and simulation of system behavior in early design stages (Eigner et al., 2014a). However, the authors' approach concentrated only on the use stage. Culler, Bougain and Gerhard, as well as Matar et al. addressed proactively several life cycle stages, but they did not include the transportation stage (Culler, 2010), (Bougain and Gerhard, 2017), (Matar et al., 2014). Sprock et al. and Steimer et al. did not address sustainability in their work, even though, they were included to fill in the gap regarding the modelling of manufacturing and transportation stage (Sprock et al., 2020), (Steimer et al., 2017). Moreover, Sprock et al. developed a generic ontology that incorporates all the production and supply chain systems.

In summary, the gap in the literature lays in the lack of a generic MBSE methodology that includes a method, process and tools to proactively assess the environmental impacts of a product from cradle-to-grave. Also, the approaches lack a global recognition that could be achieved following a standard. This can be of a great importance for industries that seek an eco-label. Also, with the deteriorating climate change conditions, it is more likely that the severity of the environmental laws will increase in the future and the industries will be forced to prove a certification that their products are environmentally friendly (IPCC, 2022).

Table 3.3: Summary of the literature review

Nr.	Name of the Publication	Life Cycle Phases						SE	MBSE	Simulation time	
		Design	Extraction	Manufacturing	Transportation	Use	Disposal			Proactive	Reactive
01	(Fet et al., 2013)							x		x	
02	(Zanetti et al., 2016)							x		x	
03	(Eigner et al., 2014a)	x				x			x	x	
04	(Bougain and Gerhard, 2017)	x	x	x		x	x		x	x	
05	(Steimer et al., 2017)			x					x	x	
06	(Bougain et al., 2017)					x			x	x	
07	(Azevedo, 2010)	x	x	x		x	x		x	x	
08	(Culler, 2010)					x			x	x	
09	(Yen, 2011)			x					x		x
10	(Matar et al., 2014)					x			x		x
11	(Steimer et al., 2017)					x			x	x	
12	(Sprock et al., 2020)			x	x				x	x	

Based on this gap in the literature, five requirements on the MBSE methodology are defined (see Tab. 3.4). The MBSE methodology shall provide an assessment of the environmental impacts in early design stage, where incurred costs are low and design changes are easy (Honour, 2013). The MBSE methodology shall include all life cycle stages from cradle-to-grave. The method covers only from cradle-to-grave due to the time constraints from a master thesis. It must be noted that such an analysis is not sufficient to give a final statement on the product's environmental impact, because that will need a complete life cycle analysis (Matthews et al., 2015, p. 15). As the name already suggests, life cycle analysis implies that all the cycles spanning the whole life of a product shall be studied, including the feedback loops from circular economy strategies, or the so-called R-strategies, (Potting et al., 2017). Otherwise, it is not a life cycle analysis. Nevertheless, this work focuses only on cradle-to-grave, taking the R-strategies out of the scope. The other stages could be studied in future work. The MBSE methodology shall provide a method, process and tools to assess environmental impact. The methodology shall define "What" to be done, "HOW" to do it and accomplish the "HOWs" using a tool. The approach shall analyze the environmental perspective of a product from cradle-to-grave based on a globally approved standard. As it was previously mentioned, it is very likely that products will be subject to strict environmental laws to fight against the climate change. Finally, a traceability shall be achieved all along the life cycle in order to identify the environmentally harmful components in the product life cycle and support decision-making.

Table 3.4: Summary of the requirements on the MBSE methodology

Req. Nr.	Requirement Description
01	The MBSE methodology shall provide a method, process and tools to assess the environmental impacts
02	The MBSE methodology shall comply with globally approved standards
03	The MBSE methodology shall provide an assessment of the environmental impacts in early design stage
04	The MBSE methodology shall describe the environmental perspective from cradle-to-grave of the SOI
05	The MBSE methodology shall provide traceability along the life cycle of the product

3.3 Presentation of the Expected Benefits

The expected benefit of this work is to support industries in their fight against the climate change. In a scenario, where humanity overcomes the challenges regarding the climate change. It is mandatory that we achieve a zero-net emission industry by 2050. Under these circumstances, the industries are urged to develop sustainable products to compete successfully against ecologically acting market participants. Just like the evolution paradigm, industries will be subject to adaption to current market changes, or in other words, industries must "Adapt or Perish" (Walker et al., 2013). In a future full of uncertainty, industries will need to plan and assess their ecological choices before taking any decision. This work can support these tasks by delivering an MBSE methodology based on ISO LCA standard.

The developed MBSE methodology can assist engineers with an internationally recognized approach that integrates the analysis of environmental impacts from cradle-to-grave in early design stages. INCOSE identified sustainability in their SE Vision 2035 as one of the six megatrends that will influence SE through 2035. Moreover, they mentioned that the fight against climate change will give birth to a new generation of engineers, who consistently assess the societal impacts of developed system (INCOSE, 2021). There are already working groups within the SE community that are being built to tackle this problem. This approach can help in supporting the already existing initiatives into developing a standardized framework that assists engineers, while they are analyzing the sustainability of their product.

This work can support the assessment of the environmental impacts of the R-strategies. Integrating MBSE and LCA will bring both communities to work together and benefit from the synergies of their cooperation. Also, the life cycle thinking paradigm will gain a new thrust with this incentive. Although, this work does not address the feedback loops from the life cycle stages, it does present an approach on how to integrate LCA with MBSE to assess the environmental impact. This is a very important aspect when applying the R-strategies. Circular economy strategies are not sustainable by definition. Each strategy implies an input of energy and resources. If the input of energy and resource is higher than the benefit from the output, then the strategy is not suitable. It is, therefore, important to assess the environmental impacts of the R-strategies before choosing one (Potting et al., 2017).

The approach developed in this study can help the growth of the SE community. Together with the approach developed by Sprock et al., not only does it become possible to assess the environmental impacts from cradle-to-grave, but also the structure and behavior of the life cycle stages can be analyzed (Sprock et al., 2020). This incentive can motivate engineers in other domains into adopting SE, which will lead to the growth of the SE community. The SE community can definitely benefit from a wide spread of its practices that will help in building task forces in order to tackle the challenges facing future engineers. A bigger community can accelerate the pace to which SE is developed.

This work develops an MBSE methodology for the life cycle of a product from cradle-to-grave. First, it studies if it is possible to model the life cycle of a product. Afterwards, it demonstrates how it is possible and what are the limitations. One could ask the questions: Why would one need a model of the life cycle of the product?

A model of the life cycle of the product can deliver a high-fidelity environmental assessment results, also, provide a great command and control in the value chain of the product. As Matthews et al. mentioned, a life cycle analysis is important to have a holistic analysis of the environmental impacts. This comes with a significant cost for the amount of time and resources needed to develop such a model. Nevertheless, it can also bring great benefits. Engineering has always been about humans who build systems in order to command and control their environment (Wasson, 2005). A model of the product life cycle allows for a high-level of command and control in the life cycle of the product. The importance of such a model can be especially remarked from the at the time of writing emerged Covid-19 crisis and the war on Ukraine. The crisis caused several effects on the product life cycle and especially the supply chain, e.g., the scarcity of goods such as vegetable oil, toiler papers, etc., that lead to soaring prices, or, especially, the chip crisis in the automotive industry that drove several industries to shut down their factories. Jastram mentioned three types of risks in the supply chain (Jastram, 2022):

1. A low number of suppliers of a specific component
2. A high number of suppliers in the supply chain
3. A high level of hierarchical levels in the supply chain

The growing complexity of systems is causing a growth in the complexity of the supply chain, additionally, to rigorous constraints and requirements such as sustainability, safety, availability, short time to market, etc. In normal times, the supply chain seems to work smoothly, but, in crisis time, the weak points mercilessly come to light. This is especially because industries do not have a model that represents their product life cycle, also because they are not benefiting from the full extent of Product Lifecycle Management (PLM) systems. Combining a holistic model with a Digital Twin concept can offer great opportunities for optimization and adaptation to unexpected situations.

As the name already suggests, a Digital Twin is an as identical as possible digital representation of a physical object. It consists of the physical object, the virtual representation and the communication between. A Digital Twin constantly senses the environment of the physical object and allows for simulation of different scenarios before their occurrence. Building a Digital Twin of the life cycle of a product can uncover new possibilities and support spontaneous decision-making in uncertain situations. Assessing the environmental impacts of a product will especially drive the need for product life cycle models due to the required life cycle thinking.

The exponentially growing complexity in systems will drive an immense adoption of the MBSE all over the product life cycle due to its great success in developing complex system that operate as intended (Rogers III and Mitchell, 2021). We can notice the same development in different areas, as an example the field of virtual product development was in the last years focused on developing systems for manufacturing. Today, virtual product development encompasses the whole product life cycle, with several feedback loops between different life cycle stages and the design stage to continually monitor, adapt and optimize the system. Hence, the growing complexity will bring failures in the supply chain that will cause conflicts, delays, higher costs and customer dissatisfaction. In the quest of command and control, MBSE will propagate all over the life cycle enhanced with artificial intelligence, data science, etc. to better understand, predict and avoid failures (INCOSE, 2021).

The great effort in modelling the complete life cycle of a product can be tackled with a widespread of the model-based paradigm. INCOSE mentioned that the model-based development will become a standard in the upcoming years (INCOSE, 2021), driven by the actual digital transformation as part of the fourth industrial revolution (Vrana and Singh, 2021). Most of the complex products are so complex that one cannot find only one company involved in its life cycle. The product life cycle of a complex system includes several suppliers. The more complex does the product get, the more suppliers are involved in the product life cycle. An OEM should and also cannot model the complete life cycle of the product. Each supplier involved in the product life cycle is the best on what he does, therefore, an OEM should not do a work that does not suit their competencies. In the real life, the OEM mostly develops the architecture and provides requirements to the suppliers. INCOSE projects in the future that this will solely be performed in a model-based approach (INCOSE, 2021). In this case, an OEM will desire to have a model of the product life cycle that represents the single source of truth. The suppliers must then provide a model of their component which represents a part from the life cycle of the product. Models could become a competitive aspect between suppliers. It is also possible that standards will be developed to define requirements for the interfaces between the models of the product life cycle. This can allow for a plug and simulate concept, where models from different suppliers can easily be integrated with each other to form a model of the product life cycle.

Model-reuse can decrease the costs involved in modelling the life cycle of the product, which needs a lot of time and resources. Nowadays, modelling the life cycle of each component of a car is definitely a very cumbersome, if not an impossible, process. Nevertheless, the more MBSE is adopted by the community, the more standardized processes, methods, libraries for modelling life cycle are developed. As mentioned from Culler, model-reuse can become a game changer in this ever-growing complexity in the product development (Culler, 2010). The library for DELS models is an example of such an initiative (Sprock, 2017). Once we reach the point where sufficient libraries are available, developing a product life cycle will become as normal as the actual state of developing system specification.

In summary, this work provides a model-based approach on the basis of the ISO LCA standard to assess the environmental impacts of a product from cradle-to-grave. It is very important to have life cycle analysis view on the product to better assess its environmental impacts and have a bigger room for creativity and optimization. Although it comes with higher costs and efforts. These challenges can be tackled with a wide spread of the model-based paradigm that will increase model-reuse.

Chapter 4

MBSE Methodology for the Integration of LCA in the Life Cycle of a Product

This chapter describes the MBSE methodology used in this work. First, the emergence of the methodology as a satisfaction of the requirements from Tab. 3.4 is described. The following section presents the MBSE method based on an extended V-Model. Section 4.2.1 explains the process steps for modelling each life cycle stage. The modelling in this work is based on the approach from Holt and Perry. The MBSE ontology and the framework are presented respectively in section 9.1 and 9.2. The views that illustrate the viewpoints and demonstrate the process are shown in chapter 6. The models presented in this work were generated using Cameo Systems Modeler version 19.0 Sp2 with SysML 1.5.

The MBSE methodology developed in this work emerged as a solution to the requirements defined in Tab. 3.4. The first requirement from Tab. 3.4 dictates that the MBSE Methodology shall provide a method, process and demonstrate the latter using tools. The method is addressed in the following section, section 4.2.1 describes the process and the demonstration using the tools is shown in chapter 6. To achieve global recognition regarding the assessment of the environmental impacts, this work has been based on the ISO LCA standard (Req. 2 from Tab. 3.4). However, this work considers only an LCI study. The LCIA stage could be studied in future work. The requirements of the LCI study according to ISO 14044, as well as their satisfaction using the MBSE methodology from this work, are summarized in Fig. 9.23.

The systematic procedure used in this work, emerged as a combination between the three publications (Eigner et al., 2014a), (Eigner et al., 2014b) (Mcginnis, 2018). The result is an iterative and a parallel V-Model that fulfills the requirements of the methodology (see Tab. 3.4). Figure 4.1 illustrates the V-Model developed in this study. The figure is described in more detail in the following section. Similarly to the V-Model from Eigner (Eigner et al., 2014a), the approach can be divided into four main parts: the upper part, the subpart, the left and the right wing of the V. In this work, the focus is only on the upper part and the left wing of the V-Model.

The reason lays in the goal of this study, which is performing an analysis in early design stages.

The three life cycle stages: development, raw material processing and transportation, are sufficient to represent the stages from cradle-to-grave (Req. 4 from Tab. 3.4). As already mentioned in section 2.1.2, cradle-to-grave means a view on the product from its birth to its death. Based on the generic life cycle stages from ISO 15288, this would include concept, development, production, use and disposal stages. As the goal of this study is to provide a methodology to show how to assess environmental impacts and not to assess them, the focus is centered on the life cycle stages. These differ when it comes to characteristics.

In the context of LCA, the characteristics of concept and development stages are similar in their characteristics. Both stages include teams of humans working on their desks and performing the tasks of their life cycle stage. The development stage could introduce a difference in the necessity of a test mock-up for test, validation and verification purposes. This can also be represented as a set of resources that consumes energy. In order to assess the environmental impacts of working in an office, the sum of the resources and energy used multiplied by the number of people working in the office. Therefore, to simplify the work, both stages will be summed up as system specification stage.

The raw material extraction and the transportation stages are sufficient to represent any production stage. The latter can be broken down to material extraction, material processing, manufacturing, assembly, transportation, etc. Based on the DELS ontology from Sprock et al., all these systems can be abstracted using the PPRFT model (Sprock et al., 2020). The PPRFT model describes a facility that contains a network of resources, where resources, which can be active or passive. Active resources transform the state of passive ones through a process, e.g., a raw material processing machine. Whereas passive resources are transformed through a process using an active resource, e.g., raw material. Products are the result of each process. A process might require capabilities of more than one resource. Processes can change location, age, or condition of passive resources to yield a product. Finally, a process is authorized by a task. Based on this abstraction, each life cycle stage in the production can be representable for the others. In this work, the raw material processing and transportation stages are chosen to represent the production life cycle stages.

The raw material processing is chosen because it is very similar to other production stages. It is based on resources that perform processes to produce products. Here, the input is the resource and the output is the product. However, in the transportation stage, there are two differences. First, in the life cycle of a product, the products are transported through a network of facilities. This stage does not physically contain a facility, but rather a network of facilities. Nevertheless, it can be abstracted as a facility that contains a network of all the facilities from the life cycle stages. Secondly, in the case of a transportation stage, the product is the input that is transported to a certain location. The output of the process is the transported product. As an example, we imagine a scenario where a battery is transported from China to Germany.

To model this use case, the battery will need to have a property that represents its geographical location. Using the DELS ontology yields the following:

1. The Passive Resource is the battery in China. Here, the value property of the geographical location is China
2. The Active Resource is the mean of transportation, e.g., truck, ship, airplane, etc.
3. The Process is transportation
4. The Product is the battery in Germany. It is the same battery, but in this case, the value property of the geographical location is Germany

Due to these differences, the transportation stage is also included in this work.

The use stage is considered within the development stage, since the latter focuses on developing the system in the context of how it will be used. The development stage is started by a concept of operation, that represent how the system will be used by the system user. Also, it is in the development stage that all functions and behaviors of the system are specified. Therefore, the use stage is included in the development stage.

The raw material processing stage is representative for the disposal stage. Since recycling is not addressed in this study, the disposal stage represents nothing more than an inverted production stage. In the production, the raw materials are the input and they are transformed through processes to generate the end-product. Whereas, in the disposal stage, the used end-product is the input that is disassembled and processed to generate raw materials from it. Therefore, any PPRF model can be representative for the disposal stage. Thus, the raw material processing stage is chosen.

In summary, the three life cycle stages: development, raw material processing and transportation, are sufficient to represent the stages from cradle-to-grave. This is aligned with the goal of this work, since the aim, the aim is to show what and how to assess environmental impacts using MBSE and not to model each life cycle stage. The method demonstrates how to model all life cycle stages from cradle-to-grave in early design stage. It is also advisable to do so, nevertheless, modelling all life cycle stages requires a great amount of time and resources. Depending on the goal and the scope of the LCA study, one has the freedom to choose, which life cycle stages to include.

This work focuses solely on the left wing of the V-Model to satisfy the need for an estimation regarding the environmental impacts of the product in early design stage (Req. 3 from Tab. 3.4). The four LCA stages can be divided according to the RFLP levels. The goal and scope definition are addressed in the RF levels. The functional level could provide a first approximation of the environmental impacts regarding the usage of the product, if LCI data can be estimated. However, other life cycle stages require at least a logical architecture that is design solution specific in order to pride any meaningful statement. Therefore, LCI analysis and life cycle

Table 4.1: Summary of the requirements on the MBSE methodology and their satisfaction

Req. Nr.	Req. Description	Fulfillment of Req.
01	The MBSE methodology shall provide a method, process and tools to assess environmental impacts	See chapter 4 and 6
02	Regarding the assessment of environmental impact, the MBSE methodology shall comply with globally approved standards	The methodology is based on the ISO LCA standard
03	The MBSE methodology shall provide an assessment of the environmental impacts in early design stage	The methodology can be performed at the left wing of the V-Model (See Fig. 4.1)
04	The MBSE methodology shall describe the environmental perspective from cradle-to-grave of the SOI	See chapter 4
05	The MBSE methodology shall provide traceability along the life cycle of a product	See chapter 4

interpretation can be performed at the LP level. The LCIA stage uses the output from LCI analysis and transforms it based on mathematical calculations into environmental impacts. Therefore, it is assumed that LCIA can also be performed in the L-P levels. This can be avaluated in future research. Following this procedure, an LCA from cradle-to-grave can be performed at the left wing of the V-model before proceeding with the discipline specific design.

It should be evident that the assessment of environmental impacts in early design stages can only provide an estimate regarding the end-product. The available data, at this stage, can only be approximated from old product versions or secondary data. Therefore, a deviation from the actual value shall be considered. In general, the result of an LCA study is a function of input and output. The quality of the output depends solely on the one of the input. The more we advance in the life cycle of the product, the better we learn about our product. As we learn more, the first estimation can be continuously and automatically updated and refined using PDM/PLM systems. The importance of an estimate in early design stages is addressed in detail in section 1.1 and 3.3. Therefore, it is beneficial to spend more time in early design stages and perform various iterations until a level of certainty is achieved before proceeding with the product development.

Traceability along the product life cycle (Req 5 from Tab. 3.4) is achieved using the RFLP approach. Combining the works from Eigner et al., as well as Mcginnis, the four levels of the RFLP approach can be spanned along the life cycle of the product. The approach provides homogeneous levels (RFLP) between the different life cycle stages. Each level of the RFLP approach, starts with its corresponding requirements. At the end of each level, the traceability relationships of that level are specified and the requirements of the next level are defined. Table 4.1 summarizes the requirements on the MBSE methodology and their satisfaction.

4.1 The MBSE Method

Figure 4.1 illustrates the extended V-Model developed in this work. The upper part contains the life cycle stages: development, production and disposal. These life cycle stages can be adapted according to the life cycle of the system under study. In this work, the use stage was considered in the development stage, since the system is developed in the context of how it will be used. The production stage encompasses all stages that work on producing the system, e.g., raw material extraction, raw material processing, manufacturing etc. Finally, the disposal stage represents the death of the product. It must be noted that the circular economy strategies are not considered in this V-Model. This could be studied in future work.

Below the life cycle stages, the development of each stage is illustrated in the form of a V. Each life cycle stage has its own V. This can be imagined as a series of serialized and/or parallel Vs. The serialized Vs represent a situation where a life cycle stage awaits information from the previous life cycle stage. As an example, during the development of a new product, the production stages can only start, when at least a logical architecture is available. After that, the production stages, e.g., raw material extraction, manufacturing, etc., can start at the same time. This can be expressed using the parallel Vs. In this study, serialized Vs were chosen, because it is a new product and the work was done by one person. In a real project with different teams, a combination of parallel and serialized Vs can be chosen to suit the development process.

This work focuses mainly on the left wing of the V, which represents the early design stages. Each left wing of the V is separated according to the RFLP approach (see section 2.2.3). To this approach, LCA stages are assigned. The first stage of LCA, goal and scope definition, can be performed at the R-L levels. The rest of the stages can be carried out at the L-P levels. The figure encompasses the LCIA stage, although it is not addressed in this work. It is assumed that LCIA can be performed at that level, since it requires only the results from LCI analysis. This could be validated in future research. This approach offers a way to study the life cycle stages from cradle-to-grave and assess their environmental impacts in early design stages. The future section described the process behind the developed methodology.

4.2 The Modelling Process of the MBSE Methodology

Following the LCA process steps from ISO 14044 standard, a generic process for model-based LCA is defined (see Fig. 4.2). The figure is separated using horizontal swimlanes into three groups representing the LCA stages. Firstly, the goal and scope parameters according to ISO 14044 are defined. Later, the context of the system under study is analyzed. The analysis includes an analysis of stakeholders, use cases, system environment, in- and output of the SOI as a black-box and in- and output of the SOI as a white-box.

In the life cycle inventory analysis, first, the relevant properties for LCA are defined. After that, the context of the analysis is defined in an ibd diagram. The context contains the elements from the model that are relevant for the LCA study and the constraints or the mathematical

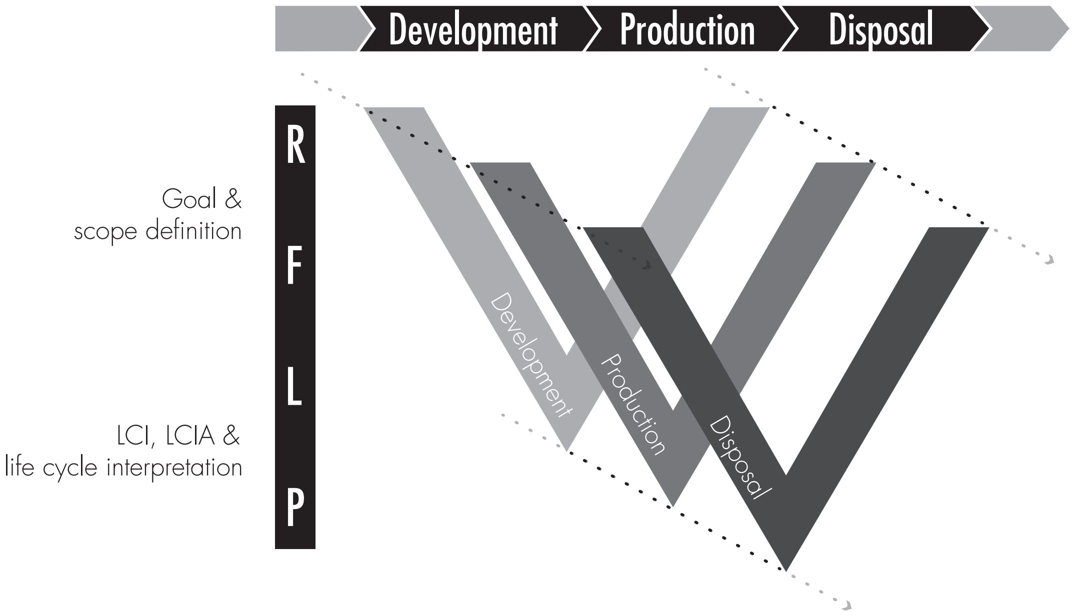


Figure 4.1: Extended V-Model for life cycle assessment from cradle-to-grave

equations to calculate the life cycle inventory. Then, the data is collected and validated. Here it is advisable to collect data in an Excel table. To my knowledge, there is no pragmatic method for the automatic collection of the LCA values from a database. The databases are organized differently from one another, therefore, one cannot find a generic scheme to automate the data from the databases. Nevertheless, one could collect all the data in an Excel table. This facilitates the collection process and the relating of the data to unit process and the functional unit. These steps are much more easy to perform in an Excel table than the SysML model. Once the data is collected and normalized, then, the Excel table can either be integrated with SysML model or the values can be entered manually in the SysML model.

However, automating the assignment of values from the Excel table to the value properties in the SysMl model also comes with a significant effort. It is assumed that a suitable naming convention and a mapping function can automate this step. This could be studied in future research. Otherwise, I currently see a manual assignment of the values from the database to be the most pragmatic. In later stages, when an LCA tool is used, then SysML model can be integrated to the LCA tool using as an example OSLC. After the data is collected, then, the analysis can be performed in the parametric diagram. Finally, the life cycle impacts assessment and life cycle interpretation can be performed.

Figure 4.2 shows a feedback loop after the life cycle interpretation that represents an iteration. It must be noted that the iteration can be performed at any process step and it should be at least performed after each stage of the LCA analysis until a level of satisfaction is achieved. The other possible iterations were omitted from the diagram for visibility reasons.

The following sections describe the specific modelling process adopted in this work.

4.2.1 The Modelling Process of the Life Cycle Stages

The modelling process of the life cycle stages, as shown in Fig. 4.3, is composed of four parts according to the included life cycle stages: top-level, system specification, raw material processing, transportation. The figure illustrates the top-level development process of the MBSE methodology used in this work. The four vertical swimlanes represent each of the aforementioned life cycle stages. The process for the other life cycle stages is described in the upcoming subsections, following the CFLP approach. The top-level does not follow a CFLP approach, but rather only a C approach. This is because the C-level was sufficient to define the broader scope of the Energy Module and to sum up the results from the LCI stages. This aligns with the goal and scope of the study. In a normal project, the Top-level would also have its CFLP stages.

The modelling of the top-level starts with the model organization. Afterwards, the context of the product life cycle is analyzed. The context analysis includes stakeholder, system environment, turnover and use cases analysis. Resulting from the context, the requirements on the top-level requirements are formulated and the traceability relationships between the elements are specified. Then, the development of each life cycle stage can be started. In this study, the development of the life cycle stages is serialized because the product is new and the model is developed by one person. Following the chronological order, first the system specification is developed, then the raw material extraction and lastly the transportation stage. After that, the context of the LCI study is specified. Once the analysis of the life cycle stages is finished, the LCI results of each life cycle stage can be fed to the top-level in order to be summed up. The activities Establish context of analysis and perform LCI are corresponding to the Life cycle inventory analysis from the ISO 14044. These steps are described in detail in section 4.2.5.

4.2.2 The Modelling Process of the System Specification Stage

Figure 4.4 shows the development process of the system specification stage used in this work. Horizontal swimlanes are used to group the activities of each level from the CFLP approach. Starting from the top-level requirements, functional requirements concerning the Energy Module are developed. Similarly to the top level, the context of the Energy Module is analyzed and context requirements are defined. Afterwards, the use cases are refined using activities and the traceability relationships on the R-Level are specified. The results from the R-level are used as an input to the F-level in order to perform the FAS-method (see section 2.2.3).

Using the FAS-plugin, the functional architecture can be deployed and the traceability relationships can be set up automatically. The F-level is terminated by the definition of system requirements that serves as an input to the logical layer.

On the logical level, logical blocks are allocated to the functional blocks from the previous layer. Consequently, the granularity of the activities is further refined to the level of the logical components. Afterwards, the system behavior can be modeled and simulated to perform the first virtual requirement validation. Then, the context for LCI analysis can be established. In this case, one can include an LCI analysis of both the use and system specification stages. The use stage of the Energy Module considers how the Energy Module will be operated. The system specification stage analyzes the energy and resource consumption on the system specification stage. To terminate the L-level, performance requirements are defined and the traceability relationships in the L-level are specified.

On the P-level, physical blocks are allocated to logical blocks. Afterwards, the BOM is defined, which serves as an input to the following life cycle stages. Finally, the LCI analysis is performed on the system specification level to calculate the emission from the system specification stage and the use stage of the Energy Module. The results of the LCI analysis are fed to the top-level in order to be aggregated with the other life cycle stages.

4.2.3 The Modelling Process of the Raw Material Extraction Stage

The development process of the raw material extraction stage is shown in Fig. 4.5. Similar to the previous life cycle stage, the CFLP-levels are shown using horizontal swimlanes. The BOM triggers the start of the raw material extraction stage. To every part of the BOM, process requirements are defined. Afterwards, the context of this life cycle stage is analyzed. Additionally to the context analysis, the product system of this stage can be defined (see Fig. 2.3). Afterwards, the traceability on the C-level is established.

The F-level starts with finalizing the processes from the previous level. Then, the properties required for the LCA analysis are specified. Afterwards, the requirements on the resources are formulated and the traceability on the F-level is established.

The L-level starts by defining the resources needed for each process and the properties of the resources that are relevant for LCA. After that, the context of LCI analysis is defined. Finally, the requirements on the facility are defined and the traceability on the L-level is established. On the P-level, the specific resource numbers and their arrangement in the facility are defined. Later, the LCI analysis is performed. The results are then sent to the top-level in order to sum them up with the results from other life cycle stages.

4.2.4 The Modelling Process of the Transportation Stage

The development process of the transportation stage is shown in Fig. 4.5. As already mentioned in chapter 4, the transportation stage is very similar to the raw material extraction stage and it can be abstracted using a PPRF model. Therefore, the development process is almost the same. The only difference lies on the P-level of Fig. 4.6. Once the processes and the resources needed for each BOM part are defined, the P-level specifies the location of the facilities and their arrangement in the network. Finally, the LCI analysis is performed and the results are fed to the top-level, similarly to the previous life cycle stages.

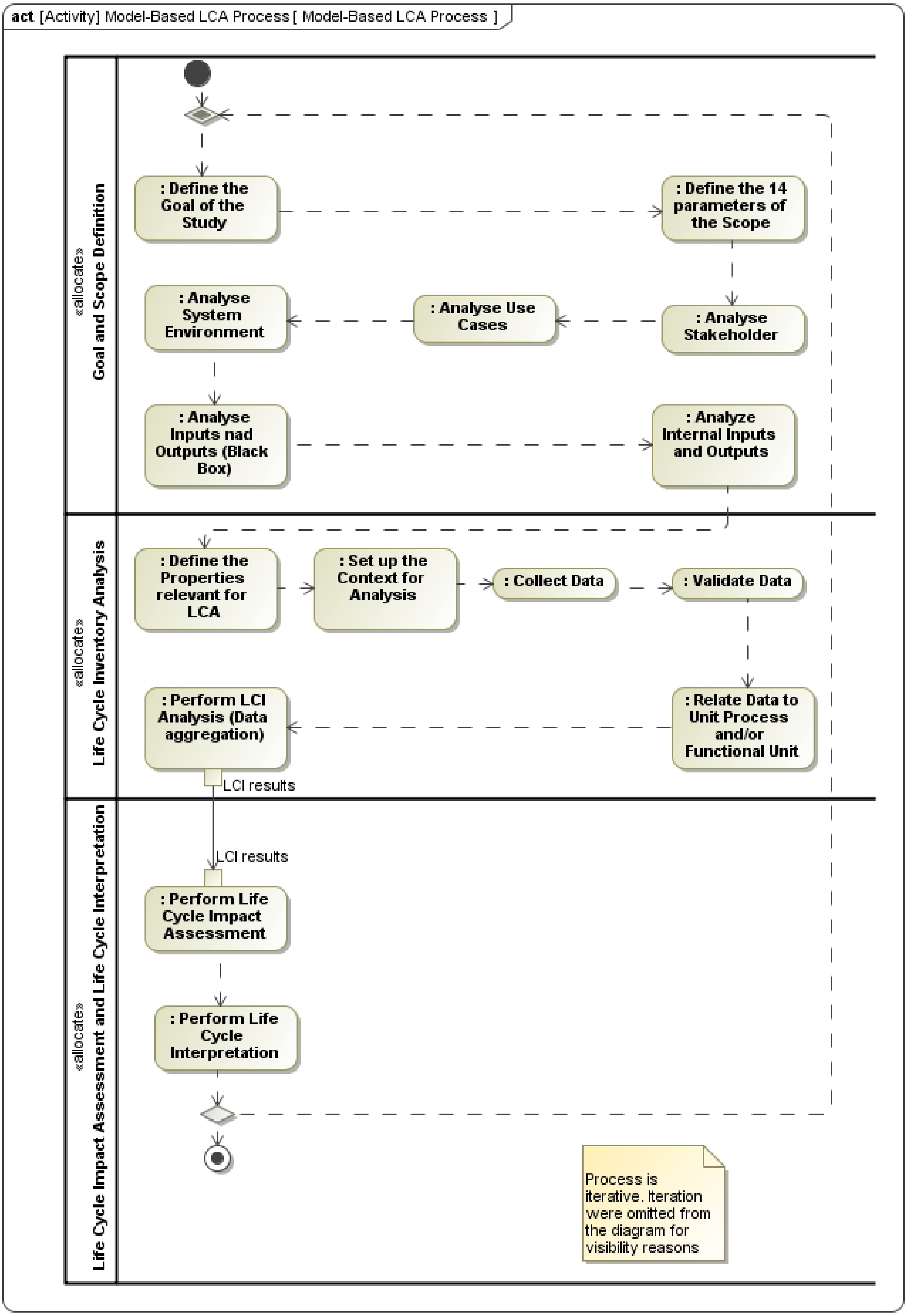


Figure 4.2: The modelling process of the MBSE Methdology

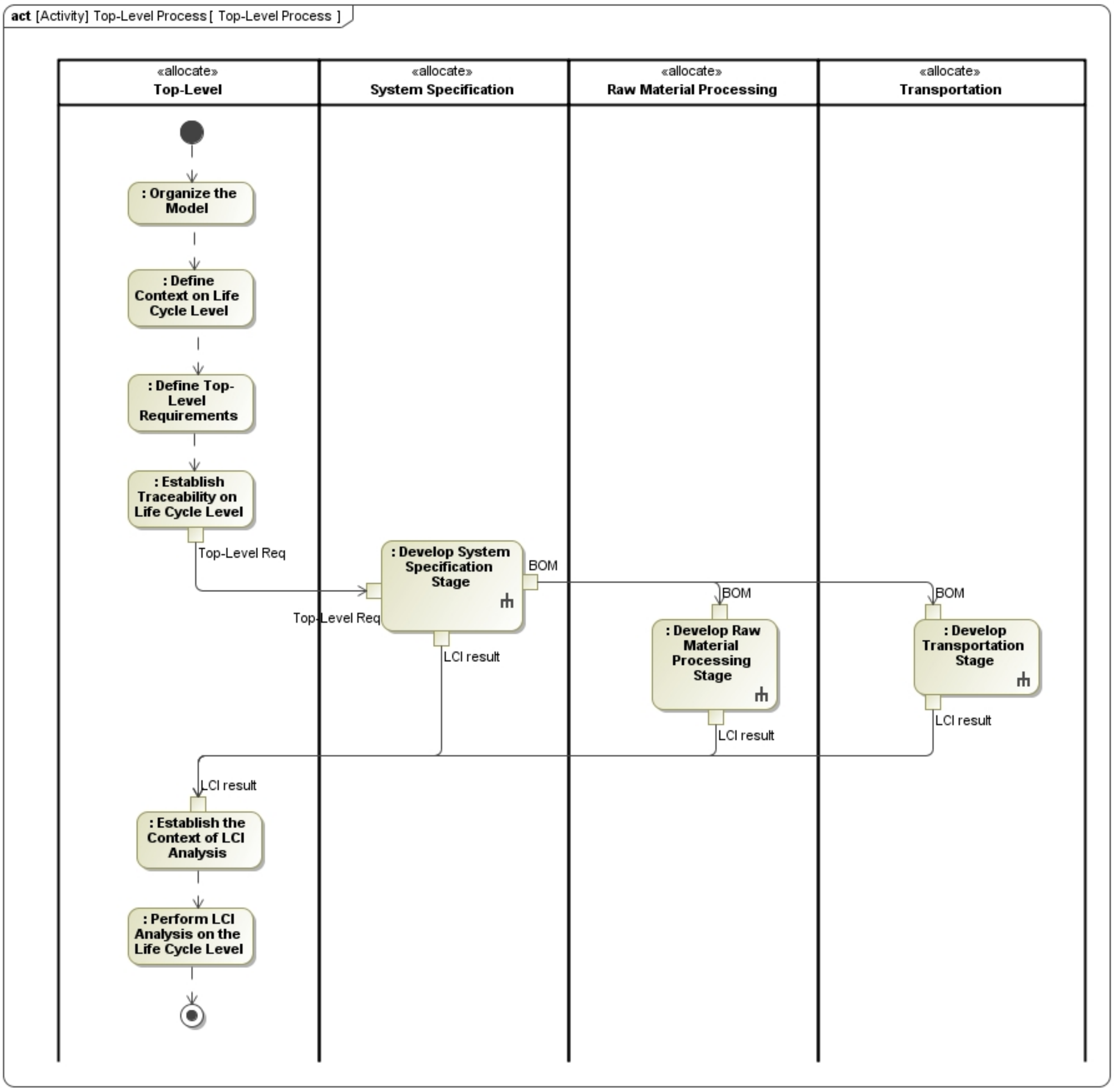


Figure 4.3: Top-level development process of the MBSE methodology used in this work

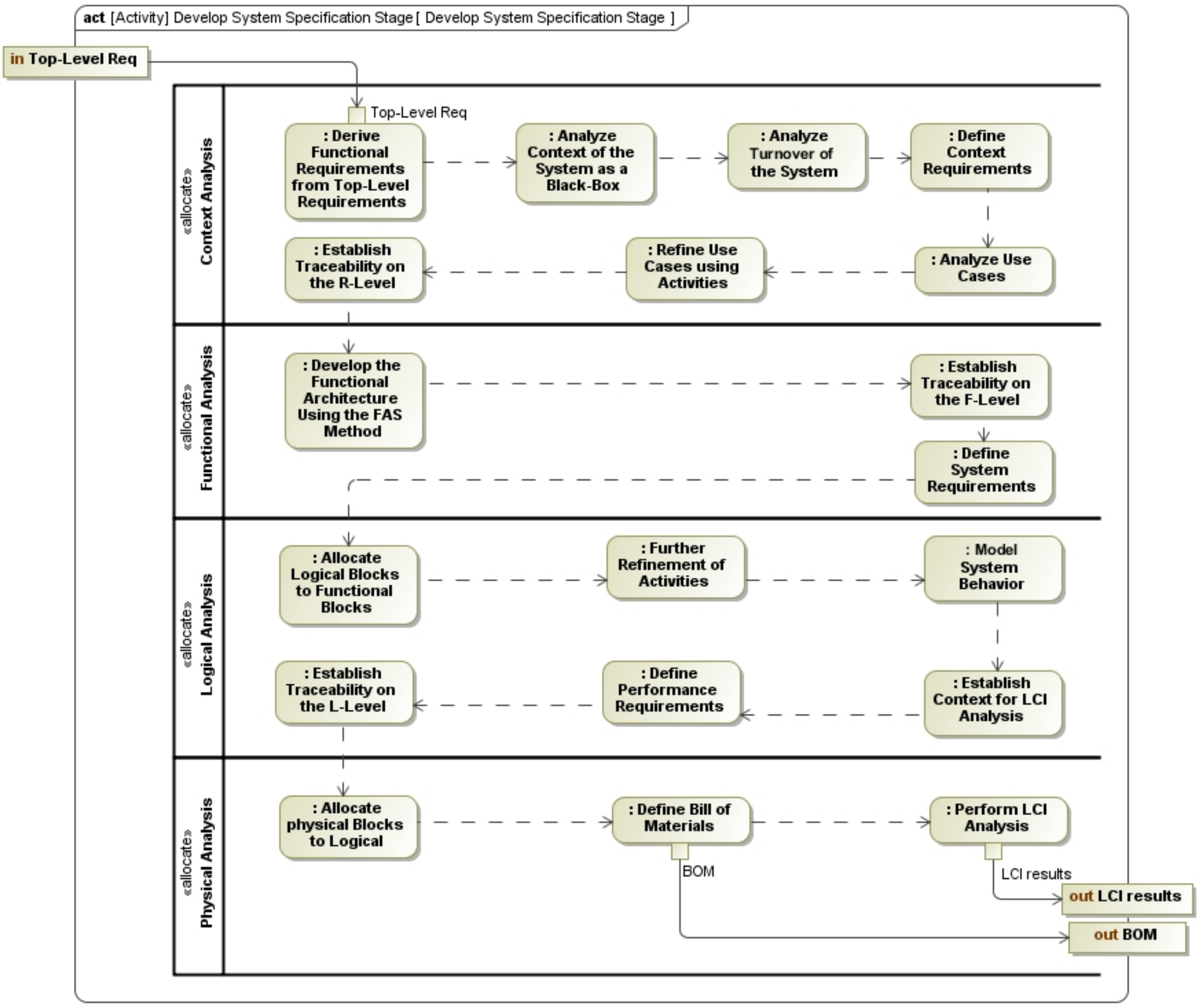


Figure 4.4: System specification stage development process of the MBSE methodology used in this work

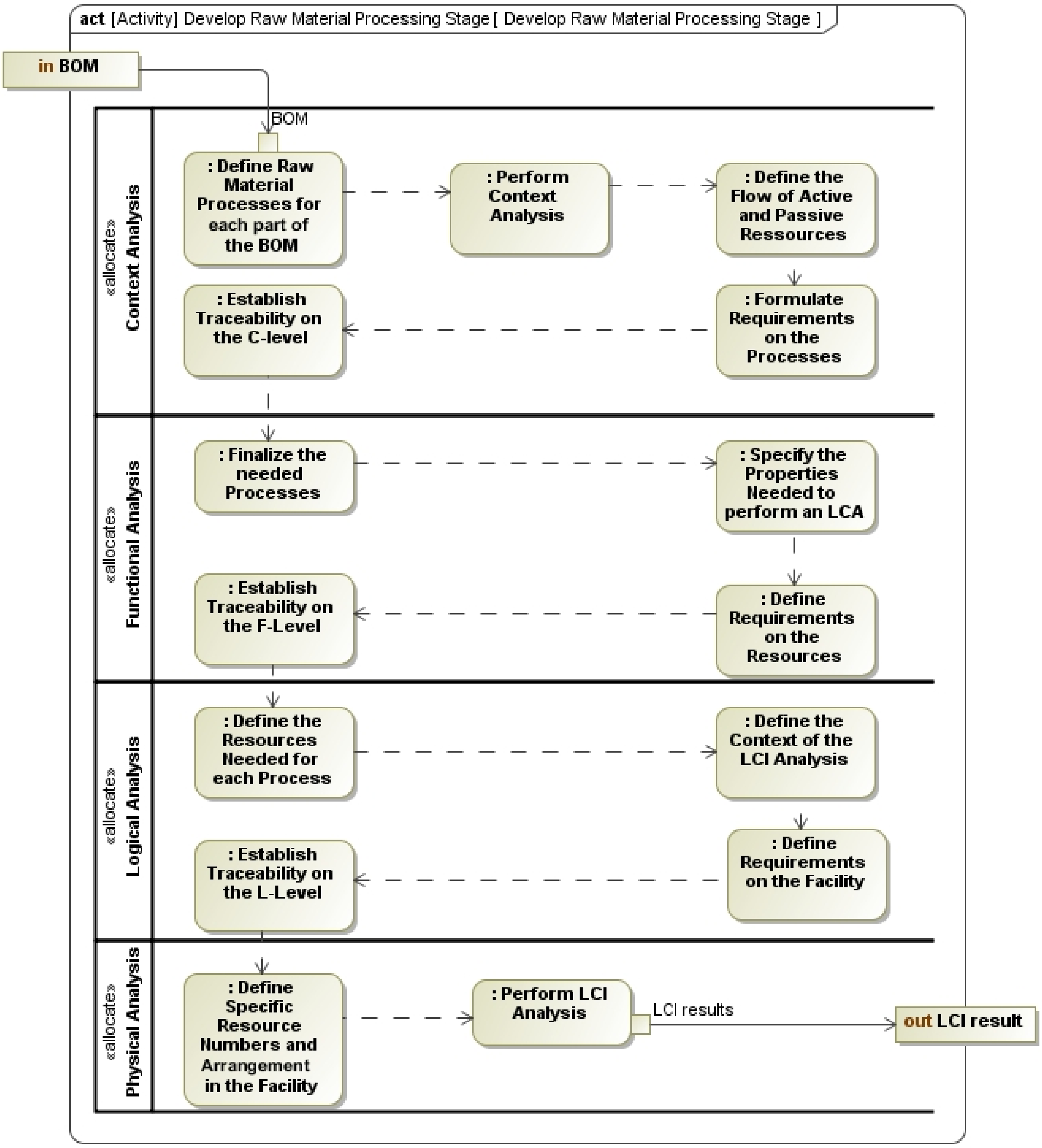


Figure 4.5: Raw material extraction development process of the MBSE methodology used in this work

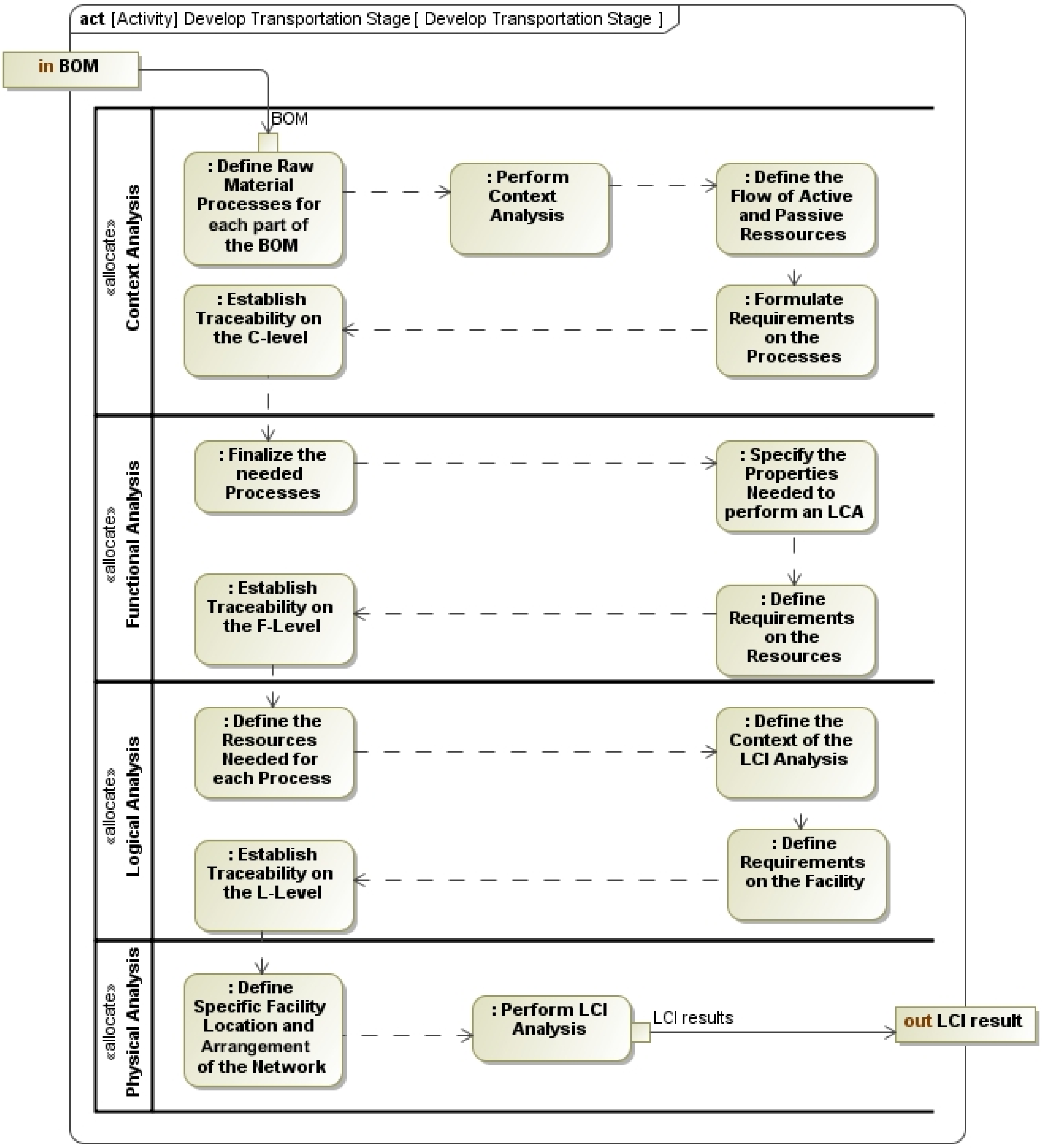


Figure 4.6: Transportation development process of the MBSE methodology used in this work

4.2.5 The Modelling Process of the Life Cycle Inventory Analysis

Figure 4.7 shows the generic process of life cycle inventory analysis based on the ISO 14044 (ISO 14044, 2021). The steps of the life cycle inventory analysis from the ISO LCA standard were described in section 2.1.1.3. The first five steps of the process are: preparing for data collection, data collection, validation of data, relating data to unit process, relating data to functional unit. These are executed on an Excel table. The results of those steps can be found in Fig. 9.13. The last two steps: data aggregation and refining the system boundary are performed in the SysML tool Cameo.

Once the work in the Excel Table is done, a bdd is created in order to define the context of the analysis. Inside of the bdd, a block is created that contains all the relevant information to the analysis. After that, the unit processes and the flows relevant for the analysis are dragged and dropped in the bdd. Then, the properties relevant for the LCA analysis and their corresponding units are defined. Following that, the constraint mathematical equations required in order to perform calculations are specified and their parameters and their units are assigned. The properties that need to be read by the Cameo engine during the simulation shall have a relationship to the context analysis block. Therefore, a composition relationship is used between the elements in the context of analysis. Finally, a parametric diagram is created inside of the context block and the constraints are mapped with their relevant properties using the wizard or manually.

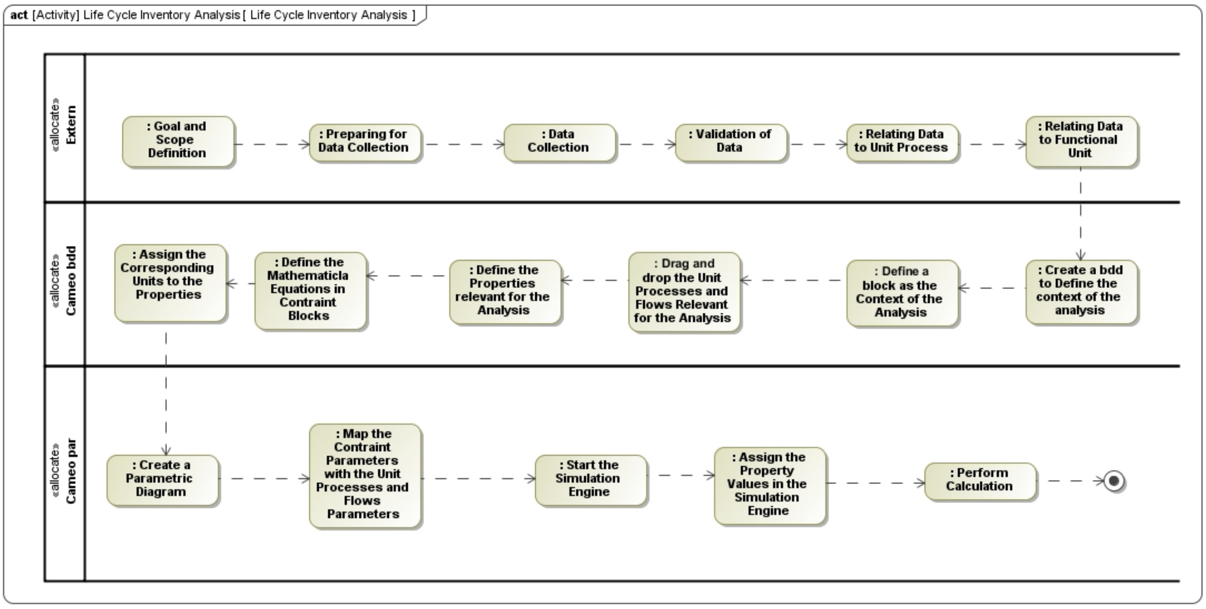


Figure 4.7: The model-based life cycle inventory analysis process

Chapter 5

The Systems of Interest

This work performs an LCI from cradle-to-grave. Due to the broad scope of the study and the time constraint of a master thesis, the scope had to be compromised from a life cycle stage to another. Figure 5.1 shows the SOI of each life cycle stage. The different SOIs will be introduced briefly in the following sections.

At the top-level, the robot ELSA and its life cycle represent the system under study. At the system specification stage, the focus is narrowed on the Energy Module. The Energy Module contain several components. One of these components is the lead-acid battery. The lead part in the lead-acid battery represents the SOI of the raw material processing stage. The transportation and use stages consider ELSA as the context.

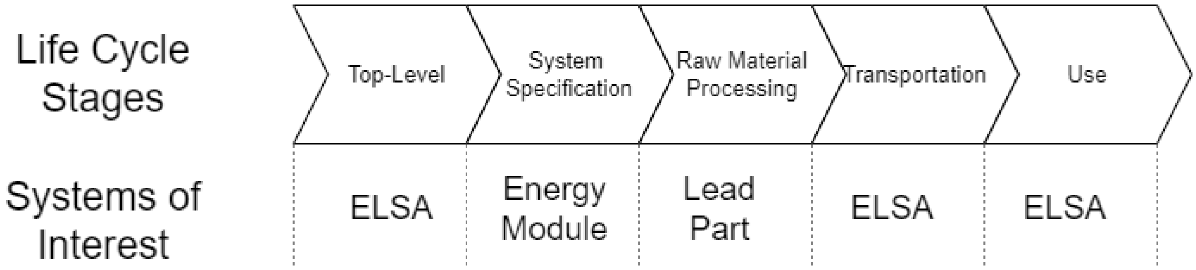


Figure 5.1: The SOIs of each life cycle stage considered in this work

5.1 Engineering Living Systems in Autonomy (ELSA)

ELSA represents the broad context of this work. The acronym ELSA stands for Engineering Living Systems in Autonomy. The goal of the ELSA project is the experimentation of different product development methodologies, techniques, etc. ELSA is a robot that operates autonomously. It has the following functions:

1. Welcome and take care of guests

2. Water plants

3. Move independently on the 5th floor of the IPK research center

4. Provide an internet access platform to guests and employees

5. Manage schedule

To achieve this, a modular and agent-based approach is adopted. ELSA is made up of the following modules:

1. The arm, working with 7 servomotors, serves at moving the arms
2. The grip is used to hold objects
3. Watering Module to water plants
4. The driving platform senses and drives ELSA autonomously across the fifth floor of the IPK research center
5. The energy module provides ELSA with electrical power
6. The camera module identifies humans, objects and environment
7. Head module is used to express emotions and talk to humans
8. A user interface to control ELSA
9. The main module communicates with the server, controls and manages the other modules

In this work, the focus is laid on the Energy Module.

5.2 The Energy Module of ELSA

The Energy Module is the system under study, it is part of the robot ELSA. This section presents the context of the Energy Module and its RFLP architecture

5.2.1 Model Organization

Figure 5.3 shows the structure of the model. The Energy Module of ELSA Project imports the SysML profile, the ISO 80000 library and the FAS profile. The model is organized following the three main pillars of MBSE: ontology, viewpoints and views (Holt and Perry, 2008). The first package contains the MBSE ontology that defines the artifacts and their relationships used in this project. Moreover, it contains the profile diagram from the FAS method. The second package contains the viewpoints, which define the information that needs to be provided for each perspective (see section 9.2). Finally, the third package realizes the defined viewpoints using SysML diagrams, dependency matrices and relation maps. The structure of the views package follows the chronological development of a product through its life cycle. The package contains four packages: top-level, system specification, raw material extraction and transportation, similar to the processes defined in section 4.2.1.

The top-level package contain five packages that define all the requirements of this project, the context from the top-level, traceability relationship, the elements that are common to all life cycle stages, e.g., Item Flow such as CO_2-Emissions and the LCA analysis.

The system specification contains eight packages. The first defines the requirement tree for this stage and the second defines its context. The following three packages represent the functional, logical and physical architecture. The sixth package represents the traceability relationships between the artifacts of this life cycle stage. The seventh package specifies the BOM for the other life cycle stages and the last package performs analysis.

The raw material processing and the transportation packages are organized following the PPRF approach. The first package contains the context analysis, followed by the processes required to fulfill the requirements. Then, the resources needed to perform these processes are defined in the third package. Afterwards, the organization of the resources is described in the facility package. The last package contains the products created through the processes. The top-level context of the model is described in Figure 6.1.

5.2.2 Context of the Energy Module

The main use case of the System User regarding the Energy Module is to provide Electrical Power to operate ELSA autonomously (see Fig. 5.2). It includes the capability of the Energy Module to turn ELSA on and off. Moreover, it shall provide the required electrical power to the external modules that are part of ELSA. In order to operate autonomously, the Energy Module shall monitor the electrical power consumption and send a signal to the System User, when it needs to be recharged. For safety reasons, the Energy Module shall also cool the electronics down when temperature and humidity increase in order to protect the electronics. The External Module, the Main Module and the Environment play a role in the last three use cases. The External Module is the one that requests electrical power from the Energy Module. The Main Module sends the data collected from the Energy Module to the server. Finally, the Environment influences the Temperature and the Humidity of the Energy Module.

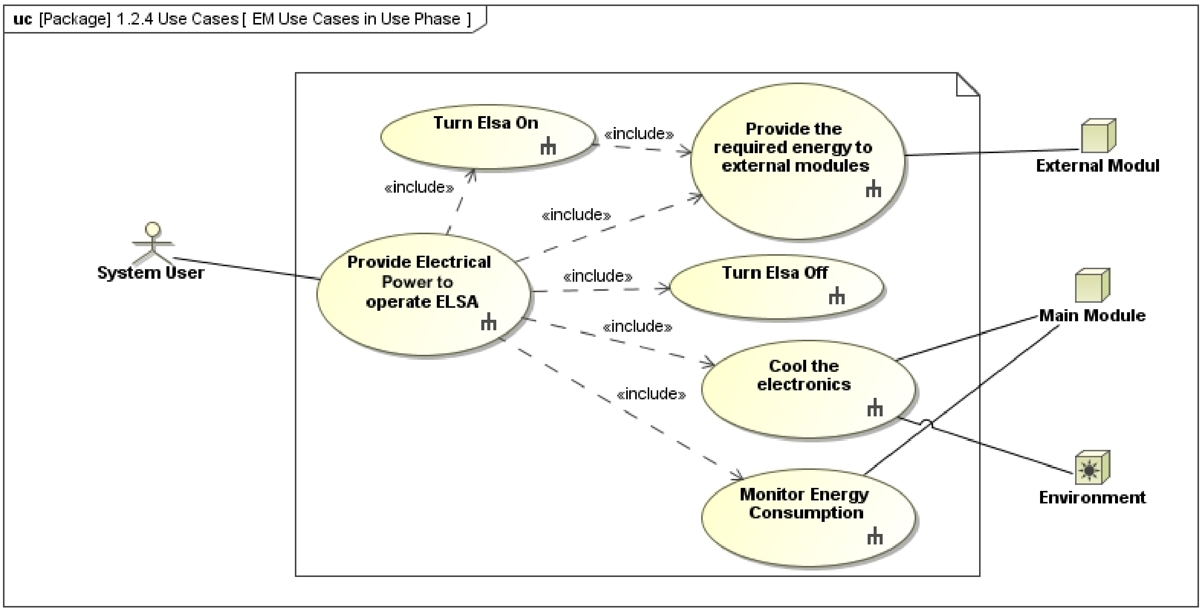


Figure 5.2: Use cases analysis of the Energy Module in the context of its usage

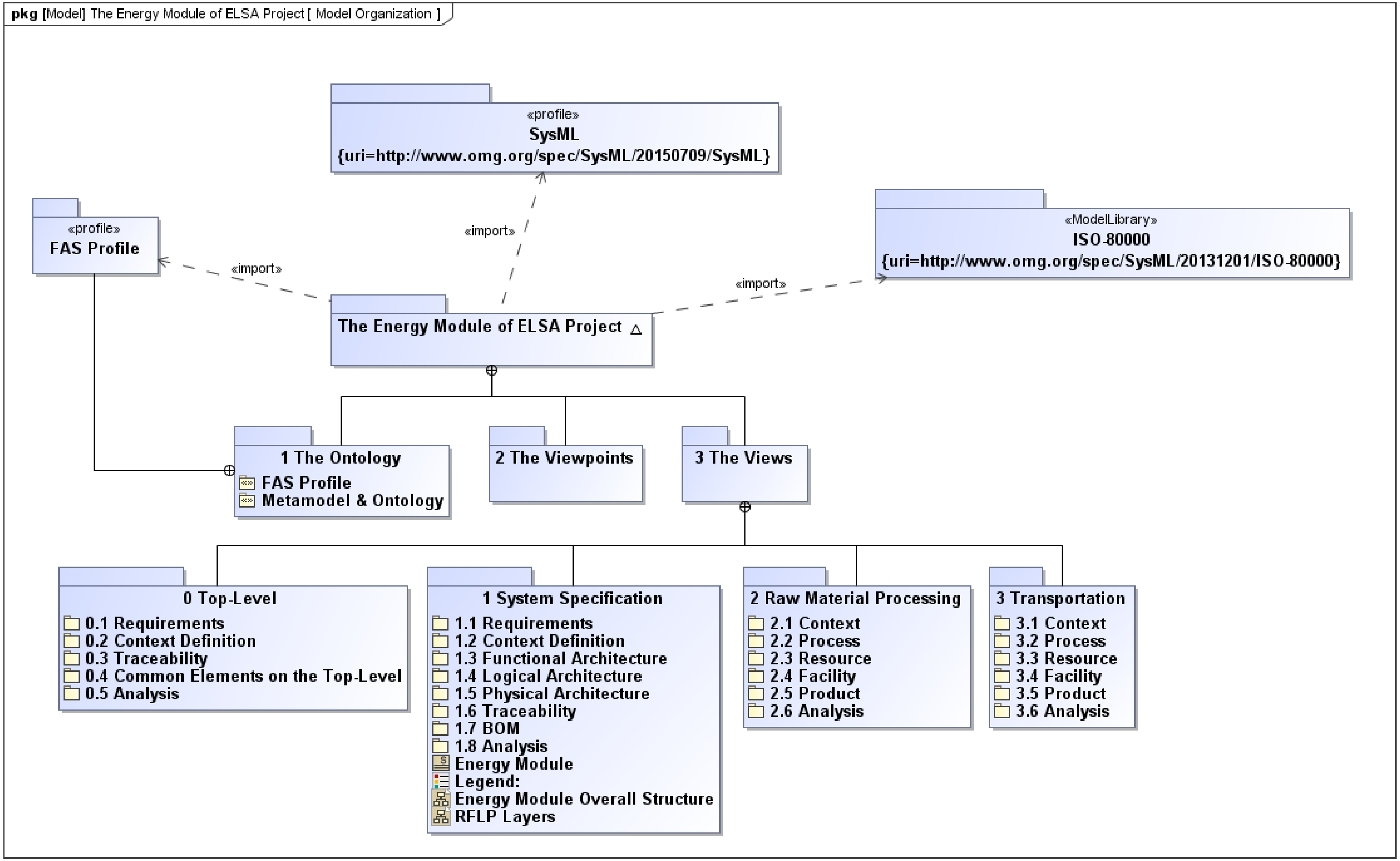


Figure 5.3: Structure of the model

Figure 5.4 shows the system environment of the Energy Module. The Energy Module is highlighted using the stereotype “system”. The latter is developed in the context of how ELSA is going to be used. This is notified by the stereotype “context”. The other blocks represent external systems that are part of ELSA but do not belong to the Energy Module. ELSA is made up of the Energy Module, the Main Module, the Network Switch and the rest of the modules are types of the External Module. Furthermore, ELSA in the use stage has an interface to the System User and the Environment that influence the Temperature and Humidity inside the system.

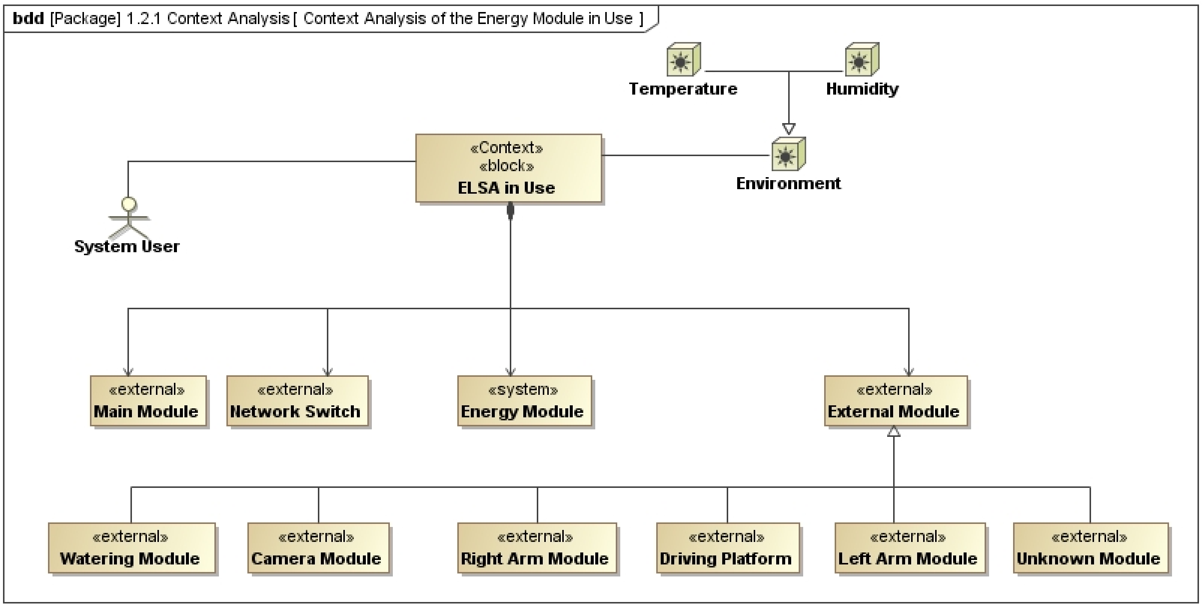


Figure 5.4: Context analysis of the Energy Module in the context of its usage

Figure 5.5 illustrates the turnover analysis of the Energy Module. In the turnover analysis, the input and output to the interfacing systems are specified. In this stage, the system of interest (SOI) is represented as a black box. A black box means that the SOI is analyzed without considering its internal structure. Figure 5.5 shows that the Energy Module has five main interfaces. The Environment and the Energy Module have a bidirectional exchange of air. The Environment transmits the Temperature and Humidity from the Environment to the Energy Module. Whereas, the computing power of the Energy Module can increase the Temperature and Humidity of the Environment. The System User sends a Control signal in order to manually turn ELSA on or off. The External Module requests Electrical Power from the Energy Module. The Energy Module sends Electrical Power to the Network Switch that transmits it further to the Modules. Finally, the Main Module receives and sends Data from/to the Energy Module.

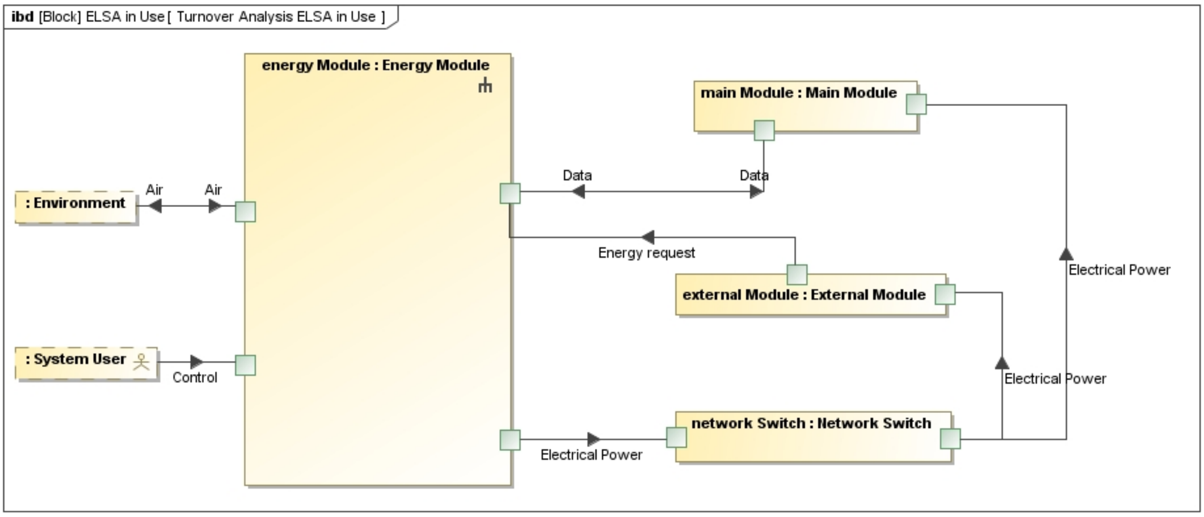


Figure 5.5: Turnover analysis of the Energy Module in the context of its usage

5.2.3 The RFLP Layers of the Energy Module

Figure 5.6 shows the RFLP layers of the Energy Module in a hierarchical form. The layers are shown respectively from the left to the right. The legend on the right side of the diagram shows the colors and their respective components. Each of the activities satisfies one or more requirements. The top-level activity of the Energy Module is to Provide Electrical Power to Operate ELSA. It is also the function to be studied in LCA. The top-level activity contains five functions: Cool the Electronics, Monitor Energy Consumption, Provide Electrical Power to ELSA Modules, Turn ELSA Off, Turn ELSA On. These activities are traced by the functional blocks from the FAS method. The functional blocks are then allocated to logical blocks, which are realized by physical blocks.

5.3 Lead-Acid Battery

The following components make up a lead-acid battery, which are housed in a plastic or ebonize box or case (see Fig. 5.7) (WHO, 2017). There are lead-based positive and negative terminals that give connection points to external devices. The plate separators are made of porous sheets of PVC or polyethylene plastic, glass microfiber, or phenolic resins that allow the free passage of ions in the electrolyte solution. The plate separators keep positive and negative plates separated. The positive plates are lead or lead alloy grids that have been coated with porous metallic lead paste, while the negative plates are lead grids that have been covered with lead dioxide paste. A battery element is made up of a series of negative and positive plates with separators. The battery elements are separated by plates made of the same material as the battery box. The elements are submerged in a sulfuric acid electrolyte solution that can be replenished via plugs. The electrolyte in sealed batteries is either a gel or poured into glass microfiber separators. Table 5.1 summarizes the components of a lead-acid battery, their quantity, percentage of mass, mass and material.

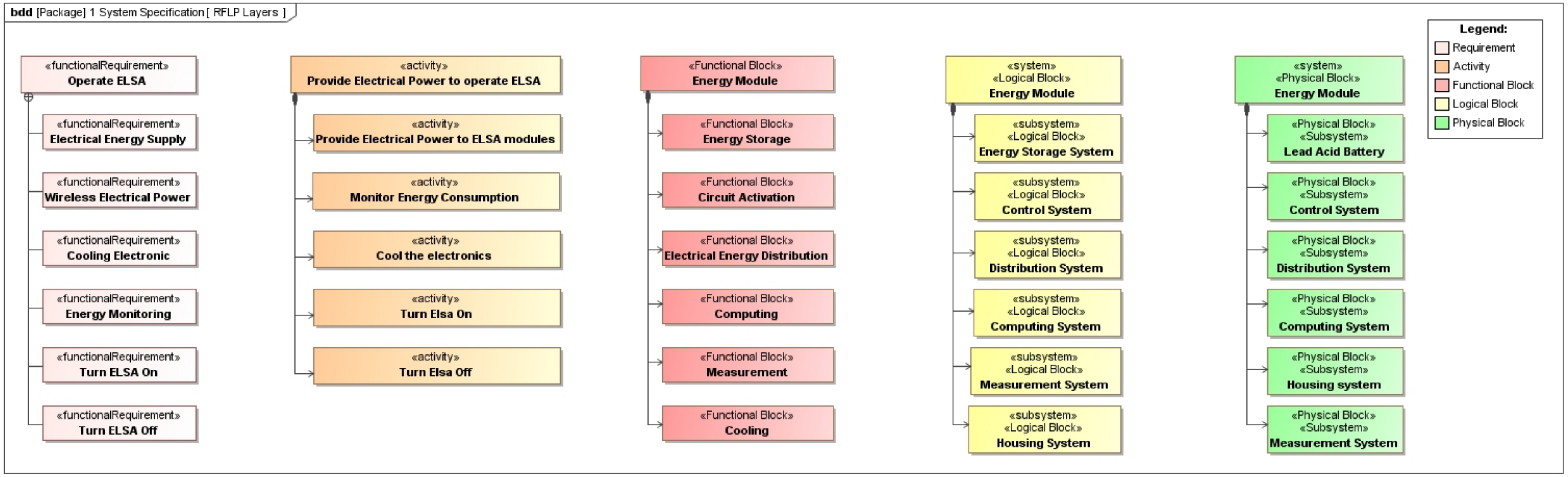


Figure 5.6: The RFLP layers of the Energy Module

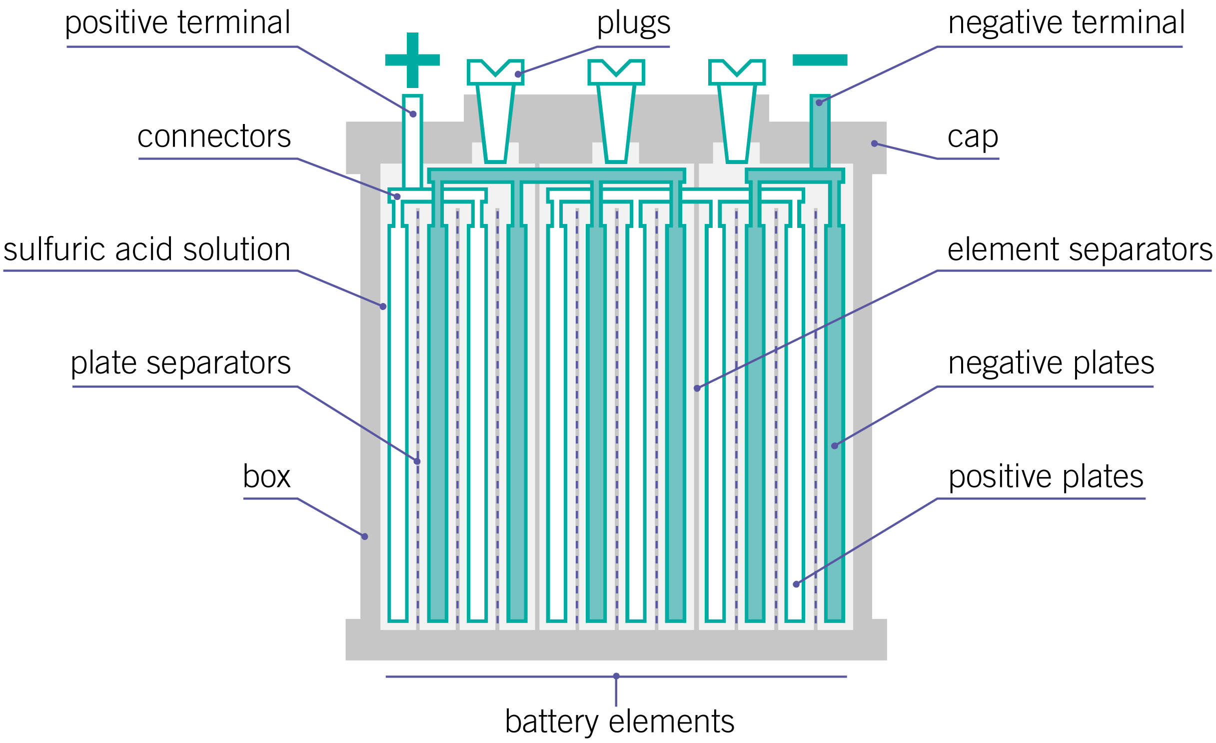


Figure 5.7: Lead acid battery (WHO, 2017)

Table 5.1: Material composition of lead acid battery by average percentage of mass

Part	Quantity	Mass [Kg]	Material
Box	1	0,3	Plastic/Ebonize
Pos/Neg Terminal	2	0,6	Lead
Plate separators	6	1,9	Fiberglass
Positive Plate	6	1,9	Lead or lead alloy coated with porous metallic lead paste
Negative Plate	6	1,9	Lead grids coated with lead dioxide paste
Electrolyte Solution	1	0,3	Sulfuric Acid
Water	1	0,3	Water (unsalted)
Total		31,5	

Figure 5.8 illustrates the processing steps of lead to lead parts, according to (Gao et al., 2021). To process lead into lead parts, first, the lead is melted, then molded through the moldboard casting process. After that, the molded parts are cooled off to produce the lead parts.

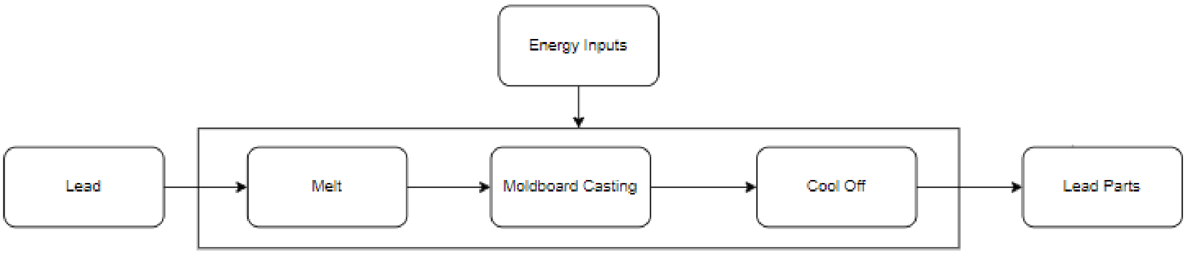


Figure 5.8: The processing steps of lead to lead parts

Chapter 6

The LCI Model of the Energy Module

This chapter presents the model developed in this LCI study. First, the goal and scope are defined. After that, the life cycle inventory of each life cycle stage is described. The interpretation stage is addressed in section 7.1. The model is developed using Cameo Systems Modeler version 19.0 Sp2. Cameo uses SysMl version 1.5. The SysML elements from the diagrams will be briefly addressed. Further information on the SysML elements can be found in the SysML specification (OMG, 2017), the practical SysML guide (Friedenthal et al., 2014) and the user manual of Cameo (No magic, 2022a).

6.1 Goal and Scope Definition of the Overall Study

Goal Definition

The goal of this study is to provide an MBSE methodology in order to perform a life cycle inventory analysis from cradle-to-grave of ELSA (see section 5.1) in early design stages. The MBSE methodology is chosen, because it is the most prevailing practice in developing complex systems. To achieve this goal and respect the time constraint of a master thesis, the CO_2 emissions of one component of ELSA's Energy Module are quantified using the ISO LCA standard integrated with an MBSE methodology. The goal of the study is not to assess the environmental impacts, but rather to define What to model, How to model it and demonstrate the How using a SysML-tool.

The reason behind this study is to support decision-making in early design stages, when incurred costs are low and design changes are easy (Honour, 2013). The integration of LCA and MBSE approaches allow the assessment of environmental impacts in parallel with product development activities. Supported by a SysML-tool, a traceability across the product life cycle can be achieved to identify the most environmentally harmful components in early design stages. Figure 1.1 highlights that changes in early design stages are easy and cheap. Therefore, investing time and effort in early design stages is certainly beneficial regarding costs and product quality. Early detection of defects will also increase the client's satisfaction. More details on induced defects and incurred reparation costs in product development can be found in section 1.1.

The study is intended for both sustainability and the MBSE community. It will be released publicly to promote the use of MBSE in solving problems regarding sustainability. The findings are especially beneficial for communities concerned about the development of environmentally friendly complex systems.

From these statements, one can understand all four of the ISO-required items of the goal statement. The intended application is to provide an MBSE methodology in order to perform a life cycle inventory analysis from cradle-to-grave of ELSA (see section 5.1) in early design stages. The reason is to support decision-making in early design stages, when changes are at their simplest and costs are their lowest. The audience is the community concerned with the development of environmentally friendly complex systems. Finally, the study will be released publicly.

Scope Definition

ISO requires 14 parameters to be qualitatively and quantitatively described for an LCA study to define its scope (see section 2.1.1.1). The allocation procedures, the LCIA Methodology, interpretation to be used, types of impacts, as well as the value choices and optional elements were not considered in this study, because they are outside of the scope. The rest of the parameters are presented in the following.

Product system and System Boundary

Figure 6.1 illustrates the context of the system of interest in terms of what is included in the study using a bdd. The top-level context is ELSA in the Life Cycle. It represents what needs to be studied in this work. The goal of this work is to provide an MBSE methodology in order to perform a life cycle inventory analysis from cradle-to-grave. To fulfill this need, the life cycle stages: development, transportation, raw material processing and use are analyzed. This is expressed using the composition relationship. The four blocks become parts of the top-level context, which will allow the specification of the material flow between the life cycle stages, as it will later be shown in Fig. 6.2. These four life cycle stages are representative for the modelling of all life cycle stages from cradle-to-grave, as already explained in chapter 4. This study considers only two external systems: the Environment to which CO_2 gases are emitted and the Energy Supplier, who supplies the whole life cycle with energy.

Using the encapsulation relationship from Cameo, one can model an ibd inside of the top-level context block to specify the internal structure between the life cycle stages. Figure 6.2 illustrates the product system of ELSA using an internal block diagram (ibd). The yellow blocks or the part properties illustrate the unit processes. In this case, they represent the unit processes at the life cycle level, or in other word, at the top-level. They describe the four life cycle stages addressed in this study. The unit processes of each life cycle stage will be shown later in the respective section. The green squares are called proxy ports, they are a type of ports in SysML. Ports and flows are used in SysML to clearly define the connection and interaction between SysML blocks (OMG, 2017, p75). One can notice that there are ports on the part properties and also

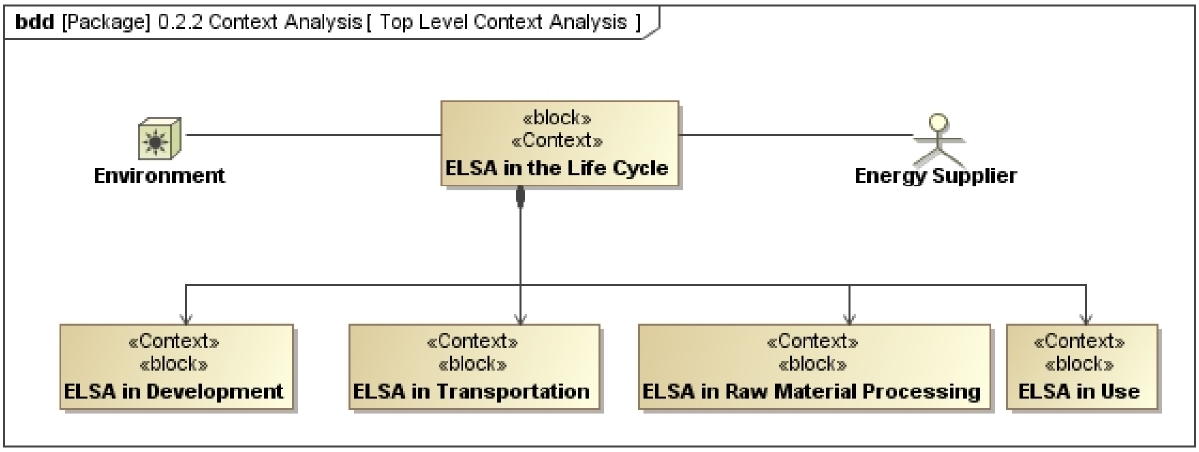


Figure 6.1: Top-level context analysis

on the big rectangle. The big rectangle represents the frame of the diagram. The ports on the frame of the diagram describe interfaces to external systems. In this case, they are interfaces to the Environment and Energy Supplier. The black colored triangle illustrates the flow direction between the blocks. The direction of the flow shows if it is an input or an output.

The diagram can be read as follows: the Energy Supplier supplies Electrical Power as an input to all four life cycle stages. The Development stage sends Bill of Materials to the Raw Material Processing. Additionally, the Raw Material Processing receives Raw Materials from Transportation stage and sends Processed Raw Materials to it. After that, the Transportation stage delivers the final product, ELSA, to the User. Finally, all four life cycle stages emit CO_2-Emissions to the environment.

In summary, Fig. 6.2 and Fig.6.1 define the product system and system boundary of this work. The scope includes four life cycle stages: development, raw material processing, transportation and use. These life cycle stages receive electrical power from the Energy Supplier and emit CO_2 to the Environment. The Energy Supplier and the Environment are considered outside of the system boundary.

Functions of the product system and Functional Unit

The functions of the Energy Module that were presented in Fig. 5.6. Figure 6.3 shows the development of the functional unit and reference flow, using the same analogy from the ISO LCA example illustrated in Fig. 2.5. The figure shows the five elements: product, function, functional unit, performance of the product and the reference flow. The product of interest is the Energy Module. The function to be analyzed is Provide Electrical Power to Operate ELSA, which is also the main function of the Energy Module. The functional unit is 1 kWh of electrical power provided in a lifetime of a battery. The performance of the battery is assumed to be 1 kWh/charge cycle and 300 charge cycles in a lifetime. This is expressed as a Performance Requirement of the Lead-Acid Battery in the model. Consequently, the reference flow is 1/300 of Lead-Acid Battery lifetime or one charge cycle of the battery.

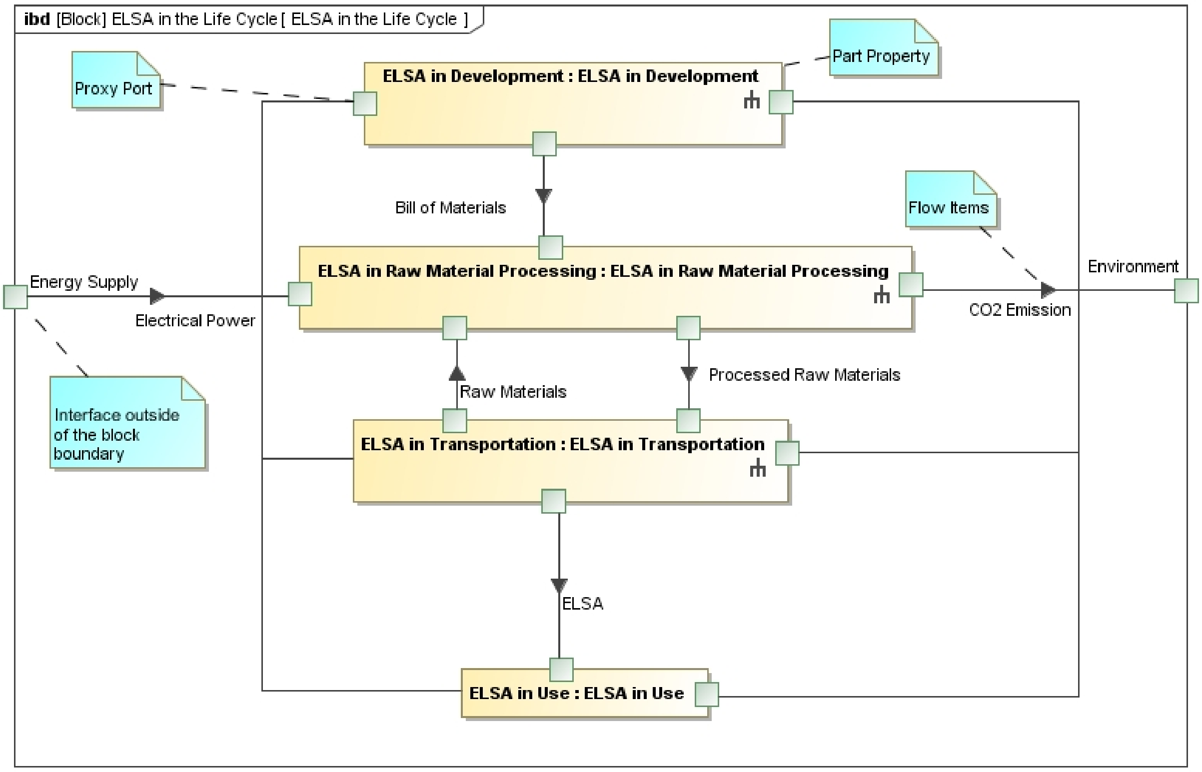


Figure 6.2: Product system of the energy module

Assumptions

The following assumptions are met in the study:

1. The source of the electrical power is coal. The specific carbon dioxide emissions of coal was calculated from (Quaschning, 2022)
2. The source of energy for transportation is gasoline. The specific carbon dioxide emissions of gasoline was calculated from (Quaschning, 2022)
3. The system is assumed to be ideal, therefore, energy losses in the system will not be considered
4. The performance of the battery is assumed to be 1 kWh/charge cycle and 300 charge cycles in a lifetime

Limitations

The results from the LCI study cannot provide any statement on the environmental impacts of the system under study, because the system boundary is compromised. LCA requires the same level of abstraction along the life cycle when willing to provide a statement regarding the environmental impacts of a product. Whereas, the level of abstraction in this study is narrowed from one life cycle stage to another in order to include all relevant life cycle stages from cradle-to-grave. Keeping the same level of abstraction along the life cycle would require more time than a master thesis allows. Therefore, this study provides only a methodology to

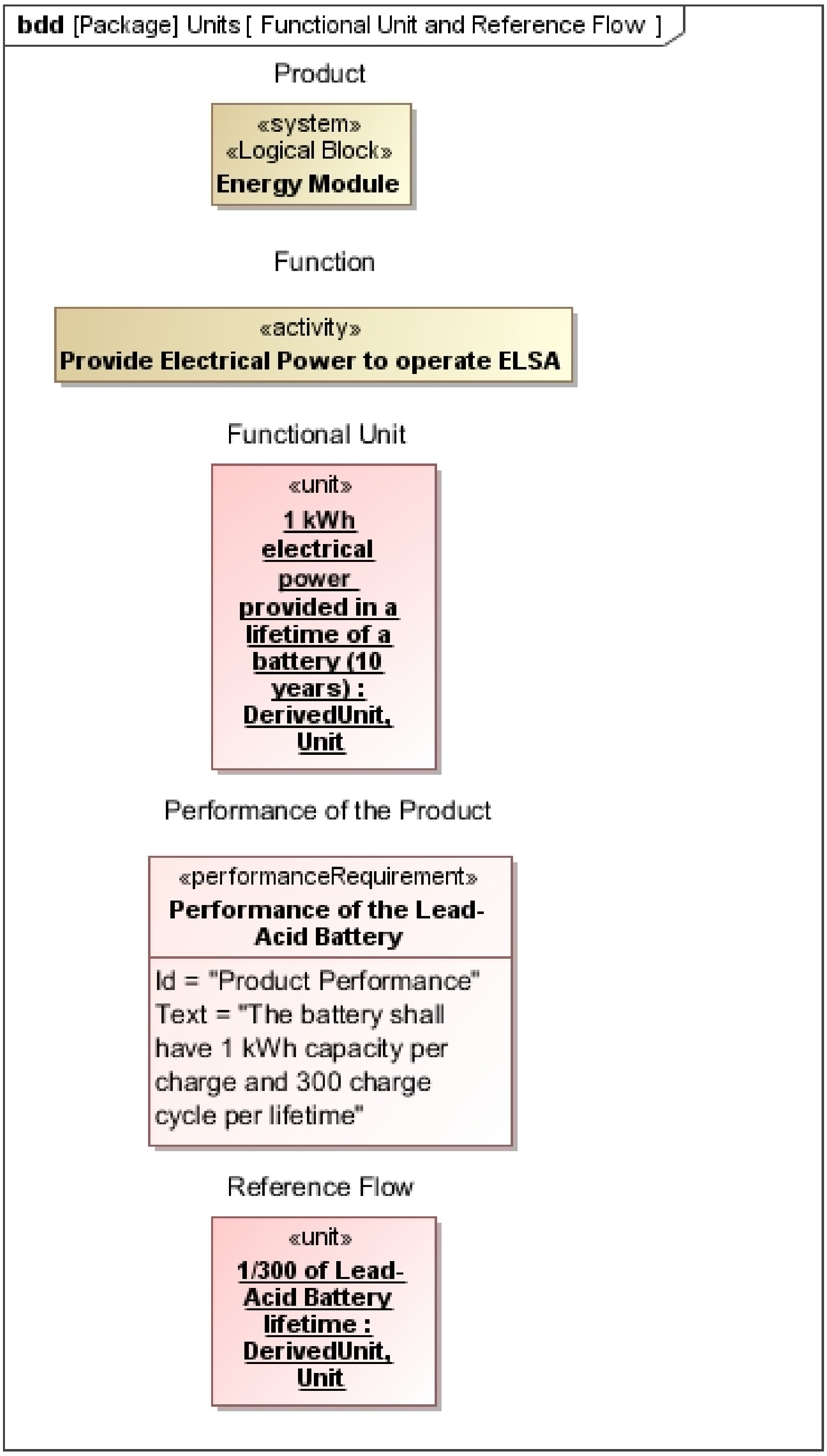


Figure 6.3: Developing the functional unit and reference flow of the energy module

perform a model-based LCA from cradle-to-grave and does not provide any statement on the environmental impacts of the product under study.

Data and Data Quality Requirements

ISO LCA standard defines ten requirements on data: 1) time-related coverage, 2) geographical coverage, 3) technology coverage, 4) precision, 5) completeness, 6) representativeness, 7) consistency, 8) reproducibility, 9) sources of the data and 10) uncertainty of the information. This study does not consider strict and rigorous requirements on data, since it will not provide any statement on the environmental impacts of the system under study, but rather a methodology to perform a model-based LCA. Therefore, only the requirements 7, 8 and 10 are considered relevant for this study. Furthermore, data from this study is based on assumptions or approximations from secondary data. However, the source of the data and methods of calculation shall be clear and transparent to ensure reproducibility of the findings.

Type of Critical Review

The ISO LCA standard mentions three important considerations regarding the critical review: 1) necessity of a critical review, 2) the type of critical review needed, 3) who conducts the review and their level of expertise. In this work, a critical review is not necessary, however, it is desirable to verify the developed methodology. In other words, it can support answering the question, "Is the methodology developed right?" The review is performed by internal colleagues and supervisors from research center IPK. The reviewers have an expertise in product development and a range from entry-level to intermediate experience with LCA. Moreover, they are well acquainted with the scientific method.

Type and Format of the Report Required for the Study

This master thesis represents the format of the required report.

6.2 LCI Context of the Life Cycle Stages

6.2.1 LCI Context of the System Specification Stage

The use case of the System Developer in the system specification stage is to develop the Energy Module in order to function as intended (see Fig. 6.4). The context, ELSA in Development, contains the System Development Facility, which in its turn contains the Developer Office (see Fig. 6.5). There are two interfaces: 1) the Energy supplier that supplies this life cycle stage with Electrical Power; 2) The Environment to which the CO_2-Emissions are emitted (see Fig. 6.6). Accordingly, inside of the System Development Facility, there is the Developer Office that is supplied with Electrical Power and emits CO_2-Emissions through the working hours.

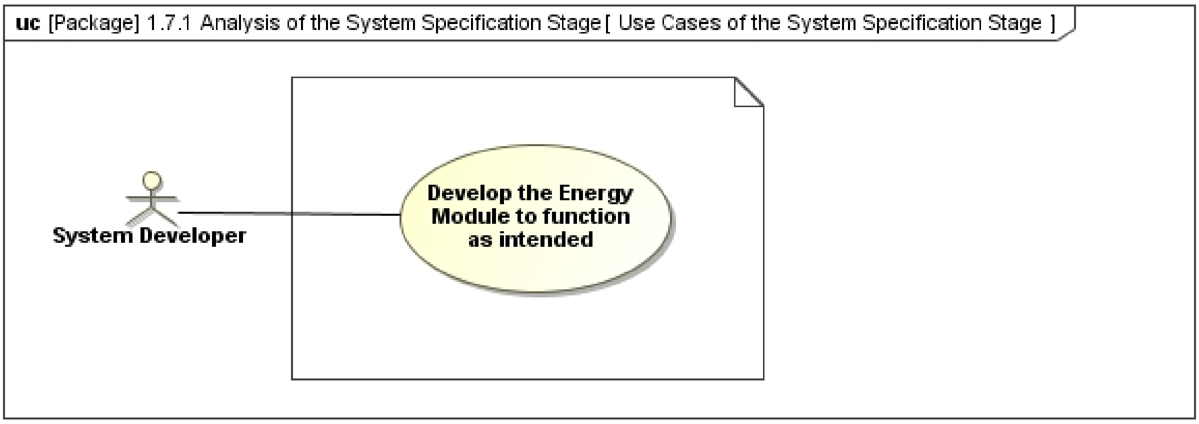


Figure 6.4: Use cases analysis of the Energy Module in the context of the System Specification Stage

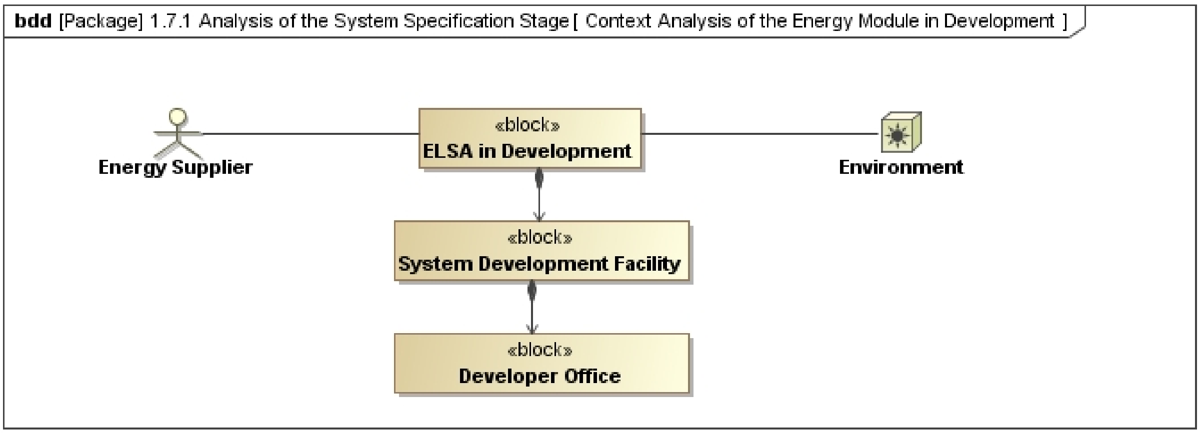


Figure 6.5: Context analysis of the Energy Module in the System Specification Stage

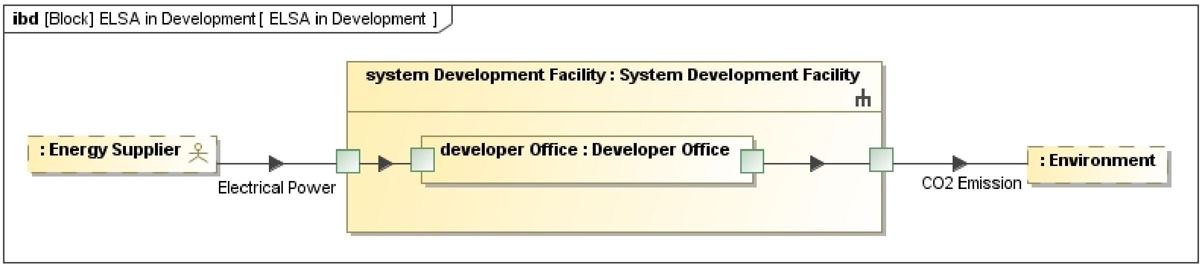


Figure 6.6: Turnover analysis of the Energy Module in the System Specification Stage

6.2.2 LCI Context of the Use Stage

In the context of the usage of ELSA, five use cases are considered. Autonomous Operation is the main use case of ELSA. It includes Guest Support, Plant Watering, Schedule Management and Autonomous Movement and Path Finding.

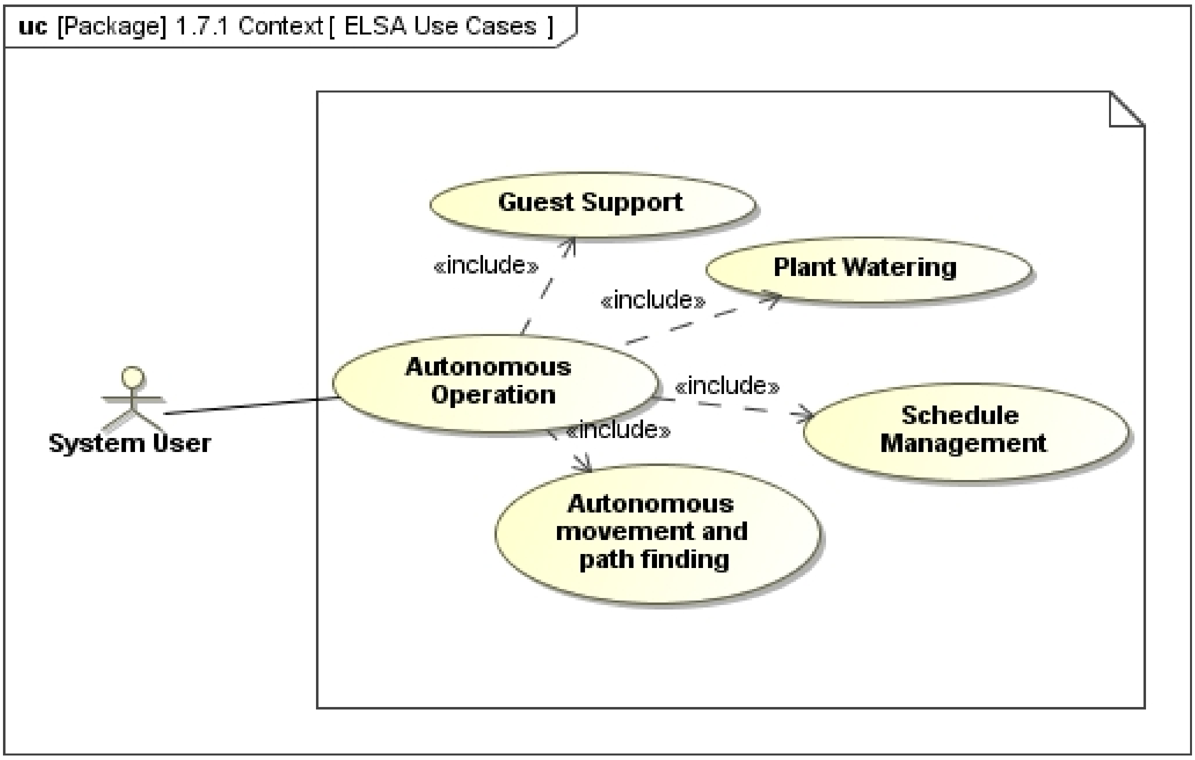


Figure 6.7: Concept of operation analysis of the Energy Module in the context of its usage

6.2.3 LCI Context of the Raw Material Processing Stage

In the raw material processing stage, the Raw Material Processor is the main Stakeholder. His use case is to Process Lead into Lead Parts (see Fig. 6.8). Furthermore, the Energy Supplier, the System Transporter and the Environment are considered to be interfacing with the raw material processing system (see Fig. 6.9). The Raw Material Processing contains its facility. Figure 6.10 shows the turnover analysis or the so-called product system for the raw material stage. The Raw Material Processor sends processing Tasks to the facility. The System Transporter delivers Lead to the facility and gets Lead Part from it. The Energy Supplier supplies the facility with the Electrical Power. Finally, the facility emits CO_2-Emission to the Environment.

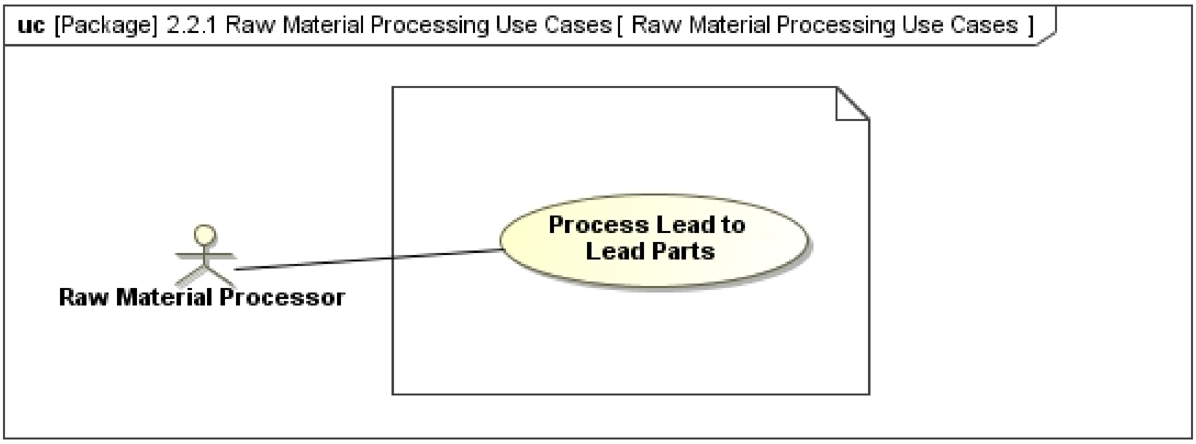


Figure 6.8: Use cases analysis of the Energy Module in the context of raw material processing

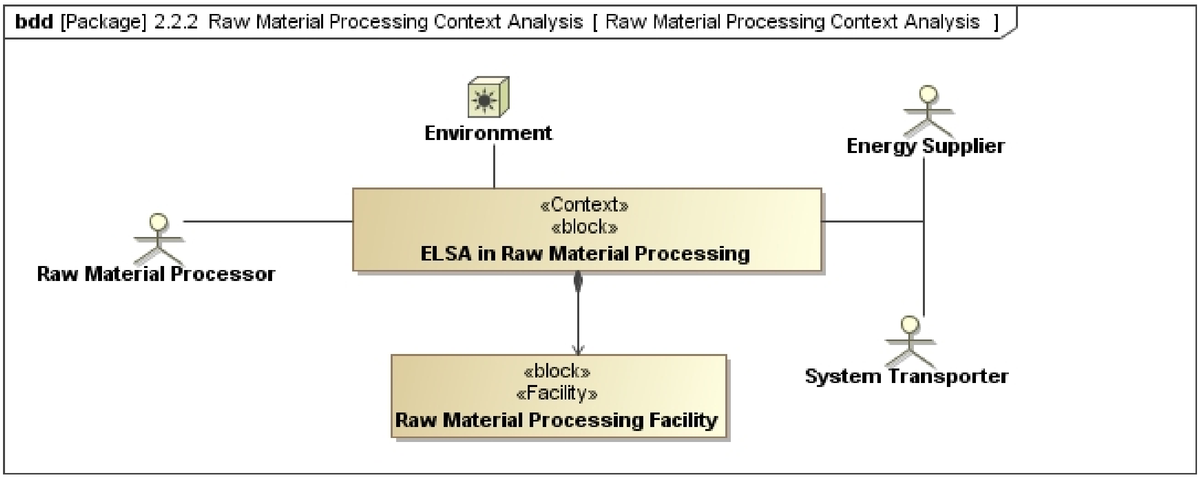


Figure 6.9: Context analysis of the Energy Module in the context of raw material processing

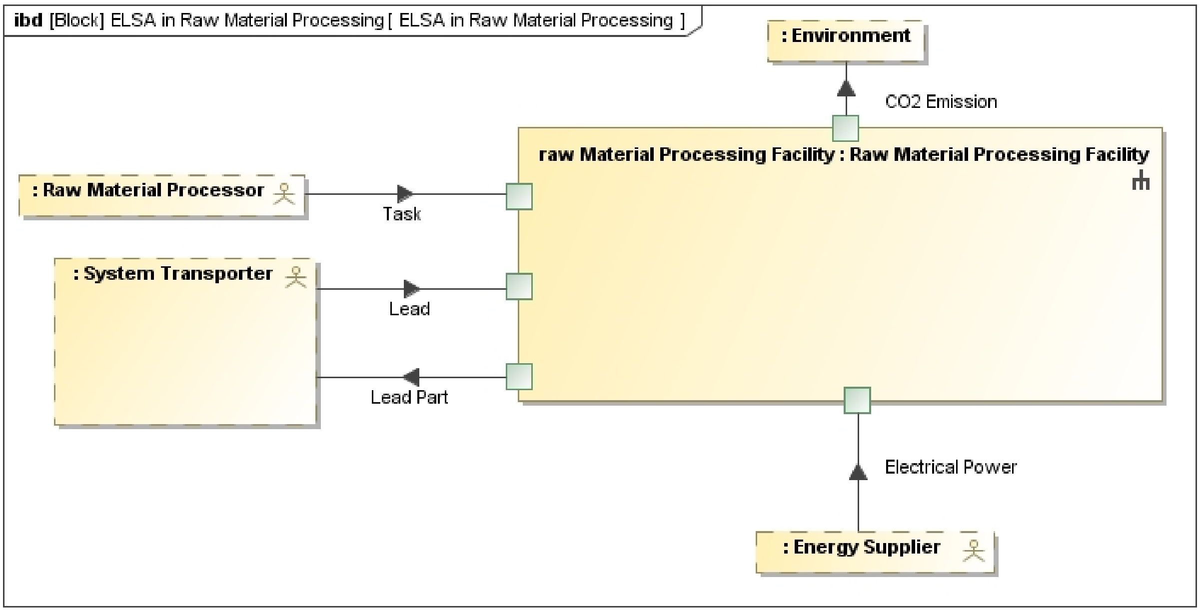


Figure 6.10: Turnover analysis of the Energy Module in the context of raw material processing

Figure 6.11 shows the product system inside the raw material processing facility. The figure contains three part properties: MeltLead, MoldBoardCasting and CoolOff. The three part properties reflect the active resources, or the machines required to process lead into lead part (see section 5.3). The MeltLead receives Lead as an input from the System Transporter and produces Melted Lead. The Melted Lead is transformed into Molded Lead by the MoldBoardCasting. Finally, the Molded Lead is cooled down, which results into Lead Part that is sent to the System Transporter. The three machines receive Electrical Power from the Energy Supplier and transmit CO_2-Emission to the Environment.

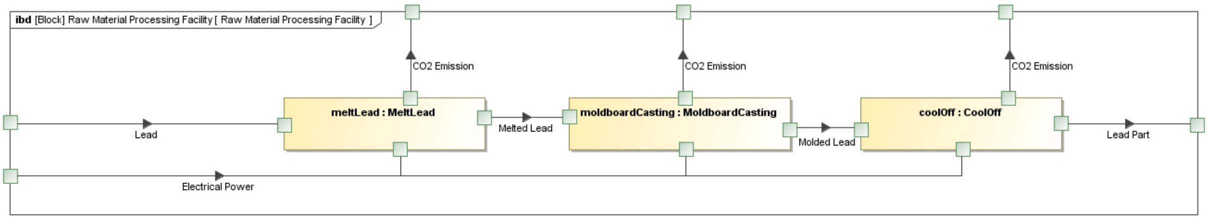


Figure 6.11: Product system of the raw material processing facility

6.2.4 LCI Context of the Transportation Stage

Figure 6.12 shows the three use cases of the transportation stage. First, the System Transporter transports raw materials to the raw material processing facility. After that, The manufactured ELSA is shipped from the Manufacturer to the System User. Once the useful life of ELSA is over, the System Transporter sends it to the System Disposer.

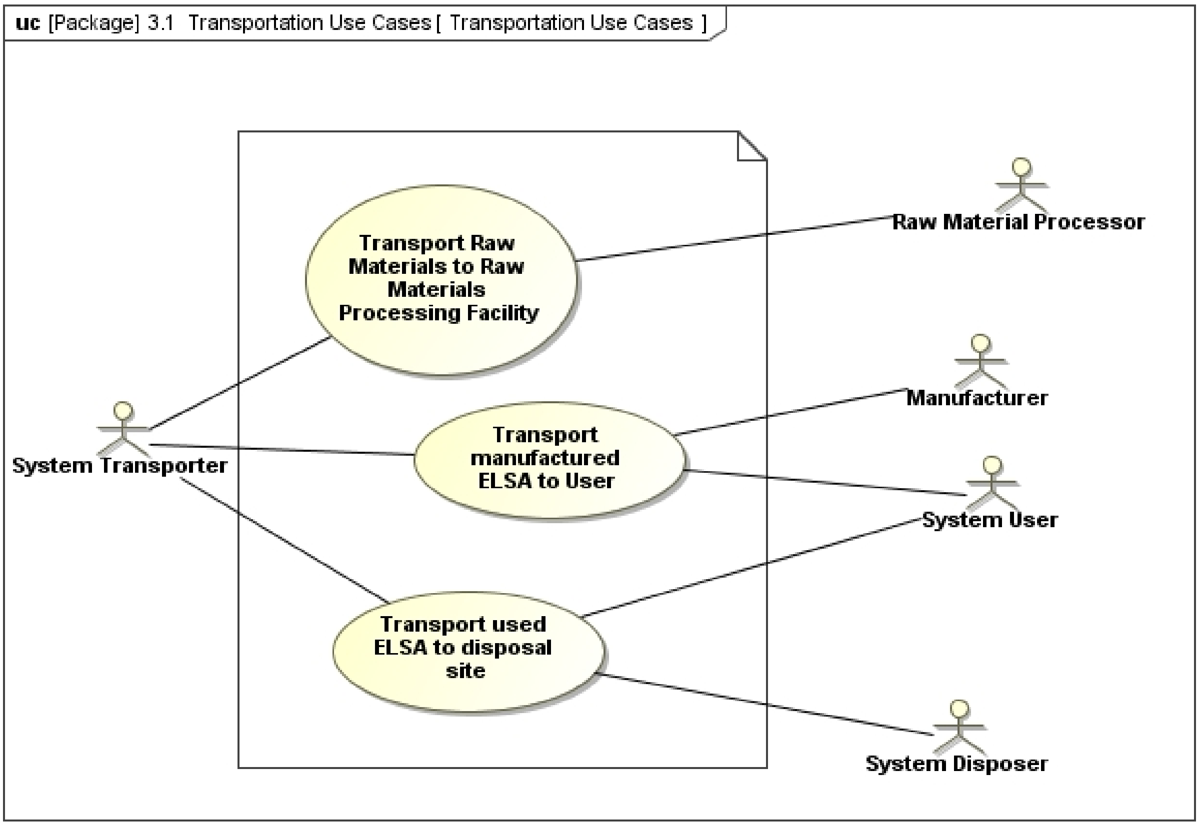


Figure 6.12: Use cases analysis of the Energy Module in the context of transportation

The context of ELSA in Transportation contains the Transportation Network. In its turn, it contains Raw Material Site, Raw Material Processing Facility, Manufacturing Facility, User Home and Disposal Site (see Fig. 6.13). The Truck and the Ship are active resources inside of the Transportation Network. Furthermore, The context of ELSA in Transportation has an interface with the Energy Supplier and the Environment. The Energy Supplier supplies the Transportation Network with Gasoline and the Transportation Network emits CO_2 to the

Environment (see Fig. 6.14).

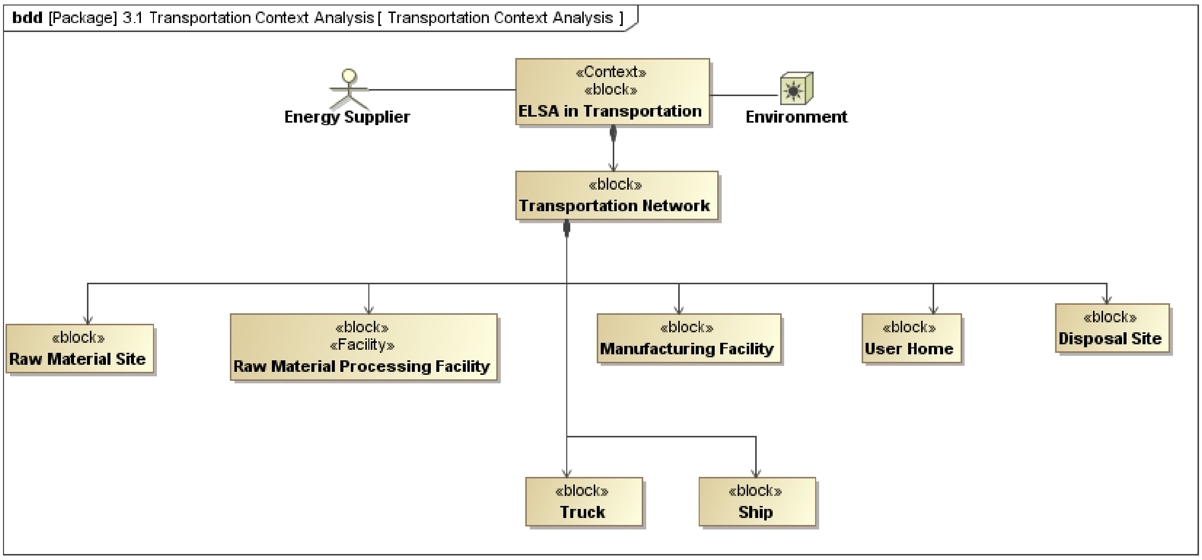


Figure 6.13: Context analysis of the Energy Module in the context of transportation

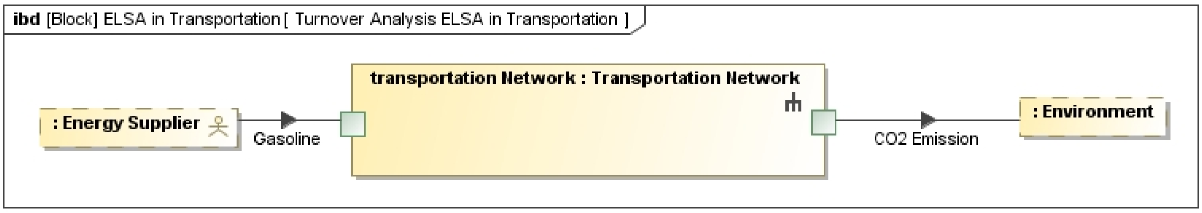


Figure 6.14: Turnover analysis of the Energy Module in the context of transportation

Figure 6.15 shows the product system inside the Transportation Network. The diagram contains seven part properties of the Transportation Network (see Fig. 6.14). The Truck is the main means of transport. For each life cycle stage, it delivers the input required and transports the output to the next life cycle stage. To illustrate the case of an intercontinental transportation, it was assumed that ELSA is manufactured in China and delivered to the System User in Germany by a Ship. Both the Truck and the Ship are supplied with Gasoline from the Energy Supplier. They are the only one that transmit CO_2 in the transportation stage. The CO_2-Emissions of the facilities were omitted from this diagram for a better readability. Their CO_2-Emissions are considered in their respective life cycle stage.

6.3 Life Cycle Inventory Analysis

As already mentioned, in Fig. 4.7, all the steps from the LCI analysis required from the ISO LCA standard are performed externally in an Excel Table. This section describes the activities from Fig. 4.7 starting from “Create a bdd to define the context of the analysis”. The Excel table can be found in Fig. 9.13 and 9.14.

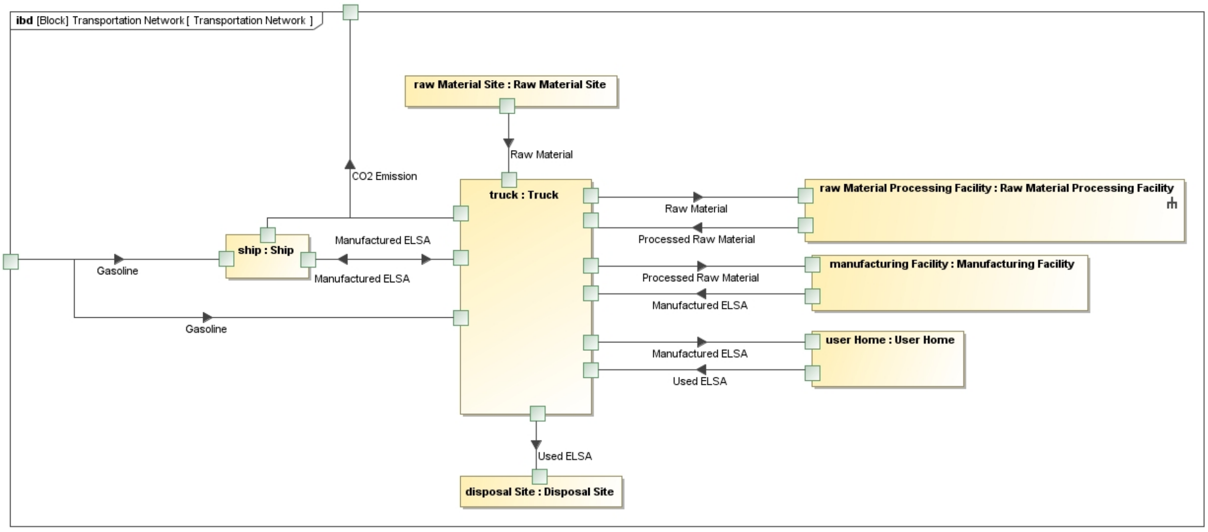


Figure 6.15: Product system of the transportation network

For a model-based LCI analysis, first, the context of the analysis is build on a bdd, as shown in Fig. 6.16. The figure illustrates the context of the LCI analysis for the system specification stage. In the bdd, a block is defined as “System Specification Context analysis” in which the analysis will be performed. This is mandatory because only blocks can own constraint blocks. The defined block can be filled with the necessary value properties that need to be calculated for the life cycle stage. In this case, CO_2 Emission is defined as a value property. This value property aggregates the CO2 Emissions of the system specification life stage. Also, it will be used as an input to the top-level (see Fig. 4.7). Aside from that, the bdd contains the unit processes that are relevant for the analysis. They are connected with the context block using composition relationship. This is important because in a par diagram, Cameo considers only the elements that have a relation to the context block.

The activity Develop System represents the unit process of the system specification stage. The process receives electrical power as input and outputs CO_2-Emissions. Correspondingly, two value properties were defined for this unit process. The unit of the value properties were chosen to be the functional unit, since all the calculation was already made in the Excel table (see Fig. 9.13). To represent the resources of the office, the CO_2-Emission of the desk and the computer were considered.

Once the inventory elements are specified, the constraint block that contains the mathematical equations and the units are defined. As an example, the total CO_2-Emissions are calculated as the sum of the single CO_2-Emissions.

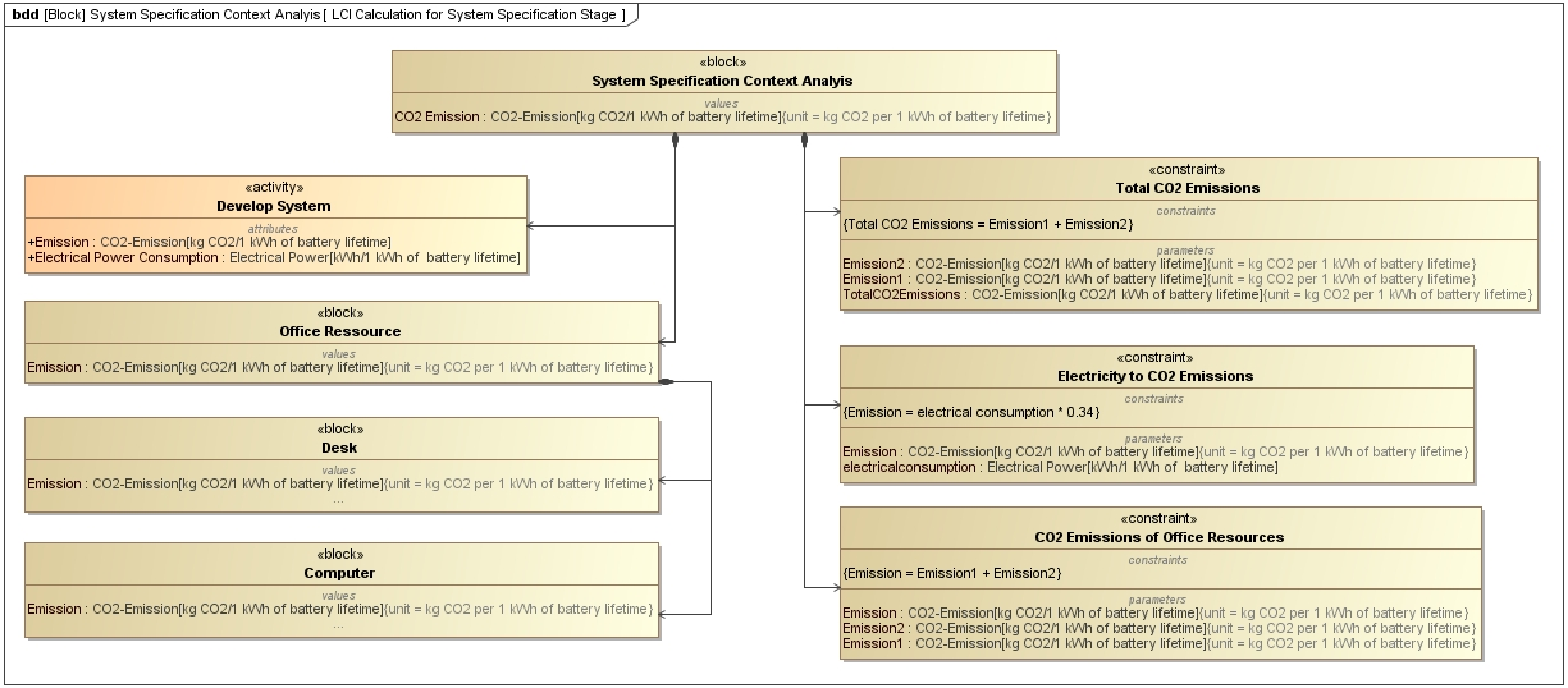


Figure 6.16: Context of the Analysis of the System Specification Stage

The unit process, their properties and the constraint blocks are defined. Then, a parametric diagram is created in order to map the components and perform the calculation (see Fig. 6.17). The blue blocks represent the constraint blocks. The mapping of the parameters can be automated using the parametric equation wizard from Cameo (No magic, 2022b). In order to use it, one has to drag the constraint block from the containment tree to the diagram. A window will open in which the properties from the equations and the properties from the context block are listed. To map between the properties, one should click on the property of the left side and drag it to the corresponding one on the right side. By clicking finish, the mapping and structuring of the diagram is automatically done. The modelling of the other life cycle stages: raw material processing, use and transportation is done in a similar manner (see section 9.4).

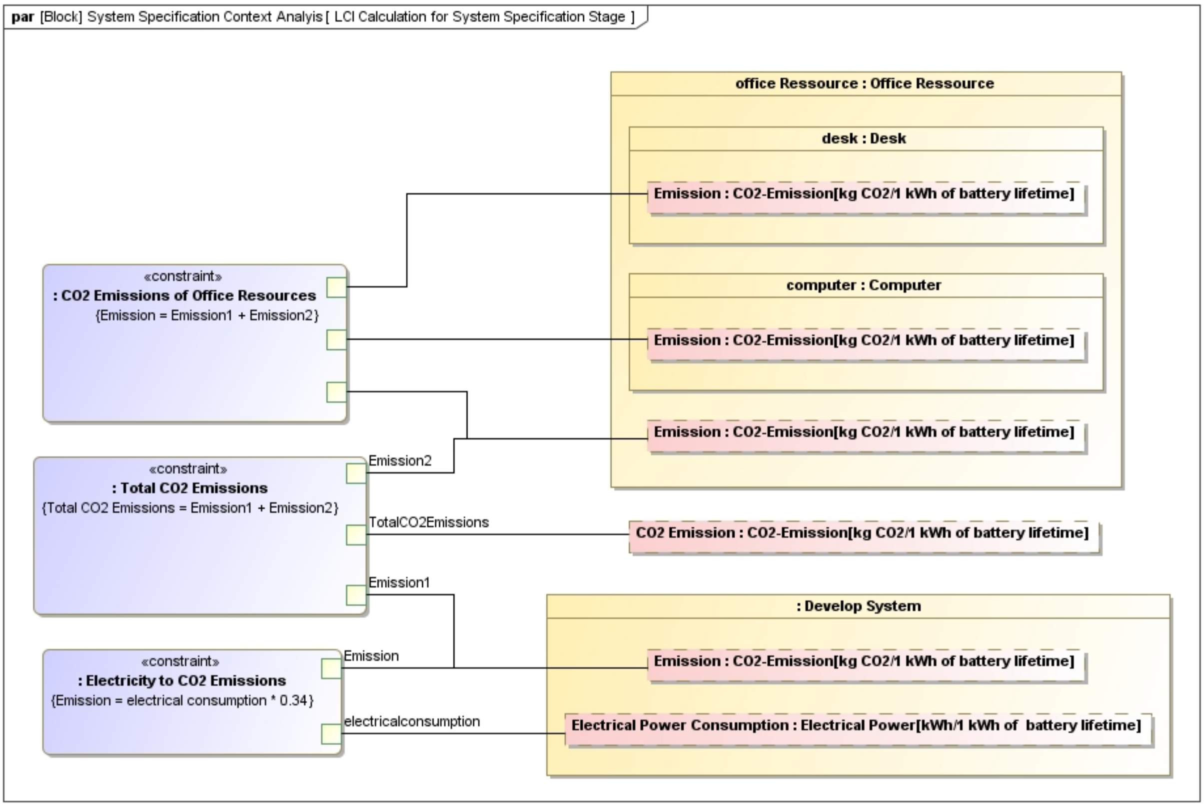


Figure 6.17: Calculation of the CO_2-Emissions in the System Specification Stage

6.4 Achieving Traceability Along the Product Life Cycle

Traceability along the product life cycle was achieved using the scheme shown in Fig. 6.18. In order to establish successful traceability, relationships shall be specified at every stage of the RFLP layers between all the relevant elements of the model. The requirements from each layer drive the development in the product life cycle and bind between the components of each layer. Moreover, the traceability relationships shall follow the same direction, from the effect to the cause.

Figure 6.18 illustrates the traceability relationships along the life cycle of the Energy Module. Horizontally, the figure is separated regarding the life cycle stages: system specification, raw material processing and transport. The elements of the use stage, such as use cases, functions, activities, are already considered in the system specification stage. Vertically, the diagram is grouped with regard to the RFLP layers. The yellow and blue rectangles express respectively what is performed in each life cycle stage and each of the RFLP layers.

Every project or developed system starts with stakeholders that express the need for a specific system. Therefore, stakeholders are represented with the actor symbol as the first element in the diagram. These stakeholders express needs that are mostly non-technical. These are then translated into technical requirements or the so-called top-level requirements.

From the top-level requirements, the functional and context requirements are derived. The context analysis identifies actors and external systems that are interacting with the system of interest. The turnover analysis refines the context and identifies interfaces and item flows of the system.

On this basis, the functional requirements are refined by use cases, which in turn are described by activities. The activities are then arranged using the FAS method into functional groups that become in a later stage functional blocks. This marks the end of the F-level.

At the start of the L-level, the functional blocks initiate the capturing of the system requirements. All requirement activities belong to the R-layer. However, developing requirements of a specific layer requires information from the previous one. In this case, the functional blocks are necessary in order to define the system requirements. The logical blocks allocate functional blocks and satisfy the system requirements. This marks the end of the L-level. Similarly, in the P-level, the physical requirements are defined and satisfied by the physical blocks. This whole process represents the traceability of the system specification stage.

The production stages have the same traceability pattern. Therefore, Fig. 6.18 illustrates only the raw material processing stages. The raw material processing stage starts with the BOM that is derived from the physical requirements and trace the physical blocks. Each part of the BOM requires a process to produce it. Therefore, process requirements are formulated.

The requirements are further refined using use case, context and turnover analysis. The use cases are described using the processes. Each process requires a resource that gets processed through it and one that executes it. At the start of the L-layer, the resource requirements are defined, which are then satisfied by the resource. Similarly, in the P-layer, the resources are organized in a facility. Therefore, facility requirements are defined, which in turn are satisfied by the facility.

This represents the traceability relationships throughout the life cycle of the Energy Module. Using this scheme, one can trace from a facility component to the stakeholder need. For feasibility, Fig. 6.18 illustrates only the most relevant relationships in a top-down approach to visualize the flow of traceability throughout the life cycle. Therefore, certain components and relationships were omitted. A transversal traceability between the layers and the life cycle stages has not been considered in this work. This could be studied in future research.

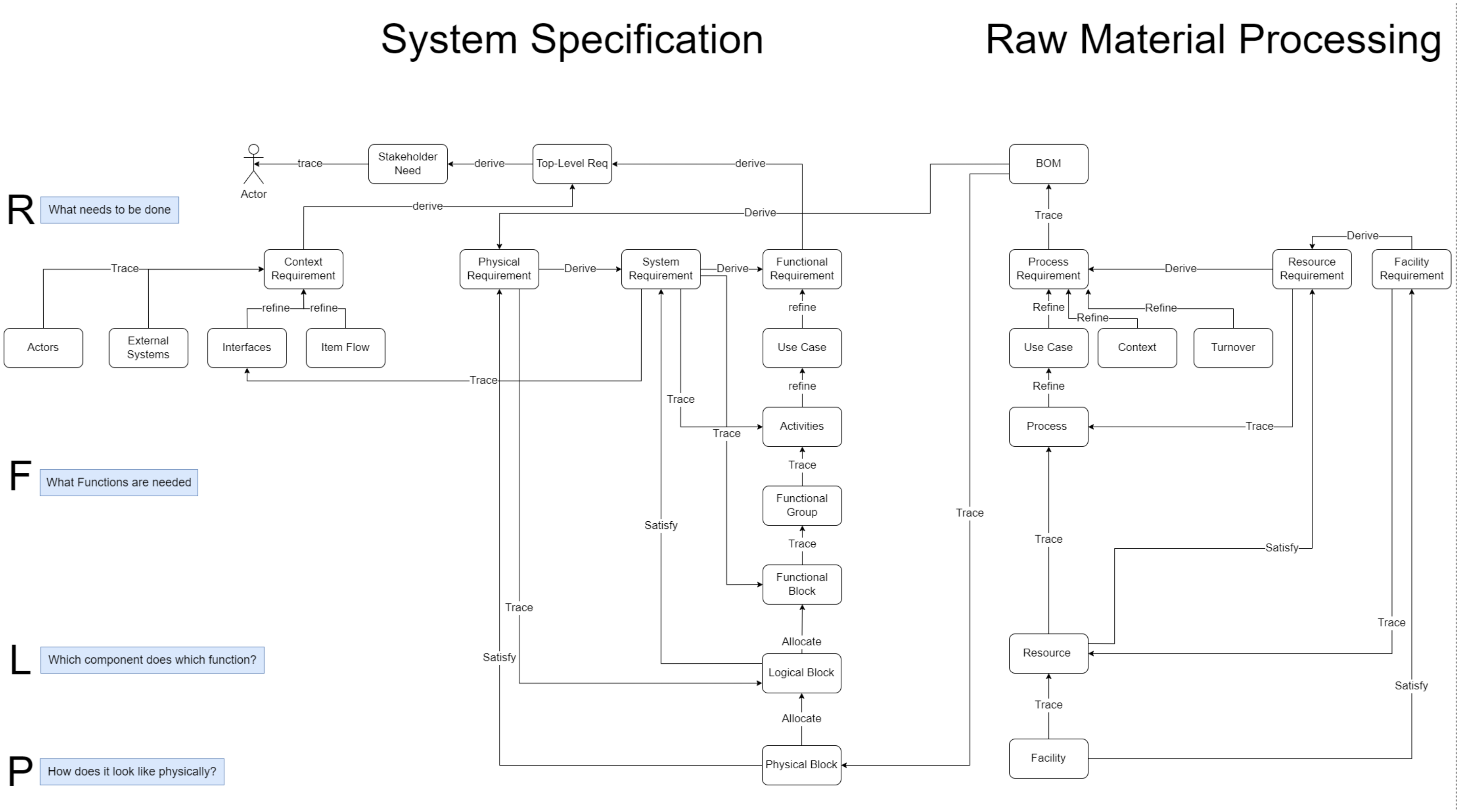


Figure 6.18: Traceability relationships along the model of the Energy Module

Chapter 7

Evaluation of the Developed Methodology

7.1 Interpretation of the Results

The goal of this work is to develop an MBSE methodology that supports the assessment of CO_2-Emissions from cradle-to-grave in early design stage. The methodology shall define What needs to be done, HOW to do it and demonstrate the HOWs using a tool. The results from this work do not offer any statement on the sustainability of the product. As already mentioned, the scope of the analysis was compromised from one life cycle stage to another (see Fig. 5.1). Therefore, one cannot compare between the emissions of the life cycle stages.

The aim of this section is to show the capabilities of applying the developed methodology and how it can support engineers in their development activities. Figure 7.1 illustrates the CO_2-Emissions resulting from each life cycle stage of the Energy Module. Section 9.3 described the calculation of the LCI. The life cycle stages: system specification, use, raw material processing and transport were considered representative for cradle-to-grave (see chapter 4). A total amount of 4.3045 kg CO_2 was emitted. The use stage is the most CO_2 emitting stage with 3.79 kg CO_2-equivalent to 88% of the total emissions. Followed by the transport stage with 0.2951 kg CO_2, then the system specification stage 0.2188 kg CO_2 and finally the raw material processing stage 0.0006 kg CO_2.

One could for example decide to further investigate the transportation stage. The results from the par diagram (see Fig. 9.21) deliver the CO_2-Emissions of the transportation stages (see Fig. 7.2). The transport of manufactured ELSA intercontinentally to the User (from China to Germany) is the highest calculated emission, with 0.14 kg CO_2. It is followed by the transport of processed raw materials to manufacturing facility, with around 0.07 kg CO_2-Emissions. Finally, both the transport of raw materials to raw material processing facility and transport of used ELSA to the disposal site emit around 0.04 kg CO_2.

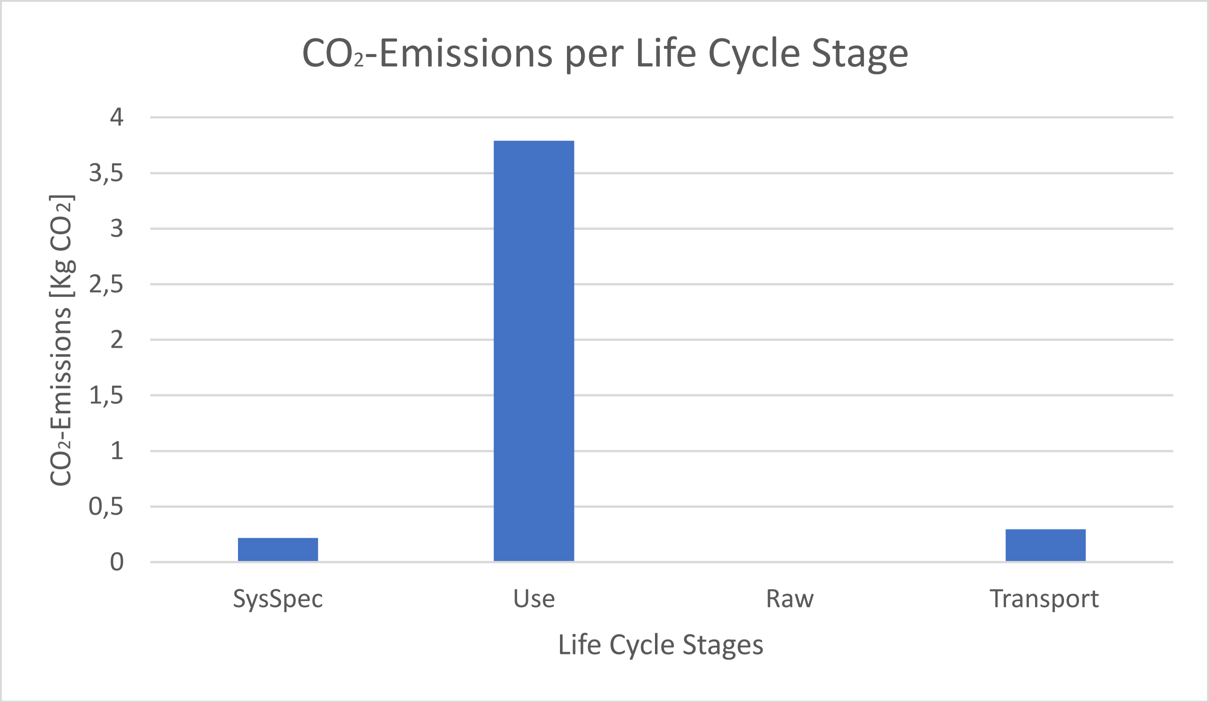


Figure 7.1: CO_2-Emissions resulting from each life cycle stage of ELSA

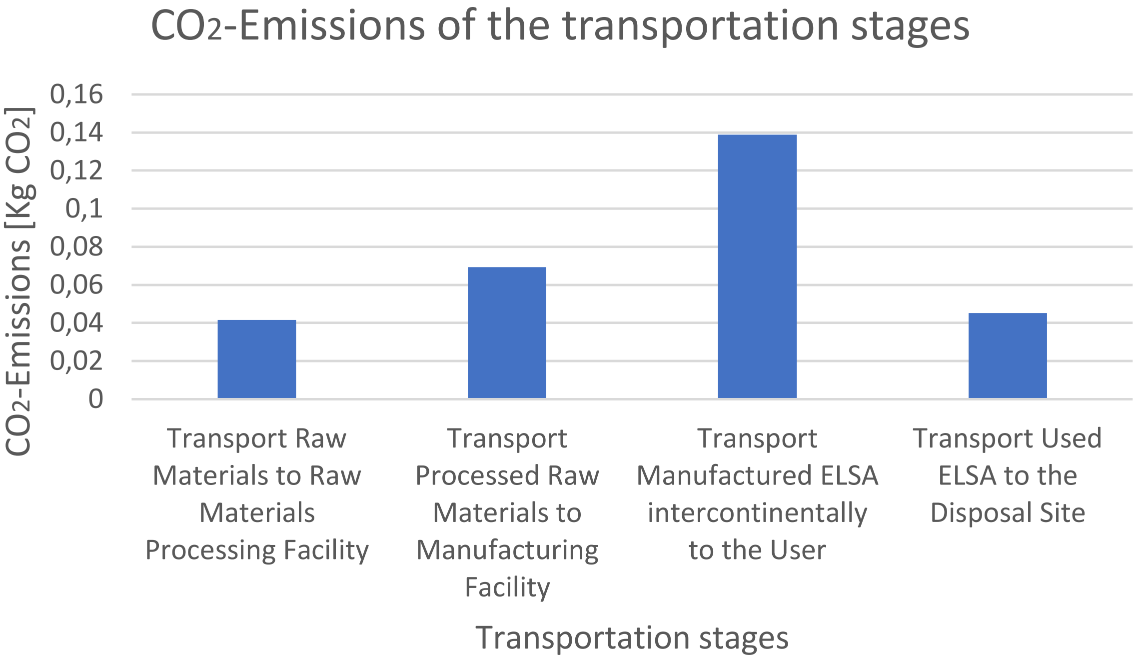


Figure 7.2: CO_2-Emissions of the transportation stages

Let's assume that we identified the active resource or the machine that executes the process MeltLead as a significant contributor to the CO_2-Emissions. Following the traceability scheme presented in section 6.4 results in the relation map illustrated in Fig. 7.3. The relation map traces all the model elements from the machine that executes MeltLead to the stakeholder need responsible for this element. The MeltLead active resource satisfies the resource requirement Lead Processing Machine and traces the MeltLead process. The resource requirement also traces the MeltLead process. Moreover, it is derived from the process requirement Process Lead. The MeltLead process refines the use case Process Lead to Lead Parts, which in its turn refines the process requirement Process Lead. The process requirement is derived from the physical requirement Battery and traces the BOM part Lead Part. The latter is also derived from the physical requirement Battery and traces the physical block Lead Acid Battery. The physical block allocates the logical block Energy Storage System and satisfies the physical requirement Battery. The energy storage system then allocates the functional block Energy Storage and satisfies several system requirements. The functional block traces the functional group, which in its turn traces the activity Distribute Electrical Energy. The latter refines the use case Provide Electrical Power to External Modules. The use case refines functional requirement Electrical Energy Supply. The functional requirement derives the top-level requirement Power ELSA Modules. The top-level requirement traces the stakeholder need Use, which in its turn traces the stakeholder System User.

7.2 Evaluating the Fulfillment of LCA Requirements

The requirements from ISO 14044 and their fulfillment are grouped in Fig. 9.23 in order to verify if the MBSE methodology developed in this work is consistent with the ISO LCA standard. The figure represents a table that groups all the requirements of the ISO LCA standard. The table also contains the requirements from the LCIA stage. It can be used as a checklist when performing an LCA analysis. The columns are separated into the number of requirement, their description and fulfillment.

This work performs an LCI study: Therefore, it includes the goal and scope definition, inventory analysis and the interpretation. The Life cycle impacts assessment is left out of the scope. The goal of the study is defined outside the SysML-Tool. There is also the option of entering the information within the SysML-Tool. The first option could be to create stereotypes that will contain this textual information. As an example, for the goal of the study, one could create a stereotype named “Goal” as a generalization of the SysML element Requirement. The second option would be to document all the textual information in a content diagram.

The scope of the study is partly defined in the SysML-Tool and the textual information is documented externally. Again, the textual information can also be documented in the SysML-Tool using a content diagram. The product system is modelled in the SysML-Tool using an ibd. The product system is similar to the turnover diagram, which is used to identify the input and output of a system. The product system is also complemented with a context and use case diagram that supports understanding the problem and the context of the system. The functions of the system are illustrated through a functional tree in a bdd. The functional unit, reference flow and the needed units are defined in a bdd. The defined units are used later in the value property during the analysis. The rest of the parameters in the scope definition are documented textually in the master thesis.

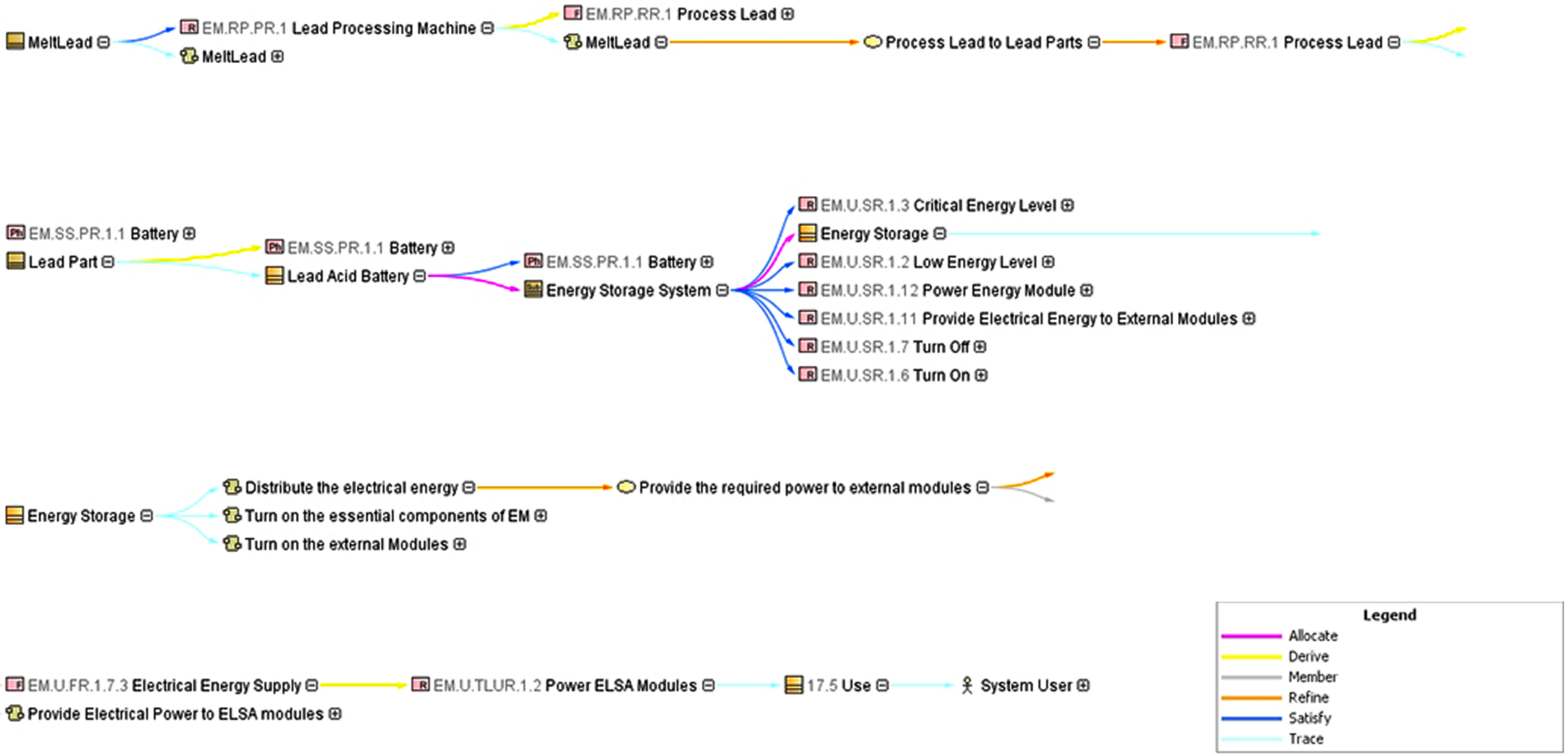


Figure 7.3: Traceability from the resource that executes the MeltLead process to the stakeholder need

The life cycle inventory analysis has nine steps. The goal and scope definition were specified in the previous stage. The rest of the steps were exectued in an Excel-Table (see section 9.3). Finally, the calculated values are queried manually in the SysML-Tool. After that, the data was aggregated in a parametric diagram. In the interpretation stage, the data was exported to an Excel-Table and the diagrams were produced.

One can notice from Fig. 9.23 that almost all requirements were fulfilled except the ones that are kept outside the scope, such as requirements on data, LCIA and allocation. The justification of leaving these requirements outside the scope can be found in chapter 6 as well as section 2.1.1 and 9.5.

7.3 Discussion

The results in section 7.1 demonstrate that the developed MBSE methodology allows the assessment of the CO_2-Emissions of a product from cradle-to-grave in early design stages. However, in this work, data was mainly based on assumptions because the goal was to demonstrate how to assess the CO_2-Emissions. Therefore, the results do not to give a statement on the CO_2-Emissions of the Energy Module. The developed methodology could be validated in future research using a use case from the real world and valid data.

In section 1.2, the research question "To what extent can MBSE support the assessment of CO_2-Emissions from cradle-to-grave in early design stages?" was formulated. It was assumed that MBSE can support in managing complexity, understanding the problem as well as facilitating the communication of information and analysis throughout the life cycle of a product. In order to manage complexity, in MBSE, the system with all its complexity is dissected into different viewpoints and analyzed individually. The grouping of all the viewpoints results in the system of interest and helps provide a holistic view of the system. Sophisticated tools such as Cameo provide the ability of easily navigating through several abstraction levels of the system. As an example, the encapsulation relationship allows zooming in and out of the system, e.g., from the top-level hierarchy to the component level or through different life cycle stages. This was illustrated in Fig. 7.1 and 7.2, where, from the results at the top-level, the transportation stage was further investigated. In a model with a higher level detail, one can further examine this particular stage going through the process, its sub-processes, up to the logical components allocated to them.

Furthermore, the MBSE methodology captures the traceability relationship between all the elements across the life cycle of the product. Figure 7.3 shows the traceability relationships from the resource that executes the MeltLead process to the stakeholder need that fulfills it. Now, we imagine that the resource MeltLead was identified as a critical element regarding sustainability. Using this approach, each step at the traceability chain is an opportunity for a creative solution. In our example, one could decide to change the resource that executes the MeltLead, or change the process MeltLead or change the physical block Lead Acid Battery into another type of battery. Except for the R and F levels of the development stage, almost all other levels of the other life cycle stages give a room for a creative solution. The requirement behind the lead-acid battery dictates that electrical energy shall be supplied cable-free to the modules of ELSA. In this case, one could as an example opt for a totally different design solution, such as equipping ELSA with photovoltaic panels. This allows the robot to recharge its battery, when it is in standby mode.

SysML offers several diagrams during the context analysis in order to better understand the problem. The stakeholder analysis helps identify the actors, who have a stake in the system and captures their requirements. The use case analysis describes how the system will be used and identify external systems interfacing with it. The context diagrams determines which external systems and actors are interacting with the system of interest. Finally, the turnover analysis specifies the flow of information or material between the interfaces. All these analyses support understanding the context of the problem before proceeding to the functional layer to develop a solution to the problem.

Models facilitate the communication between different teams with different disciplines. On the one side, diagrams are used that simplify the understanding of information. It is much easier for a human being to capture information from a drawing or a diagram than a page full of text. Of course, the diagram must then adhere to certain rules and use symbols that can be understood by everyone. This is also the main goal of SysML, but it is still not fully attained. However, SysML is still in its course of development. When working with SysML, one has also to take in consideration the effort and learning curve for SysML or SysML- tools. On the other side, the collection of the views that illustrate the viewpoints represents the model of the system, which in its turn becomes the Single Source of Truth. Once a model, which contains all the information regarding the system is developed and supported with a reliable change management, the room for ambiguity and communicating false information decreases.

A model of the whole life cycle of a product generates lakes of data. This data can be continually analyzed and the processes optimized using artificial intelligence and machine learning algorithms. Also, holistic analysis of the product can be performed. One can change one parameter and observe the impact on the life cycle of the product. This will offer the possibility to perform several “what if” analyses, detect vulnerabilities in the value chain and prevent them. Consequently, the life cycle of the system becomes more resilient towards uncertainties of the future.

In section 1.2, the main research question was divided into four sub-questions. These sub-questions are answered as follows:

- How to model the life cycle of a product from cradle-to-grave?

  This work uses the V-Model and the RFLP approach to develop each stage of the life cycle from cradle-to-grave. As assumed in the beginning of this work, there was no model of the whole life cycle of a product in scientific literature. The modelling of the life cycle stages from cradle-to-grave was achieved through the combination of different approaches. The ISO 15288 recommends the following life cycle stages: conception, development, production, use and disposal. The conception, development and use stages are addressed in a great amount in scientific literature, especially the SE or SysML literature (Eigner et al., 2014a), (Bougain and Gerhard, 2017). The modelling of the production stage was successfully accomplished by the PPRF approach from Sprock et al. (Sprock et al., 2020). The disposal stage is considered as a reversed version of the production stage. In the production stage, raw materials are fed as an input, which are transformed throughout processes to into a product. In the disposal stage, the product is fed as an input, which is in turn transformed through process to raw materials. In summary, The V-Model can be used as a top-level development method for each life cycle stage. The RFLP approach is used at the left wing of the V and provides a way to develop each life cycle stage from requirements to the physical architecture. The PPRF model can be used as the basis for the production and disposal stages.

- How to assess the CO_2-Emissions of a product from cradle-to-grave?

Scientific literature provides several approaches to assess the CO_2-Emissions of a product from cradle-to-grave. However, in this work, the focus was laid on the ISO LCA standard. The choice was justified through the global recognition of the ISO standard. The global recognition guarantees that a certain quality will be maintained through the standard. Moreover, it is beneficial for industries who are looking for a globally recognized product quality. Future research could perform an analysis of different sustainability assessment methodologies in order to evaluate them.

- How can this approach be integrated into an MBSE methodology?

The ISO LCA standard is seamlessly integrated within the V-Model and the RFLP approach. The goal and scope definition can be performed at the R-F level. The rest of the LCA stages can be accomplished at the L level. Regarding the SysML-Tool, the context analysis supports the understanding of the problem and the definition of system boundary. The value properties are used to store information regarding the sustainability of the product. These properties can then be used for several analyses, e.g., calculating CO_2-Emissions, trade-off analysis, validation and verification activities. The only encountered burden is that SysML was found to not be optimal for calculation. Especially, when the system under study is complex and the analysis of several parameters regarding the environmental impacts is required. Therefore, it is advised to perform all calculation externally, e.g., Excel-Table and to manually enter the values in the SysML-Tool. The aggregation of the data can be performed in a parametric diagram.

- How meaningful are the results?

  The ISO LCA standard is a valid approach that has been used intensively in recent years for assessing the sustainability of a product. This work uses this approach and integrates it in a model-based one. It does not delete any of the recommendations of the standard, but rather enhances it using models. The quality of the results is mainly dependent on the quality of the data, the methods of calculations and the allocation procedure. Therefore, it is assumed that if one fulfills the requirements of the ISO LCA standard, then the results should be valid. Validation of the methodology could not be performed during this work due to the time constraint of a master thesis. This could be carried out in future research.

In section 1.2, the following success criteria and measurable success criteria were defined as measures against which the outcome of the research could be evaluated:

- Success Criteria: increase sustainability and profit
- Measurable success criteria: increase sustainability, completeness, correctness, recognition, applicability, simplicity and effort

The developed methodology provides a way to assess and increase sustainability of a product. This work demonstrates that the developed methodology supports the assessment of the environmental perspective of a product from cradle-to-grave. The methodology allows one to investigate the characteristics of the product in different hierarchical levels throughout the whole life cycle of a product. As an example, one can start from the top-level perspective that reveals the total CO_2-Emission in the whole life cycle. Once a specific life cycle stage is identified as critical, one can investigate further from that stage, to a specific function, a specific component up to the corresponding requirement in order to identify the most environmental harmful elements. After identifying the latter, design alternatives can be analyzed with the aim of supporting decision-making in early design stages. This makes it possible to measure the actual state of the system and support design-changes in order to achieve a better state. Therefore, the first success criteria "increase sustainability" is considered to be fulfilled by the developed MBSE methodology. Obviously, the change of the state cannot be forced by the MBSE methodology, since it is only a tool. The decisions made during the project are the ones that influence the sustainability of the product for better or worse.

After demonstrating that the developed MBSE methodology can increase sustainability of the product. The next measurable success criterion to investigate is correctness. This criterion asks, "Does the MBSE methodology provide a viable sustainability statement?" To answer this question, the ISO LCA standard was used as the basis for the assessment of CO_2-Emissions. It is a globally recognized standard for life cycle assessment. To verify if all requirements from the ISO LCA standard are fulfilled, a table containing all the requirement from the ISO LCA standard and their fulfillment was created (see Fig. 9.23). The table was elaborated and the procedures for fulfilling the requirements were explained in section 7.2. The table shows that all the requirements from an LCI study were fulfilled except for the ones that were kept outside the scope. Subsequently, the developed MBSE methodology offers a correct way to assess the sustainability of a product. However, this work performs only an LCI, future work could include the LCIA stage and evaluate the methodology on a real project using valid data.

A life cycle analysis is mandatory in order to provide a reliable statement on the sustainability of a product. However, this work analyses only the life cycle stages from cradle-to-grave due to the time constraint of a master thesis. This leads us to the next criterion: completeness. This criterion assesses if the methodology considers all the life cycle stages from cradle-to-grave. However, there is no one defined group of life cycle stages that forms cradle-to-grave. The life cycle stages differ from each product and each company. Therefore, the life cycle stages from ISO 15288 are used as a basis of the analysis. According to ISO 15288, cradle-to-grave encompasses the life cycle stages: conception, development, production, use and disposal (ISO 15288, 2008). The production stage and the disposal stage are considered similar in their nature, the difference is that they are reversed. The production stage transforms raw materials through processes into a product. Meanwhile, the disposal stage transforms the product through processes into raw materials. Both life cycle stages can be abstracted using the PPRF model from (Sprock et al., 2020). Therefore, the raw material processing stage is considered as representative for all life cycle stages that can be abstracted using the PPRF model. The concept and development stage are grouped in this work as system specification stage. In the system specification, the system is developed in the context of how it will be used. This includes all necessary analysis for the use stage. Please note that the maintenance is kept outside this work, as it is part of the circular economy strategies. Consequently, one can conclude that the developed methodology considers all life cycle stages from cradle-to-grave. Hence, the criterion of completeness is fulfilled.

The aforementioned criteria focus on the environmental aspect of the product. From the discussion, it was demonstrated that the developed methodology provides a viable and globally recognized way to assess the environmental perspective and increase the sustainability of a product. Moreover, the developed methodology supports in analyzing the life cycle stages from cradle-to-grave. This means that the first part of the goal has been reached.

The second part of the goal focus on the economical aspect with the aim of reducing development costs and increasing profit. To reduce the development costs, three criteria are considered: applicability, simplicity and effort. The applicability criterion focuses on when the MBSE methodology can be applied. Chapter 4 describes how the methodology can be applied at the left wing of the V-Model, which represents early design stages. Since this work analyzes the several life cycle stages and considers a V for each life cycle stage. It is possible to increase efficiency and shorten time-to-market through parallel development of different life cycle stages.

Here, one can distinguish between two cases, depending on the product if it is new or old. In a new product, one has no information about the product. Therefore, the start of the other life cycle stages can only be started after a logical architecture of the product is available. In the case of an old product, one already has information about the system of interest. Therefore, the parallel processing can be started from the beginning. Consequently, the methodology offers the possibility to analyze the system throughout its life cycle in early design stages and in a concurrent way in order to increase efficiency and shorten time-to-market. Thereby, the applicability criterion is considered as fulfilled.

The next criterion focus on the simplicity of application. The methodology was developed to accompany engineers during the development activities in order to analyze the environmental perspective of the product. This work uses well-known development methods such as V-Model and RFLP approach with the aim of increasing similarity to common development methodologies. Several activities from the scope definition in LCA are similar to the ones in the MBSE practice. As an example, the product system and the system boundary are similar to the activities used in SysML to define the context of the system. SysML is even more rigorous in this aspect. It provides four diagrams to define the context of a system: stakeholder, use case, context and turnover. The rest of the activities is additional and necessary to analyze the environmental aspect of a product. In this work, it was observed that the LCI activities were cumbersome in the SysML-Tool, despite Cameo offering possibility of automatic generation of parametric diagrams. In this case, it was noticed that an Excel-table is more suitable. Excel is a table that is designed for doing an inventory, contrarily to SysML. The results of the LCI analysis can be queried manually in the SysML-Tool. One could ask the question, what is the benefit of an MBSE method, when all the LCI analysis steps are performed externally of the SysML-Tool or in an Excel-table. This was elaborated in detail at the beginning of this section.

In summary, the methodology can be easily integrated to the common development methodologies. Specifying the context of the system under study is a common activity in both MBSE and LCA. The activities from LCI analysis are considered as additional work, but also necessary in order to analyze the environmental perspective of a product. Therefore, the developed methodology is considered to be simple to apply. However, it still must be evaluated in a real project by developer who are unfamiliar with it.

Being sustainable requires an assessment of the whole product life cycle, which needs a great amount of time and resources that needs to be invested. This brings us to the last criterion of effort that assesses the input needed to apply the methodology. This work assumes that the effort behind the methodology can be reduced, when performed in parallel with mandatory tasks. As an example, when developing a product the production stage must be planned, its behavior must be simulated and analyzed. The environmental assessment should be performed in parallel to these activities. Then, the effort behind the methodology will be minimal, since this will require only performing a calculation in an Excel-Table and adding the value properties concerning sustainability to the corresponding elements.

This work advises the analysis of all life cycle stages early in design and spend several iterations in order to reduce failures as well as increase the quality of the whole life cycle. Despite, numerous literature demonstrating the benefits from it, in real life, one is mostly obliged to show results, mainly physical ones, in early design stages. Therefore, engineers are often forced to accelerate the design stage and skipping several steps. This results in inducing defects in the design and late detection of failures, which increases the costs of development.

The great effort in modelling the complete life cycle of a product can be tackled with a wide spread of the model-based paradigm. INCOSE mentioned that the model-based development will become a standard in the upcoming years (INCOSE, 2021), driven by the actual digital transformation as part of the fourth industrial revolution (Vrana and Singh, 2021). Most of the complex products are so complex that one cannot find only one company involved in its life cycle. The product life cycle of a complex system includes several suppliers. The more complex does the product get, the more suppliers are involved in the product life cycle. An Original Equipment Manufacturer (OEM) should and also cannot model the complete life cycle of the product. Each supplier involved in the product life cycle is the best in what he does. Therefore, an OEM should not do a work that does not suit their competencies. In the real life, the OEM mostly develops the architecture and provides specifications to the suppliers. INCOSE projects in the future that this will solely be performed in a model-based approach (INCOSE, 2021). In this case, an OEM will desire to have a model of the product life cycle that represents the single source of truth. The suppliers must then provide a model of their component which represents a part from the life cycle of the product. Models could become a competitive aspect between suppliers. It is also possible that standards will be developed to define requirements for the interfaces between the models of the product life cycle. This can allow for a plug and simulate concept, where models from different suppliers can easily be integrated with each other to form a model of the product life cycle.

Model-reuse can also decrease the costs involved in modelling the life cycle of the product. Nowadays, modelling the life cycle of each component of a car is definitely a very cumbersome, if not an impossible, task. Nevertheless, the more MBSE is adopted by the community, the more standardized processes, methods, libraries for modelling the life cycle are developed. As mentioned from Culler, model-reuse can become a game changer in this ever-growing complexity in the product development (Culler, 2010). The library for DELS models is an example of such an initiative (Sprock, 2017). Once we reach the point where sufficient libraries are available, developing a product life cycle will become a casual task.

In summary, being sustainable comes with a lot of effort when considering the whole life cycle of a product. However, this should be used as a chance to develop a life cycle thinking, systems thinking and a holistic perspective on the product. The assessment of the sustainability of a product should be performed in parallel to other mandatory tasks such as planing and development of other life cycle stages. The effort behind modelling a whole life cycle of a product can be decreased through a great adoption of MBSE and an increase of model-reuse in the community. This work advises an analysis of the complete life cycle early in design. Rogers III and Mitchell shows that spending more time in design stage reduces defects induced in the project, hence, increases the product quality (Rogers III and Mitchell, 2021). With the right decision, the quality of the product can also be increased. As a result, customer satisfaction is assumed to increase, hence, the success of the product and the profit. Furthermore, one should also take in consideration the learning curve required for mastering SysML, the SysML-tool, the

MBSE paradigm as well as consider the costs for the tool and trainings required. In total, I assume that the methodology requires a great amount of resources to be invested in, but the profit is considered to exceed it. This, however, cannot be validated in this work, but could rather be a subject of study in future research.

Chapter 8

Conclusion and Outlook

Being sustainable comes with a great investment in time and resources. A reliable statement on sustainability requires the analysis of the whole life cycle of a product. This increases the complexity of the system under study to become a System of Systems. MBSE represents a method that can be used to tackle such complex problems. Supported with sophisticated tools, MBSE can help in managing the complexity of the problem, support the understanding of the problem, facilitate the communication of information between the teams and help in analyzing the life cycle of the product. However, this work does not validate the outcome of the methodology, but rather evaluates the methodology against sustainability and profit criteria (see section 1.2). The developed methodology could be applied in a real world project in order to quantitatively and qualitatively measure the input required and the benefit of this methodology.

The costs and efforts needed for applying the methodology should be considered and compared against the benefits. One should also take in consideration the costs of teaching engineers the MBSE paradigm, SysML and the MBSE tools. However, the comparison can only be meaningful when the capabilities of MBSE are fully exhausted. This includes the analysis of the whole life cycle of a product in early design stages. Further, the integration of different tools of different life cycle stages and the exchange of information established. Feedback loops between different life cycle stages can provide an early statement on the design and the results can be used to analyze several alternatives with the aim of identifying the most adequate solution. Furthermore, a model of the life cycle of a product generates lakes of data that can thoroughly inspected by artificial intelligence and machine learning algorithms in order to continually optimize the life cycle of the product.

The developed methodology uses the ISO LCA standard as the basis for assessing the environmental aspect of the product. The ISO LCA standard has, over the past years, been proven a valid procedure for such environmental assessments. This work does not suppress any requirements from the ISO LCA standard, but rather integrates it into a model-based approach. Therefore, the correct use and application of ISO LCA standard sustains the assumption that its results would be valid. However, this work considers only an LCI study. Future research could include the LCIA stage and use valid data in order to evaluate the assumption regarding the validity of the results.

The modeling of the life cycle from cradle-to-grave was accomplished through combining formal design approaches and the DELS ontology from (Sprock et al., 2020). In this work, however, not all life cycle stages were modelled. It was assumed that the production and disposal stages can be abstracted using the PPRFT model. Future research could evaluate to which extent is the assumption valid. Also, one could study the modelling of the structure, behavior and analysis of all the life cycle stages along with the sustainability aspect.

As mentioned earlier, a reliable statement on sustainability requires the consideration of the whole life cycle of a product from cradle-to-cradle. This work considers only from cradle-to-grave due to the time constraint of the master thesis. The remaining circular economy strategies could be integrated to this approach in future research (Potting et al., 2017). Material circularity indicator developed by Ellen MacArthur Foundation is one of the most used methods in measuring circularity of a product. However, a fully circular product is not always sustainable. The circularity strategies shall also be assessed regarding sustainability. If the input of the R-strategies is more resource intensive than the outcome, then the strategy is not adequate. Future research could integrate LCA and the circular economy strategies in order to support decision-making.

In summary, sustainability requires an analysis of the whole life cycle of a product, which needs a great amount of resources and time. This work shows that it is possible to model and analyze the life cycle of a product in early design stages. The challenge of modelling the life cycle should not be considered as a hurdle, but rather as a chance to develop the life cycle thinking, systems thinking or in general the holistic thinking paradigm. The problems in our current days are characterized by a high degree of complexity, which, therefore, require holistic views and sophisticated methods such MBSE. MBSE is assumed to be beneficial in this regard when its potential is used to the fullest. Especially when the methodology is applied early in design. This work does not validate this assumption, but rather evaluates the developed methodology against certain criteria. Future research could implement the methodology on a real world project and validate the assumption.

Chapter 9

Appendix

9.1 The MBSE Ontology Used in This Work

The MBSE ontology used in this work is illustrated in Fig. 9.1. The ontology defines all the artifacts used in this work. It is adapted from both ontologies (Holt and Perry, 2008, p. 474) and (Sprock et al., 2020, p. 18). The artifacts from the MBSE ontology cannot all be explained in this work due to the time constraints of a master thesis. Therefore, the source literature that explains the artifacts of the ontology is referenced. Afterwards, the differences between the source ontologies and the one used in this work are highlighted. Finally, the integration between both ontologies is described. The ontology can be separated into 5 different parts that represent the artifacts used in the five different perspectives. A perspective is the collection of views and viewpoints. Each part of the ontology will be addressed in the corresponding section from the perspective (see from section 4.2.1 to 4.2.5).

The ontology can be read following the rules described in section 2.2.2. In addition to the previously defined rules, the dashed line connects an association block and two other blocks. The association block provides more details on the relationship between two blocks. The word “via” can be used, when reading an association block. As an example, let’s focus on the ontology elements: requirement, use case and context from the top-side of Fig. 9.1. The ontology shows that one use case describes one requirement via a context. To ease the understanding of the model, the elements from the models will be written in the text in the form of Camel Case.

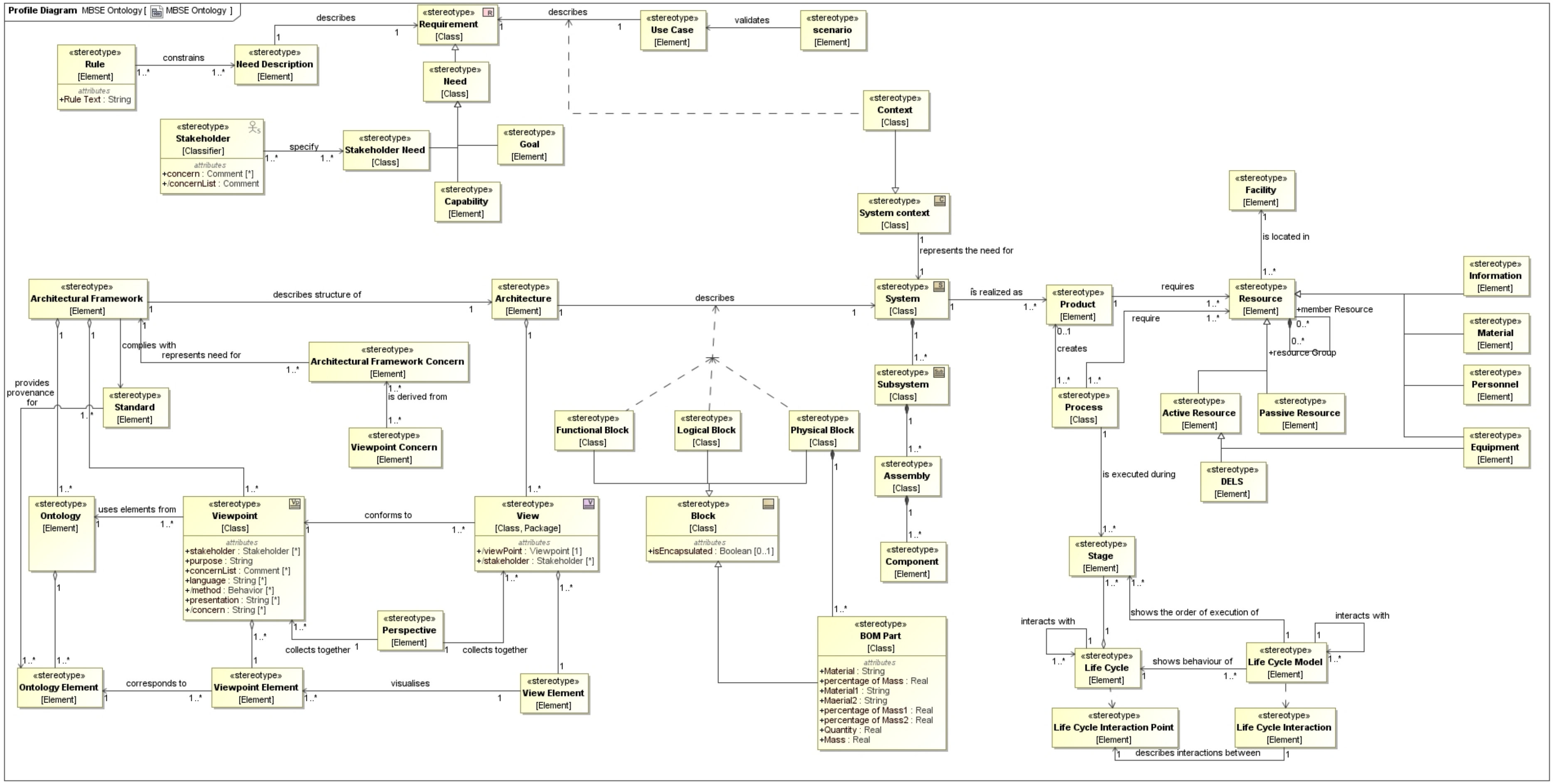


Figure 9.1: The MBSE ontology used in this work, adapted from (Holt and Perry, 2008) and (Sprock et al., 2020)

9.2 The Framework

The framework defines the scope of the model. It defines the information that will be described by the model. Figure 9.2 shows the structure of the MBSE methodology framework and its perspectives. The MBSE methodology framework is made up of five perspectives: architectural framework perspective, need perspective, system perspective, process perspective and life cycle perspective. The perspectives are described briefly in the following sections. First, the relevant part of the MBSE ontology is presented, afterwards, the viewpoints of each perspective are introduced. Finally, the differences between the source ontology are highlighted.

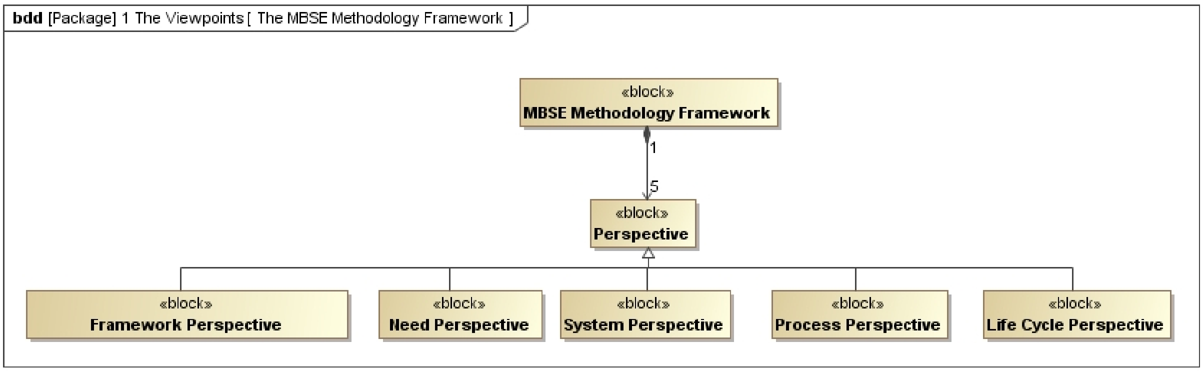


Figure 9.2: The MBSE methodology framework showing the perspectives

In the following sections, the different perspectives are described briefly.

9.2.1 The Architectural Framework Perspective

The subset of the ontology used in the architectural framework perspective is shown in Fig. 9.9. The figure adds to Fig. 2.12 the artifacts element and concern. The element is used to represent the elements from the ontology, viewpoint and view. The concern is used to express the need for the architectural framework or viewpoint. More detail on the ontology can be found in (Holt and Perry, 2008, p. 430).

The Architectural Framework (AF) Perspective defines the viewpoints needed to develop the MBSE methodology framework. It is adapted from the Framework for Architectural Framework (FAF) (Holt and Perry, 2008, p. 462). FAF is a framework to define a specific framework. In this work, it was used to define the MBSE framework. Figure **??** illustrates the relationship between the viewpoints of the architectural framework. The AF perspective contains three viewpoints. The ontology definition viewpoint defines the artifacts used in this work. The viewpoint definition viewpoint defines the information that needs to be represented in this work. Finally, the viewpoint relationships viewpoint specifies the relationship between the viewpoints.

9.2.2 The Need Perspective

The subset of the ontology used in the need perspective is shown in Fig. 9.5. The ontology is similar to the one used in (Holt and Perry, 2008, p. 349). The difference is that in Fig.

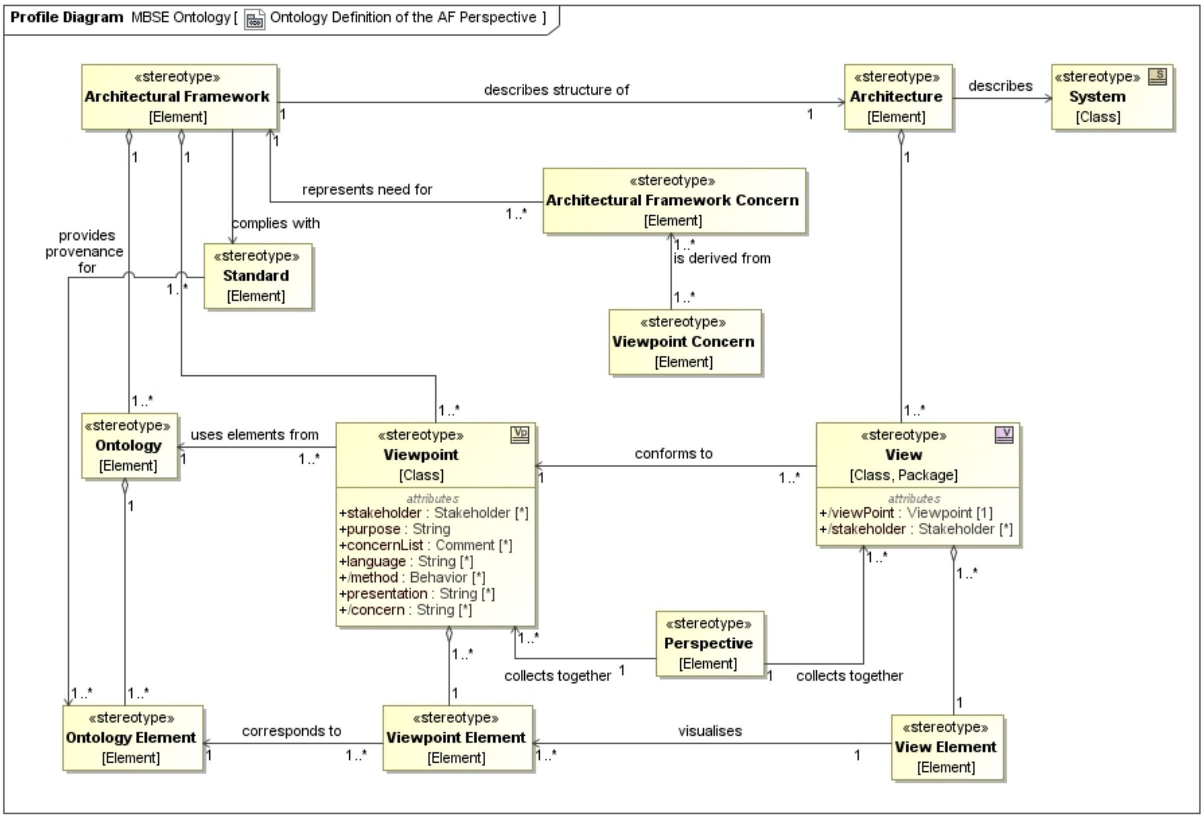


Figure 9.3: Ontology definition of the architectural framework perspective adapted from (Holt and Perry, 2008, p. 430)

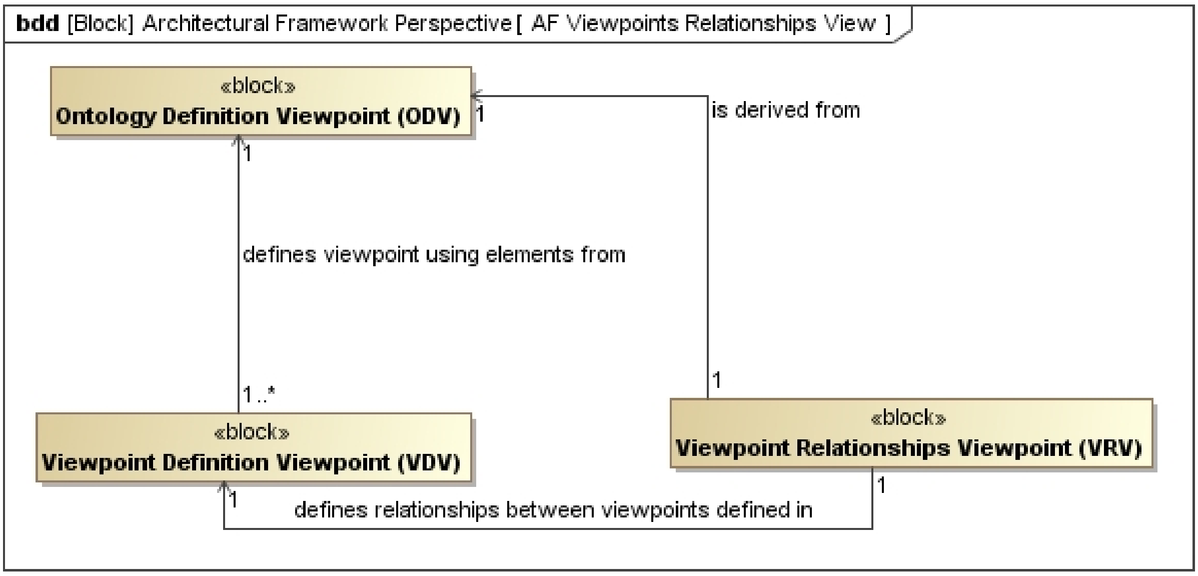


Figure 9.4: Relationship between the viewpoints of the architectural Framework, adapted from (Holt and Perry, 2008, p. 477)

9.5 the ontology element Need is shown to be a type of Requirement, whereas Holt and Perry defines on the other around. This decision has been chosen because Requirement is an element of the Cameo SysML Metamodel. Therefore, it is impossible to change its definition. However, the inheritance relationship allows Need to inherent all the properties of a Requirement. The element System Context is represented as a type of Context, which represents the need for the system. This represents the interface of the need perspective and the system perspective. More detail on the ontology can be found in (Holt and Perry, 2008, p. 349).

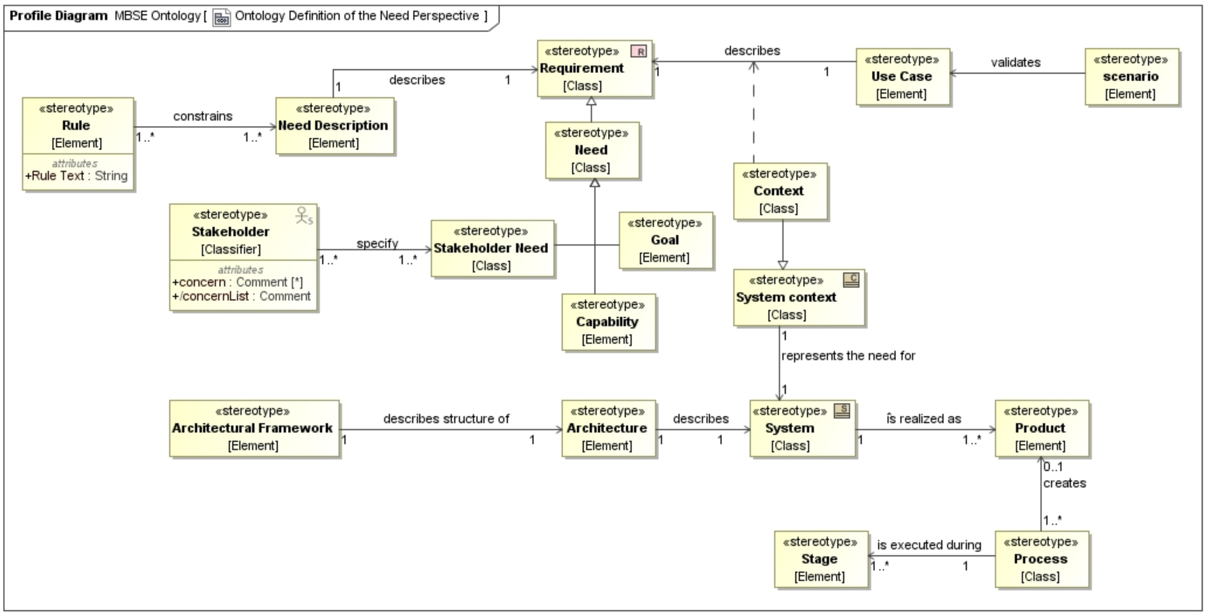


Figure 9.5: Ontology definition of the need perspective, adapted from (Holt and Perry, 2008, p. 349)

The Need Perspective captures the needs for the system, puts them into context, structures them and traces them across the development process (Holt and Perry, 2008, p. 489). Figure 9.6 illustrates the relationship between the viewpoints of the need perspective. The perspective contains six viewpoints similar to the ones defined in (Holt and Perry, 2008, p. 347). First, rules are set up that define how to write the requirements. Secondly, the context, use case and turnover analysis define the borders of the system and its interfaces. Afterwards, the requirements are defined and organized hierarchically. Finally, the traceability is set up between requirements and the model elements. The text in the yellow background represents a note in Cameo. It notifies that the Traceability Viewpoint is normally connected to all other viewpoints. The relationships to other viewpoints were omitted from this diagram for clarity. More detail on the need perspective can be found in (Holt and Perry, 2008, p. 347).

9.2.3 The Life Cycle Perspective

The subset of the ontology used for the life cycle perspective is shown in Fig. 9.9. The ontology is similar to the one in (Holt and Perry, 2008, p. 323). In Figure 9.7 the element stage is named in the original ontology as Stage. The name has been changed to align it with the life cycle stages from the LCA standard and the states, modes and stages from SE (Wasson, 2011). More detail on the ontology can be found in (Holt and Perry, 2008, p. 323).

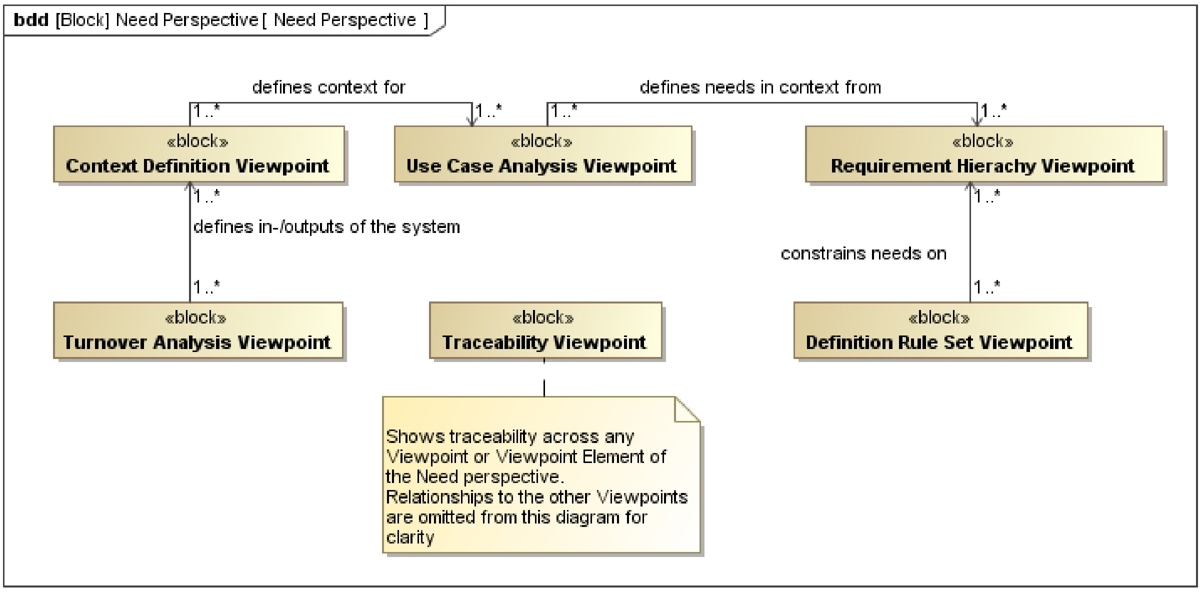


Figure 9.6: Relationship between the viewpoints of the need perspective, adapted from (Holt and Perry, 2008, p. 347)

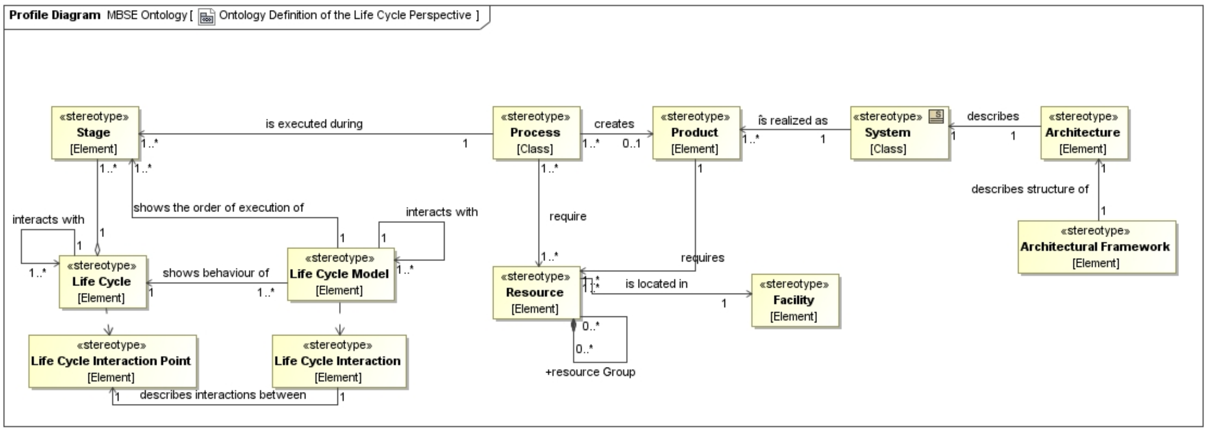


Figure 9.7: Ontology Definition of the life cycle perspective, adapted from (Holt and Perry, 2008, p. 323)

The Life Cycle Perspective defines the life cycle stages focused on in this work, their interaction and analysis its life cycle inventory (Holt and Perry, 2008). Figure 9.8 illustrates the relationship between the viewpoints of the life cycle perspective. The perspective contains three viewpoints. The Life Cycle Viewpoint defines the life cycle stages included in the model. Afterwards, the interaction between the life cycle stages is identified in the context of LCA. This means that the relevant in-/ output of each life cycle stage are specified. Finally, the life cycle inventory of each stage is calculated and summed up.

9.2.4 The Process Perspective

The Process Perspective shows how the development method (see section **??**) is applied to each life cycle stage (Holt and Perry, 2008). More detail on the ontology can be found in (Haskins

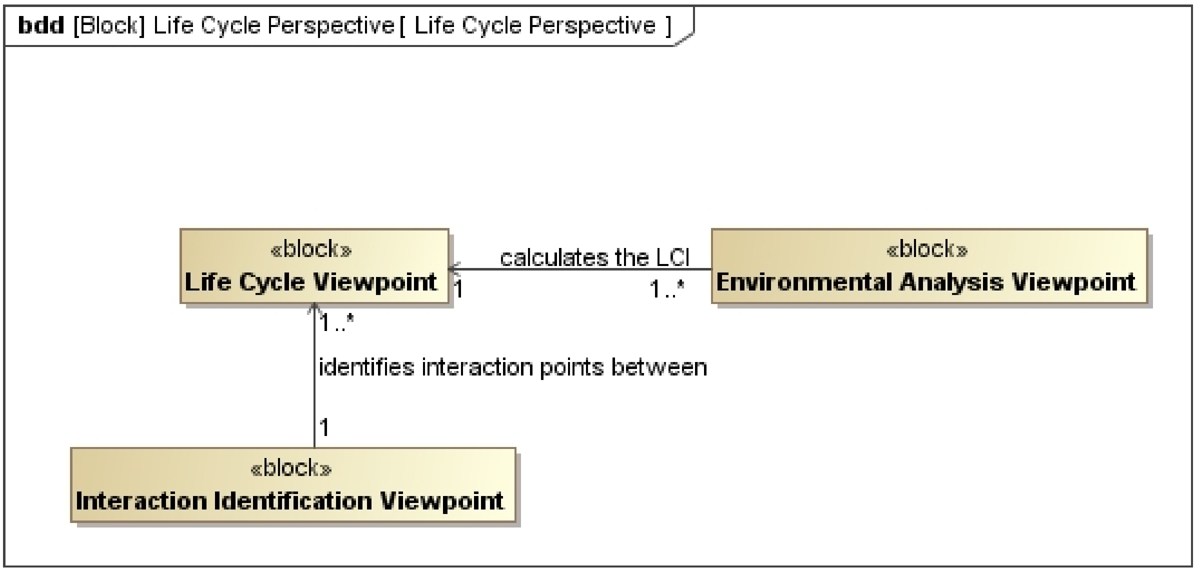


Figure 9.8: Relationship between the viewpoints of the life cycle perspective, adapted from (Holt and Perry, 2008, p. 323)

et al., 2006, p. 21)

The subset of the ontology used in the architectural framework perspective is shown in Fig. 9.9. The figure adds to Fig. 2.12 the artifacts element and concern. The element is used to represent the elements from the ontology, viewpoint and view. The concern is used to express the need for the architectural framework or viewpoint. More detail on the ontology can be found in (Haskins et al., 2006, p. 21).

The Architectural Framework (AF) Perspective defines the viewpoints needed to develop the MBSE methodology framework. It is adapted from the Framework for Architectural Framework (FAF) (Holt and Perry, 2008, p. 462). FAF is a framework to define a specific framework. In this work, it was used to define the MBSE framework. Figure **??** illustrates the relationship between the viewpoints of the architectural framework. The AF perspective contains three viewpoints. The ontology definition viewpoint defines the artifacts used in this work. The viewpoint definition viewpoint defines the information that needs to be represented in this work. Finally, the viewpoint relationships viewpoint specifies the relationship between the viewpoints.

9.2.5 The System Perspective

The subset of the ontology used in the architectural framework perspective is shown in Fig. 9.11. The ontology defines System, Subsystem, Assembly, Component to illustrate the hierarchy in the system. Moreover, the Functional, Logical and Physical Blocks are added in order to depict the necessary elements from the RFLP approach. The System Perspective have an interface to both the AF Perspective and the Process Perspective. This is shown with the elements Architecture and Product. The Architecture describes the System and is made of one to many Views. Whereas the System is realized as a Product that created through a Process.

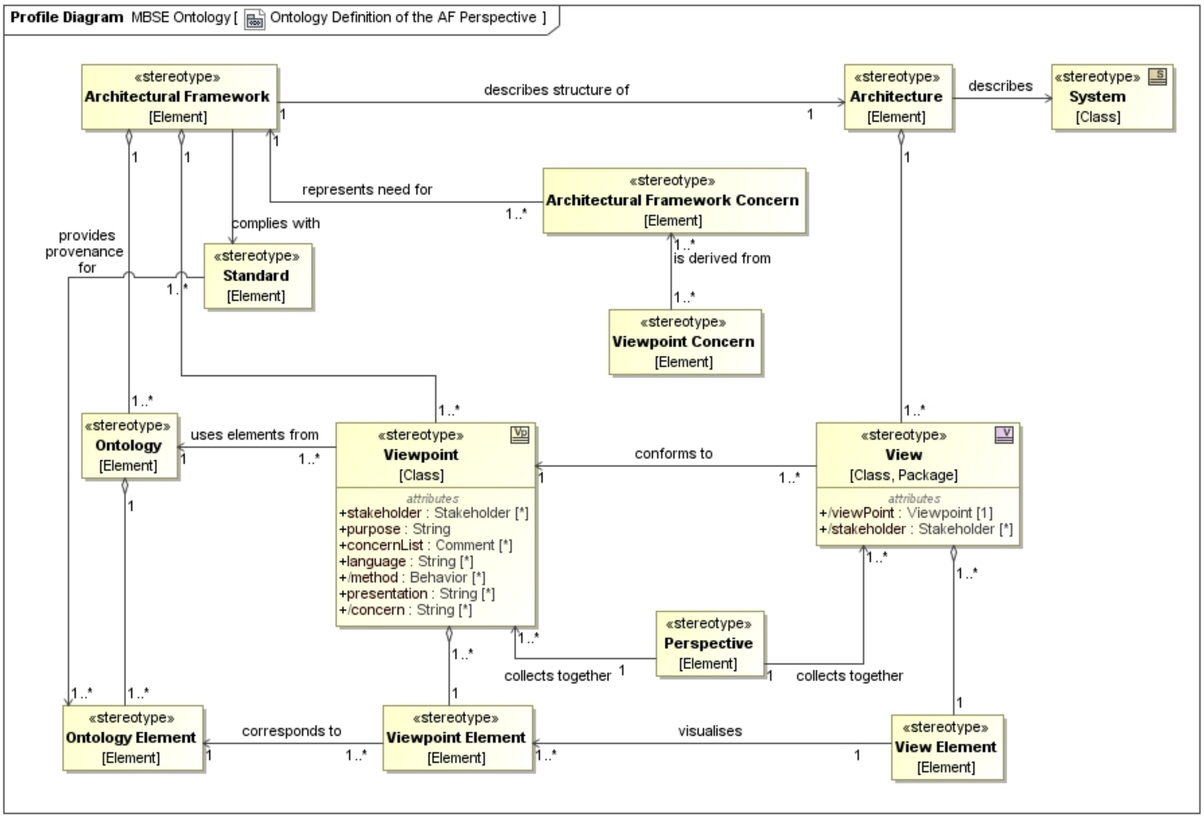


Figure 9.9: Ontology definition of the architectural framework perspective adapted from (, p. 21)

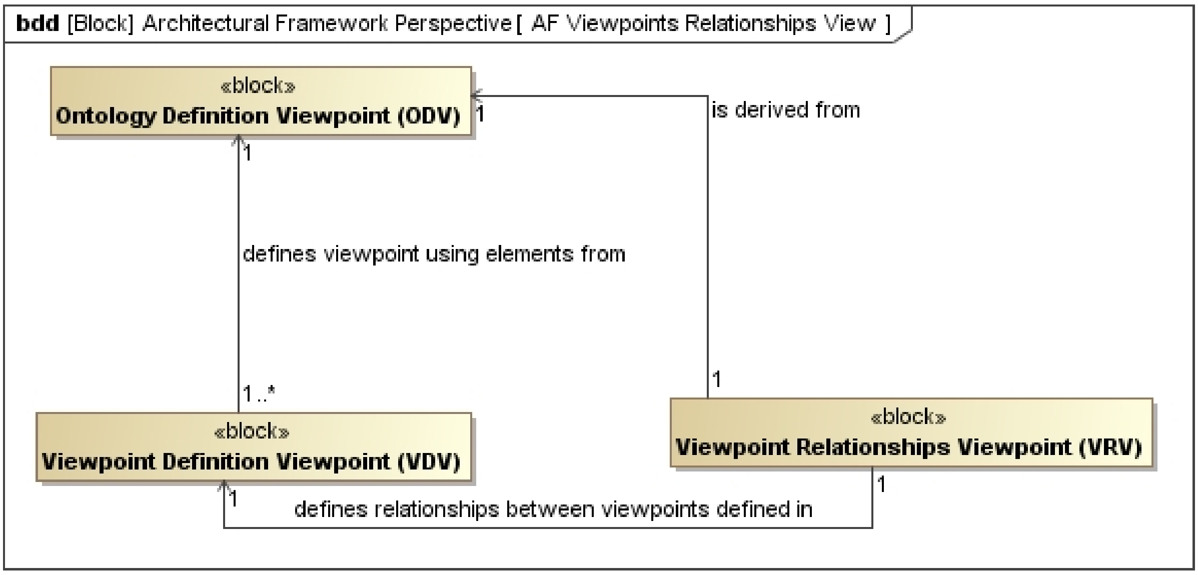


Figure 9.10: Relationship between the viewpoints of the architectural Framework

The System Perspective describes the context, structure and behavior of the system of interest (Holt and Perry, 2008). Figure 9.12 illustrates the relationship between the viewpoints of the System Perspective. The perspective contains 11 viewpoints. Most of the viewpoints are similar to the one from (Holt and Perry, 2008, p. 476). Figure 9.12 adds the Functional, Logical and Physical Structure Viewpoints as types of the System Structure Viewpoint in order to align

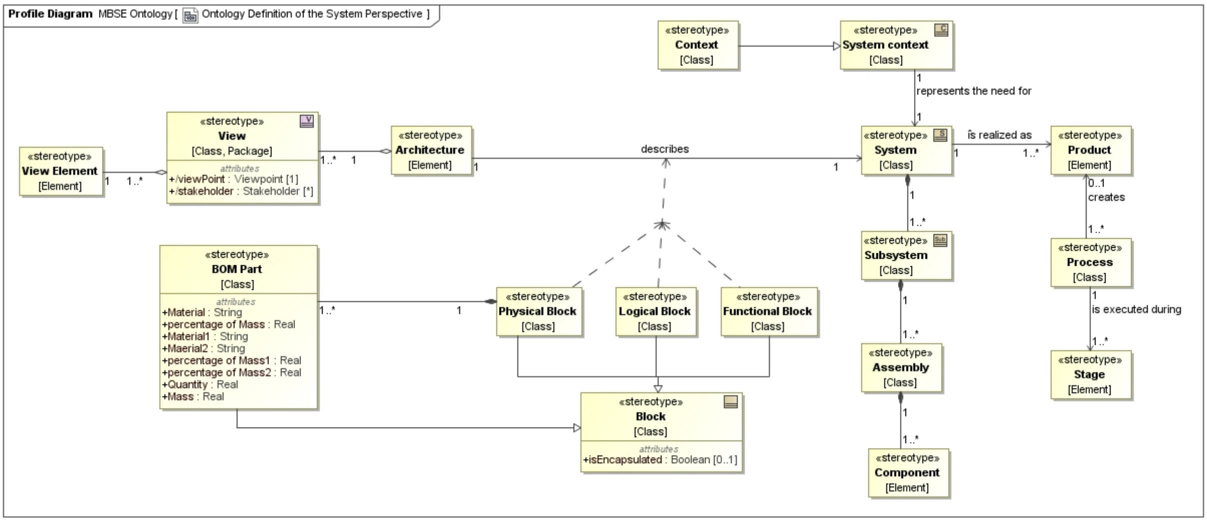


Figure 9.11: Ontology definition of the system perspective, adapted from (Holt and Perry, 2008, p. 474)

it with the RFLP approach. More details on the System Perspective can be found in (Holt and Perry, 2008, p. 478)

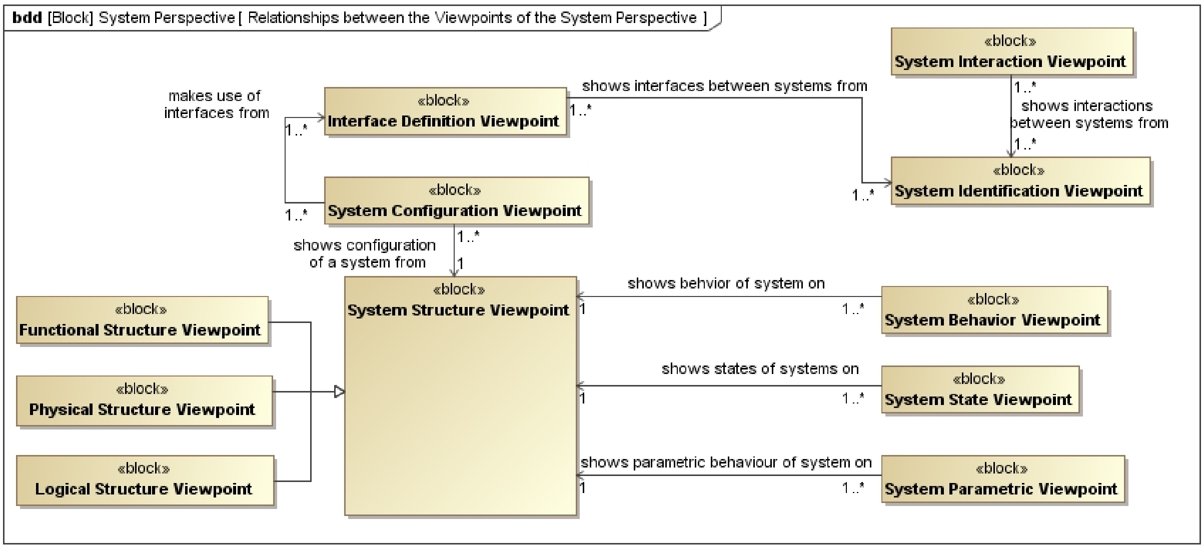
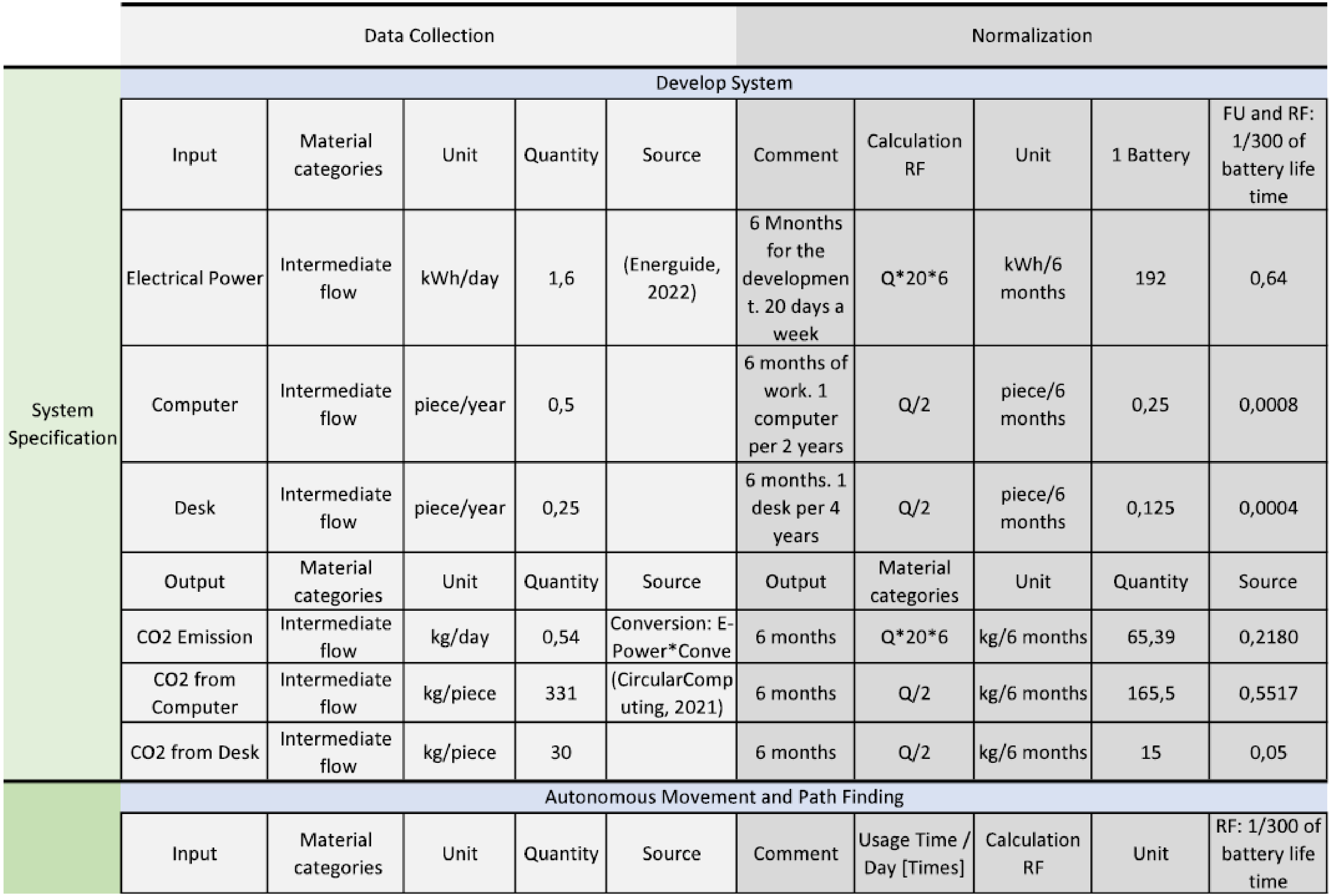


Figure 9.12: Relationships between the viewpoints of the system perspective, adapted from (Holt and Perry, 2008, p. 476)

9.3 Life Cycle Inventory Analysis Data Sheet

Figure 9.13 summarizes the data of all life cycle stages. Horizontally, the table is separated in a hierarchical manner. First comes the separation regarding life cycle inventory steps: data collection and data normalization. Then, the unit process is presented. Afterward, the in-/output, material category, unit, quantity, source, reference flow, functional unit. Vertically, the table is grouped regarding the life cycle stages: system specification, use, raw material processing, transportation. The first five steps of the life cycle inventory analysis are mostly concerned with data activities. These activities were performed in an Excel table. Tab. **??** shows the data collection and normalization sheet for the system specification stage. Horizontally, the table is separated in a hierarchical manner. First comes the separation regarding life cycle inventory steps: data collection and data normalization. Then, the unit process is presented. In this stage, the activity Develop System represents the unit process. Afterwards, the columns are separated into: in-/output, material category, unit, quantity, source, reference flow and functional unit. Vertically, the table is grouped regarding the life cycle stages.

The input of the unit process Develop System are electrical power, computer and desk. These elements are categorized as intermediate flows. The output of interest in this stage are the CO_2-Emissions from each component. The third column shows the unit of the element. As an example, kilowatt-hour per day (kWh/day) was chosen for the electrical power. The quantity used is 1.6 kWh/day. The quantity was calculated from the yearly consumption of an office. The source of the information can be found in the fifth column. To proceed with the calculation, it was assumed that system development was done by one person for six months. Therefore, the electrical power consumption of the unit process was calculated as a multiplication of the quantity, the number of working day in a week and the six months. Then ninth column shows the result for one battery and the final one for the functional unit.



	Data Collection					Normalization				
	Develop System									
System Specification	Input	Material categories	Unit	Quantity	Source	Comment	Calculation RF	Unit	1 Battery	FU and RF: 1/300 of battery life time
	Electrical Power	Intermediate flow	kWh/day	1,6	(Energuide, 2022)	6 Mnonths for the development. 20 days a week	Q*20*6	kWh/6 months	192	0,64
	Computer	Intermediate flow	piece/year	0,5		6 months of work. 1 computer per 2 years	Q/2	piece/6 months	0,25	0,0008
	Desk	Intermediate flow	piece/year	0,25		6 months. 1 desk per 4 years	Q/2	piece/6 months	0,125	0,0004
	Output	Material categories	Unit	Quantity	Source	Output	Material categories	Unit	Quantity	Source
	CO2 Emission	Intermediate flow	kg/day	0,54	Conversion: E-Power*Conve	6 months	Q*20*6	kg/6 months	65,39	0,2180
	CO2 from Computer	Intermediate flow	kg/piece	331	(CircularComputing, 2021)	6 months	Q/2	kg/6 months	165,5	0,5517
	CO2 from Desk	Intermediate flow	kg/piece	30		6 months	Q/2	kg/6 months	15	0,05
	Autonomous Movement and Path Finding									
	Input	Material categories	Unit	Quantity	Source	Comment	Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life time

Figure 9.13: LCI analysis for system specification, use and raw material processing stages

Use	Electrical Power	Intermediate flow	kWh	0,5		1 charge per 3 days	20	Q*UT	kWh/Day	30
	Output	Material categories	Unit	Quantity	Source		Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life
	CO2 Emission	Elementary flow	kg	0,17		Conversion: 0,34kg CO2/kWh	20	Q*UT	kg/Day	3,41
	Guest Support									
	Input	Material categories	Unit	Quantity	Source	Comment	Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life time
	Electrical Power	Intermediate flow	kWh	0,1			5	Q*UT	kWh/Day	1,5
	Output	Material categories	Unit	Quantity	Source		Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life
	CO2 Emission	Elementary flow	kg	0,03		Conversion: 0,34kg CO2/kWh	5	Q*UT	kg/Day	0,17
	Plant Watering									
	Input	Material categories	Unit	Quantity	Source	Comment	Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life time
	Electrical Power	Intermediate flow	kWh	0,2		assumption: 1 time per week	0,14	Q*UT	kWh/Day	0,084
	Output	Material categories	Unit	Quantity	Source		Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life time
	CO2 Emission	Elementary flow	kg	0,07		Conversion: 0,34kg CO2/kWh	0,14	Q*UT	kg/Day	0,01
	Schedule Management									
	Input	Material categories	Unit	Quantity	Source	Comment	Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life time

Figure 9.13: LCI analysis for system specification, use and raw material processing stages

Electrical Power	Intermediate flow	kWh	0,2			3	Q*UT	kWh/Day	1,8
Output	Material categories	Unit	Quantity	Source		Usage Time / Day [Times]	Calculation RF	Unit	RF: 1/300 of battery life time
CO2 Emission	Elementary flow	kg	0,07		Conversion: 0,34kg CO2/kWh	3	Q*UT	kg/Day	0,20
Melt Lead									
Input	Material categories	Unit	Quantity	Source	Comment	Calculation RF	Unit	1 Battery	RF: 1/300 of battery life time
Lead	Elementary flow	kg/day	1000		Lead is 64,3% of the battery	[Lead %]*[Battery weight]/100	kg	22	0,07
Electrical Power	Intermediate flow	kWh/day	10		2,2% of Q to process 22kg	Q*2.2/100	kWh/22kg Lead	0,22	0,001
Output	Material categories	Unit	Quantity	Source	Output	Material categories	Unit	Quantity	Source
Melted Lead	Product	kg/day	1000		Lead is 64,3% of the battery	[Lead %]*[Battery weight]/100	kg	22	0,07
CO2 Emission	Elementary flow	kg/day	3,41		2,2% of Q to process 22kg	Q*2.2/100	kg/22kg Lead	0,075	0,0002
Moldboard Casting									
Input	Material categories	Unit	Quantity	Source	Comment	Calculation RF	Unit	1 Battery	RF: 1/300 of battery life time
Melted Lead	Intermediate flow	kg/day	1000		Lead is 64,3% of the battery	[Lead %]*[Battery weight]/100	kg	22	0,07

Figure 9.13: LCI analysis for system specification, use and raw material processing stages

Raw Material Processing	Electrical Power	Intermediate flow	kWh/day	10		2,2% of Q to process 22kg	Q*2.2/100	kWh/22kg Lead	0,22	0,001
	Output	Material categories	Unit	Quantity	Source	Output	Material categories	Unit	Quantity	Source
	Molded Lead	Product	kg/day	1000		Lead is 64,3% of the battery	[Lead %]*[Battery weight]/100	kg	22	0,07
	CO2 Emission	Elementary flow	kg/h	3,41		2,2% of Q to process 22kg	Q*2.2/100	kg/22kg Lead	0,075	0,0002
	Cool Off									
	Input	Material categories	Unit	Quantity	Source	Comment	Calculation RF	Unit	1 Battery	RF: 1/300 of battery life
	Molded Lead	Intermediate flow	kg/day	1000		Lead is 64,3% of the battery	[Lead %]*[Battery weight]/100	kg	22	0,07
	Electrical Power	Intermediate flow	kWh/day	10		2,2% of Q to process 22kg	Q*2.2/100	kWh/22kg Lead	0,22	0,001
	Output	Material categories	Unit	Quantity	Source	Output	Material categories	Unit	Quantity	Source
	Lead Part	Product	kg/day	1000		Lead is 64,3% of the battery	[Lead %]*[Battery weight]/100	kg	22	0,07
	CO2 Emission	Elementary flow	kg/h	3,41		2,2% of Q to process 22kg	Q*2.2/100	kg/22kg Lead	0,075	0,0002

Figure 9.13: LCI analysis for system specification, use and raw material processing stages

	Unit Process	Transport Raw Materials to Raw Materials Processing Facility	Transport Processed Raw Materials to Manufacturing Facility	Transport Manufactured ELSA to the Ship	Transport ELSA Intercontinentally
Transportation	Distance [km]	120	200	150	7219
	Actual Load [Tonnes]	16	16	16	860
	Empty Return	No	No	No	No
	Unit	l/km	l/km	l/km	l/km
	Fuel Consumption [L/km]	3	3	3	0,015
	Total Consumption [L]	360	600	450	108,285
	Total Emission [Kg CO2]	90	150	112,5	27,07125
	Source	(USDE,2015)	(USDE,2015)	(USDE,2015)	(TGTS,2022)
	Comment	Transport only Lead	Transport only Lead Parts	Transport only ELSA	Transport 16 T of ELSA
	1 Battery	12,4875	20,8125	15,609375	0
	RF: 1/300 of battery life time	0,041625	0,069375	0,05203125	0

Figure 9.14: LCI analysis for the transportation stage

9.4 Life Cycle Inventory Analysis Diagrams

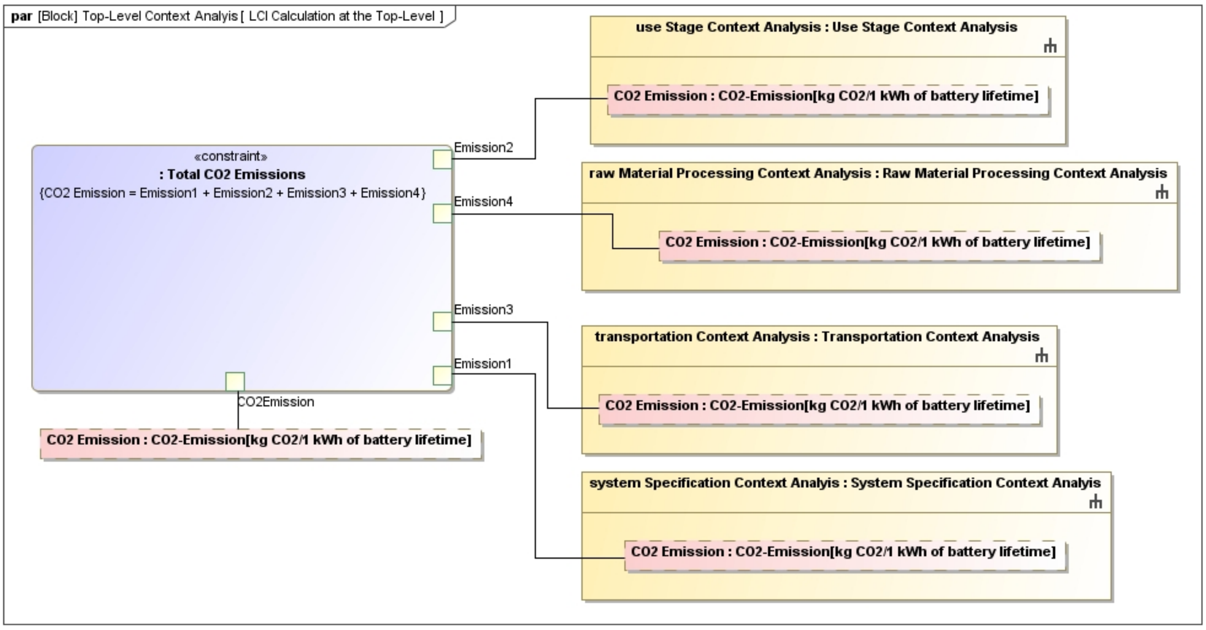


Figure 9.15: LCI Calculation at the top-level

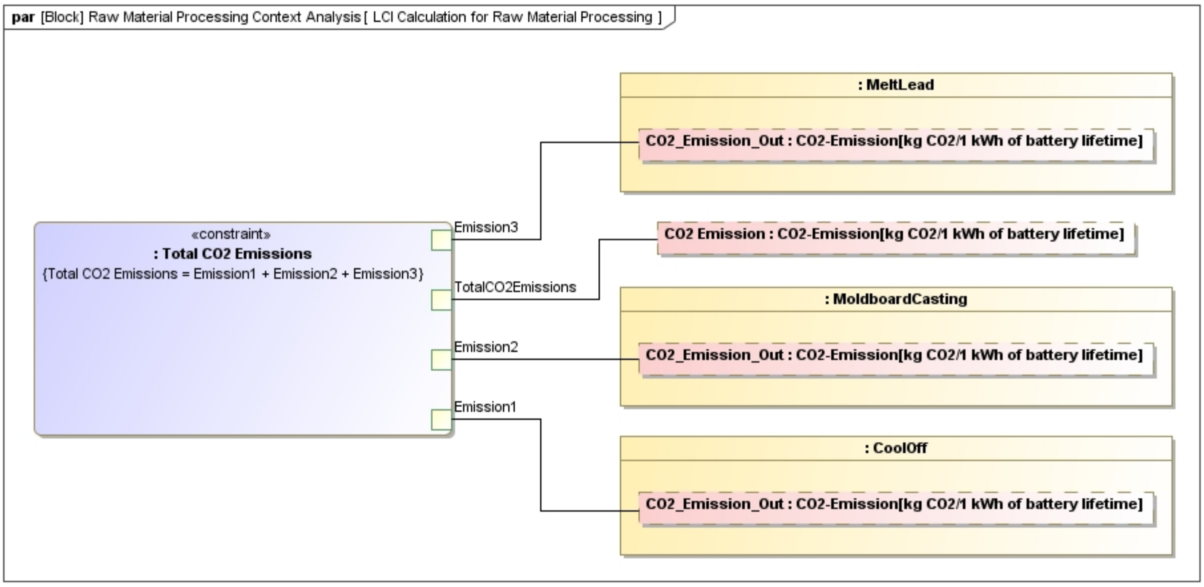


Figure 9.16: LCI calculation for raw material processing

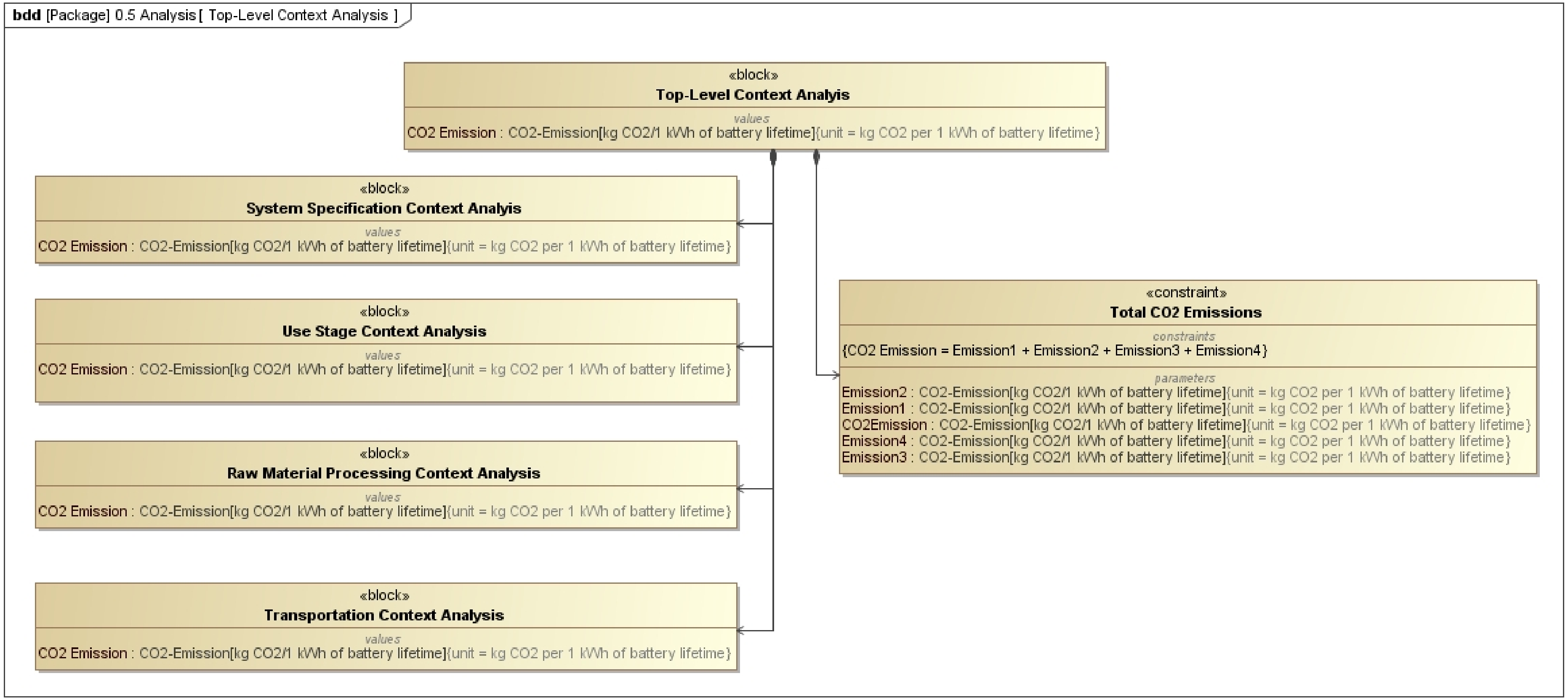


Figure 9.17: Top-Level LCI context analysis

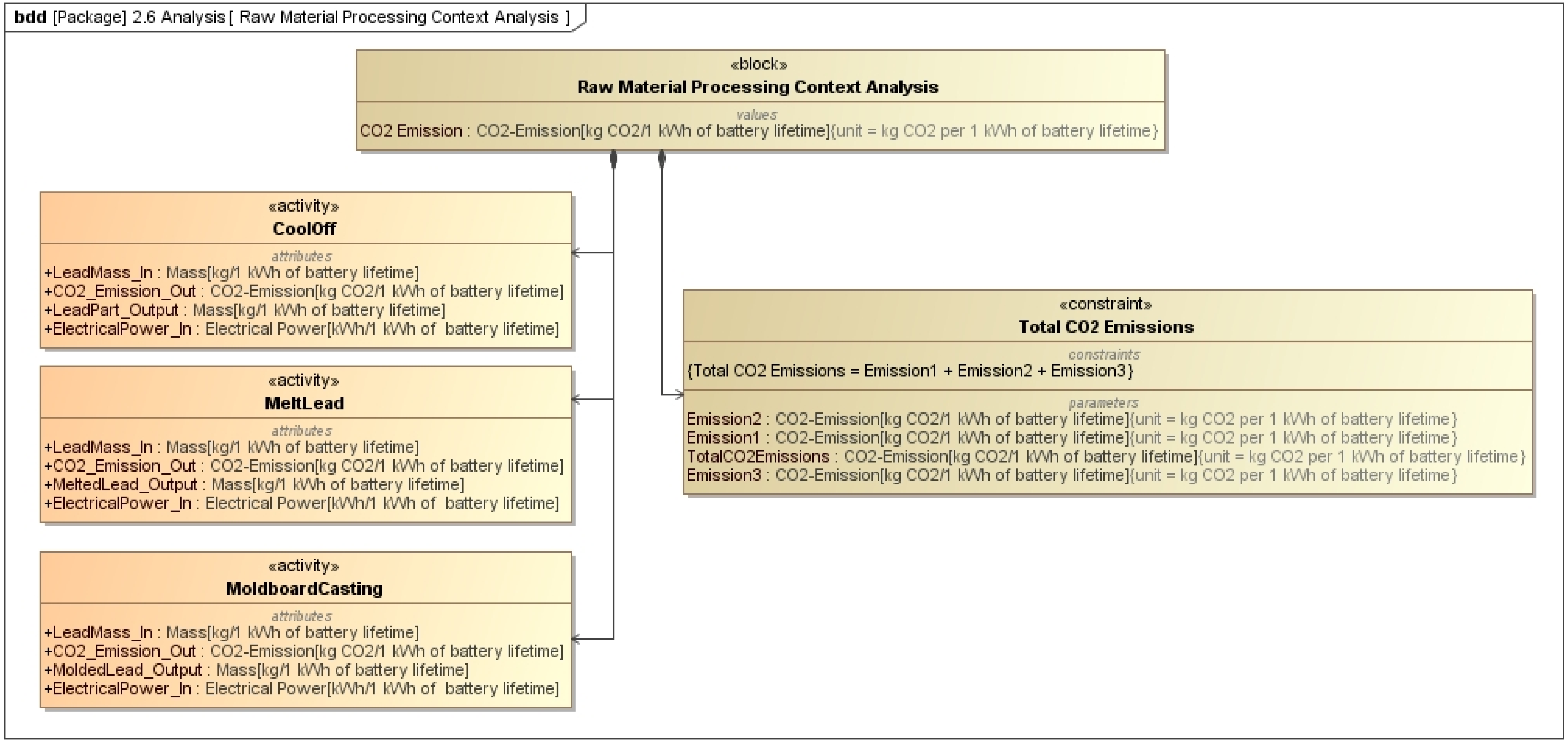


Figure 9.18: Raw material processing LCI context analysis

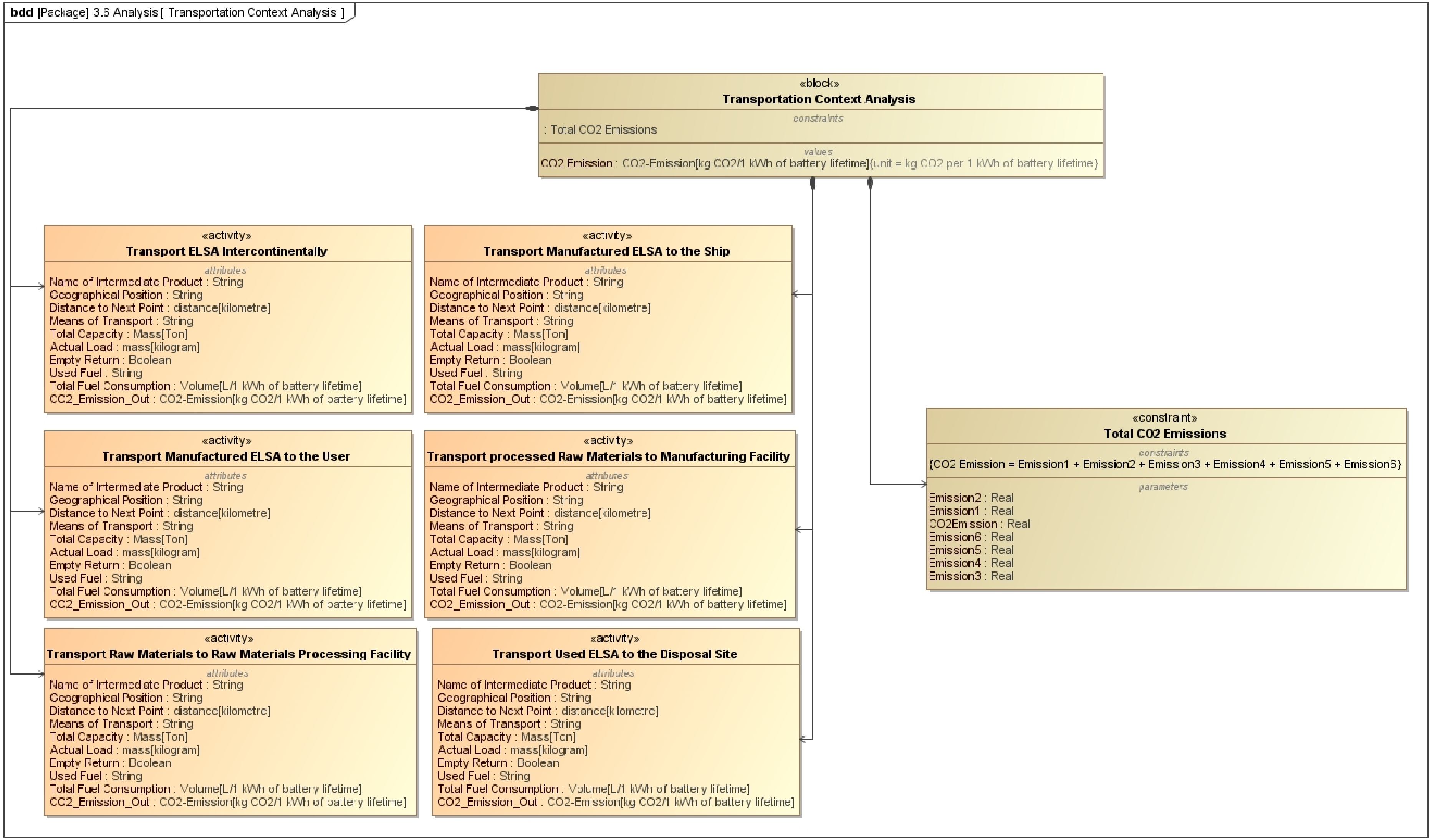


Figure 9.19: Transportation LCI context analysis

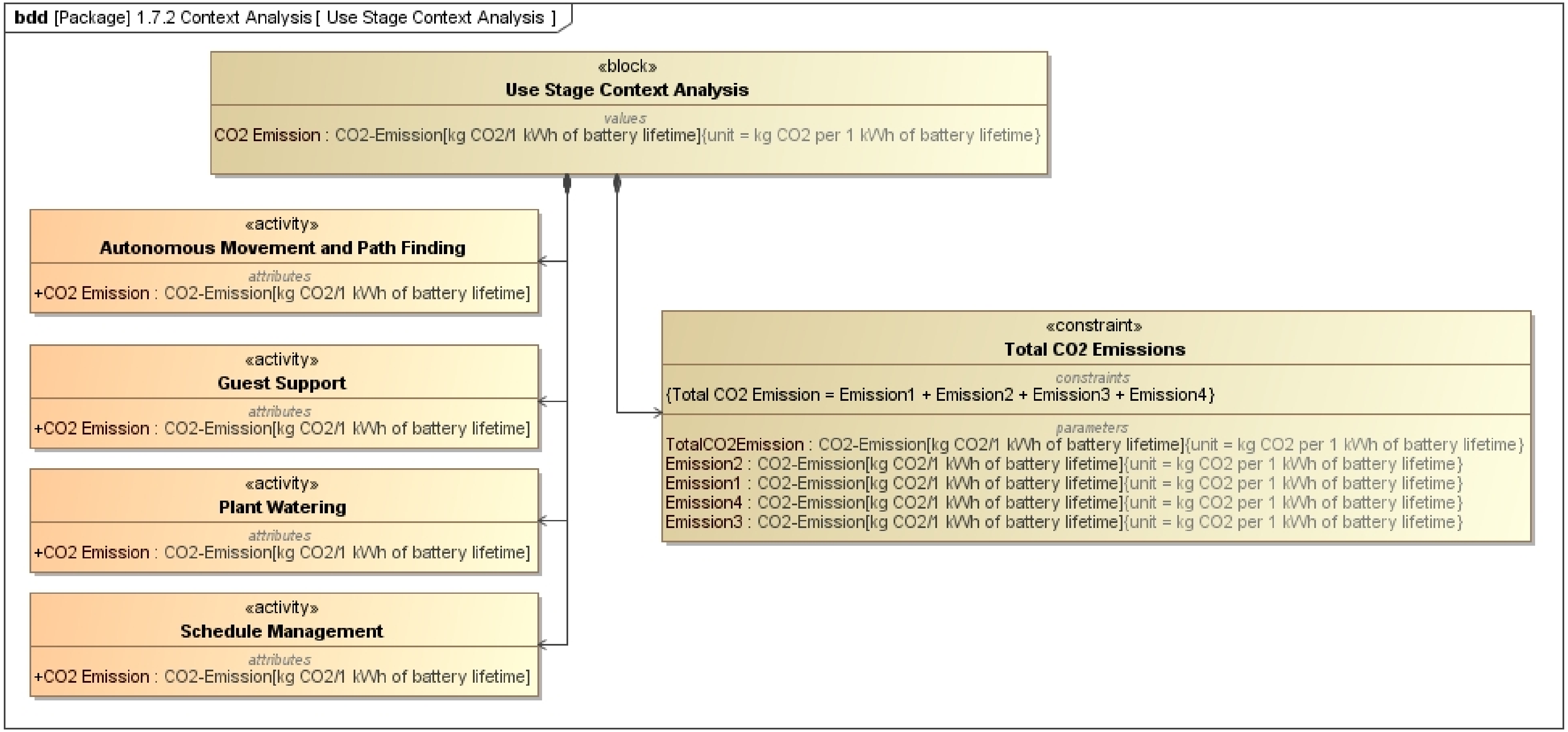


Figure 9.20: Use stage LCI context analysis

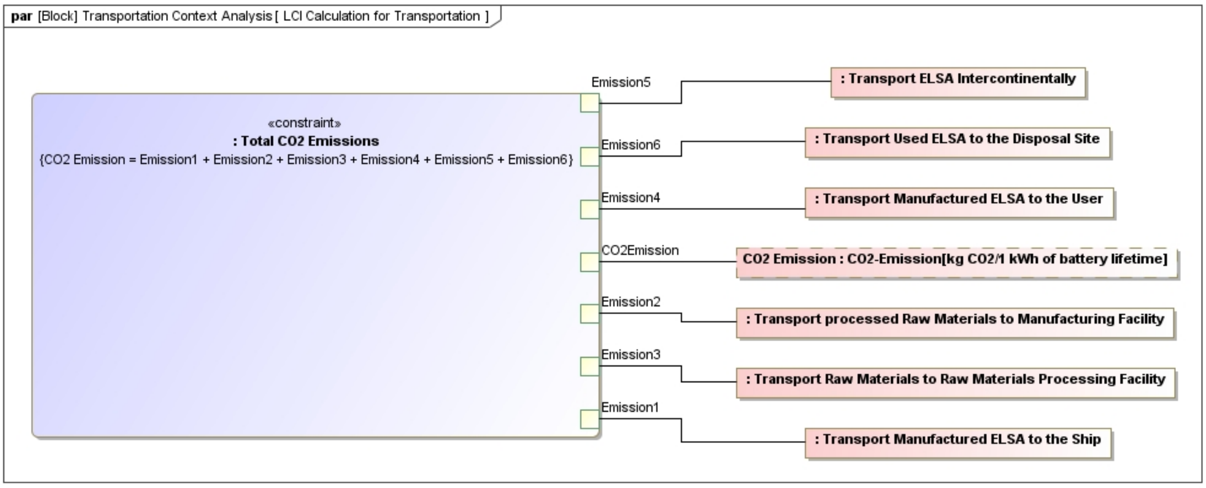


Figure 9.21: LCI calculation for transportation stage

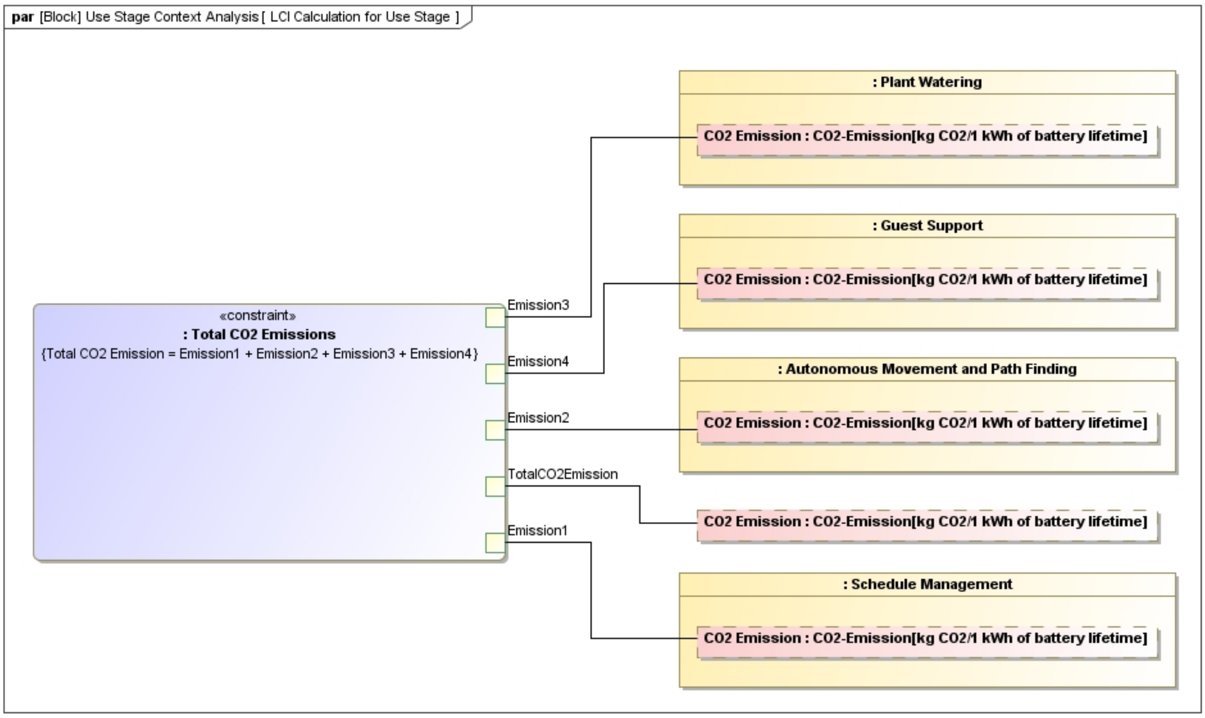
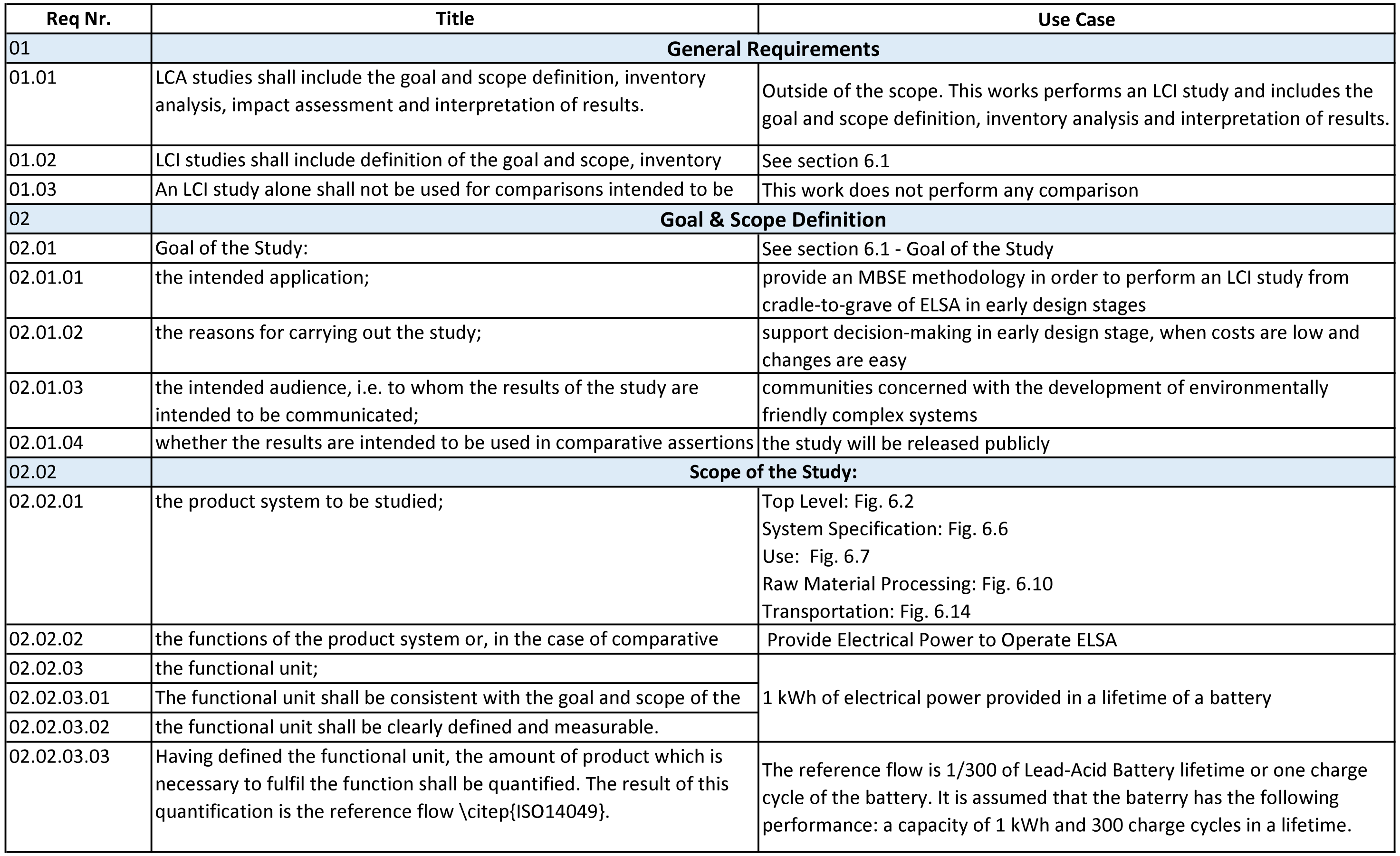


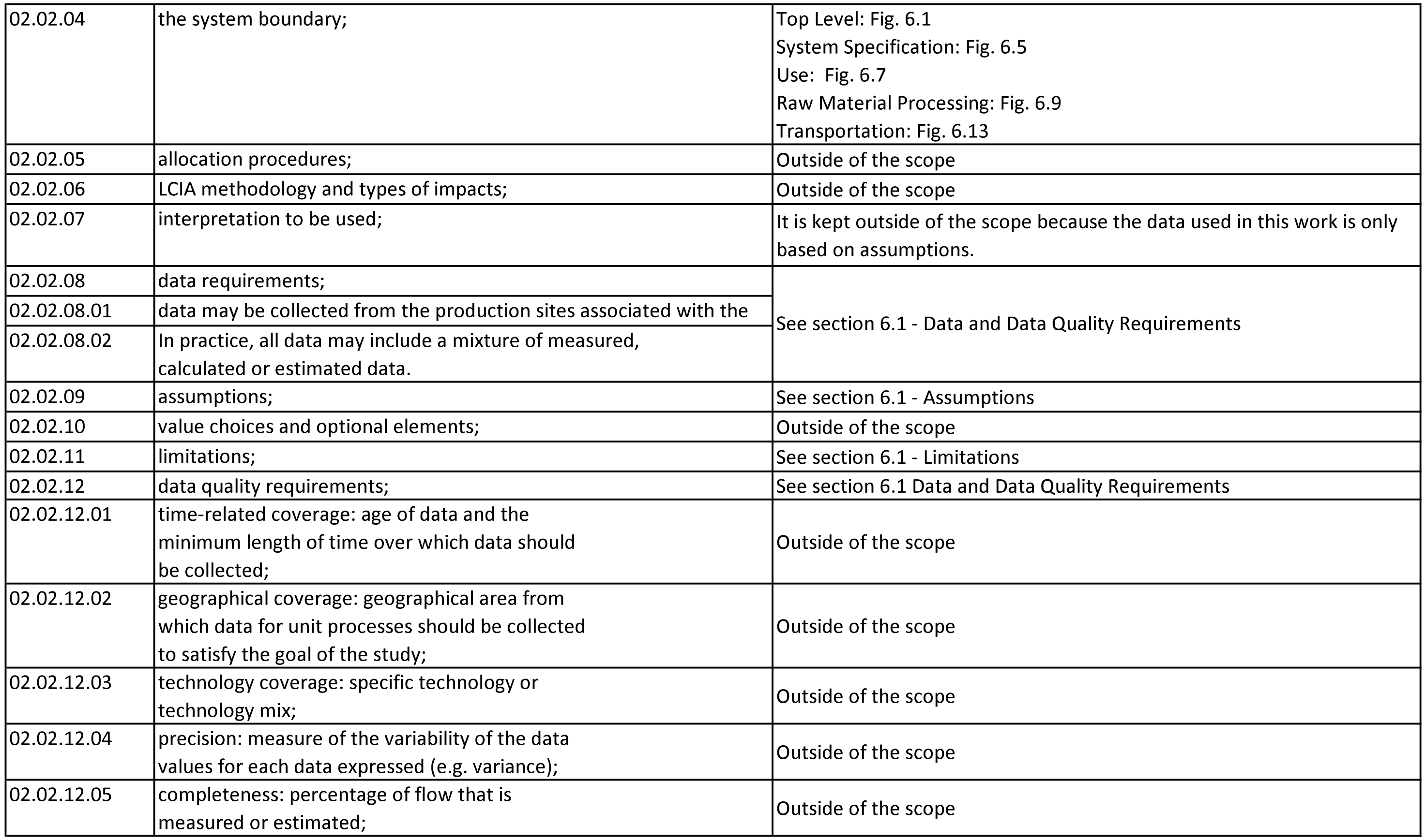
Figure 9.22: LCI calculation for the use stage

9.5 LCA Requirements and their Fulfillment



Req Nr.	Title	Use Case
01	**General Requirements**	
01.01	LCA studies shall include the goal and scope definition, inventory analysis, impact assessment and interpretation of results.	Outside of the scope. This works performs an LCI study and includes the goal and scope definition, inventory analysis and interpretation of results.
01.02	LCI studies shall include definition of the goal and scope, inventory	See section 6.1
01.03	An LCI study alone shall not be used for comparisons intended to be	This work does not perform any comparison
02	**Goal & Scope Definition**	
02.01	Goal of the Study:	See section 6.1 - Goal of the Study
02.01.01	the intended application;	provide an MBSE methodology in order to perform an LCI study from cradle-to-grave of ELSA in early design stages
02.01.02	the reasons for carrying out the study;	support decision-making in early design stage, when costs are low and changes are easy
02.01.03	the intended audience, i.e. to whom the results of the study are intended to be communicated;	communities concerned with the development of environmentally friendly complex systems
02.01.04	whether the results are intended to be used in comparative assertions	the study will be released publicly
02.02	**Scope of the Study:**	
02.02.01	the product system to be studied;	Top Level: Fig. 6.2 System Specification: Fig. 6.6 Use: Fig. 6.7 Raw Material Processing: Fig. 6.10 Transportation: Fig. 6.14
02.02.02	the functions of the product system or, in the case of comparative	Provide Electrical Power to Operate ELSA
02.02.03	the functional unit;	1 kWh of electrical power provided in a lifetime of a battery
02.02.03.01	The functional unit shall be consistent with the goal and scope of the	
02.02.03.02	the functional unit shall be clearly defined and measurable.	
02.02.03.03	Having defined the functional unit, the amount of product which is necessary to fulfil the function shall be quantified. The result of this quantification is the reference flow \citep{ISO14049}.	The reference flow is 1/300 of Lead-Acid Battery lifetime or one charge cycle of the battery. It is assumed that the baterry has the following performance: a capacity of 1 kWh and 300 charge cycles in a lifetime.

Figure 9.23: LCA requirements and their fulfillment

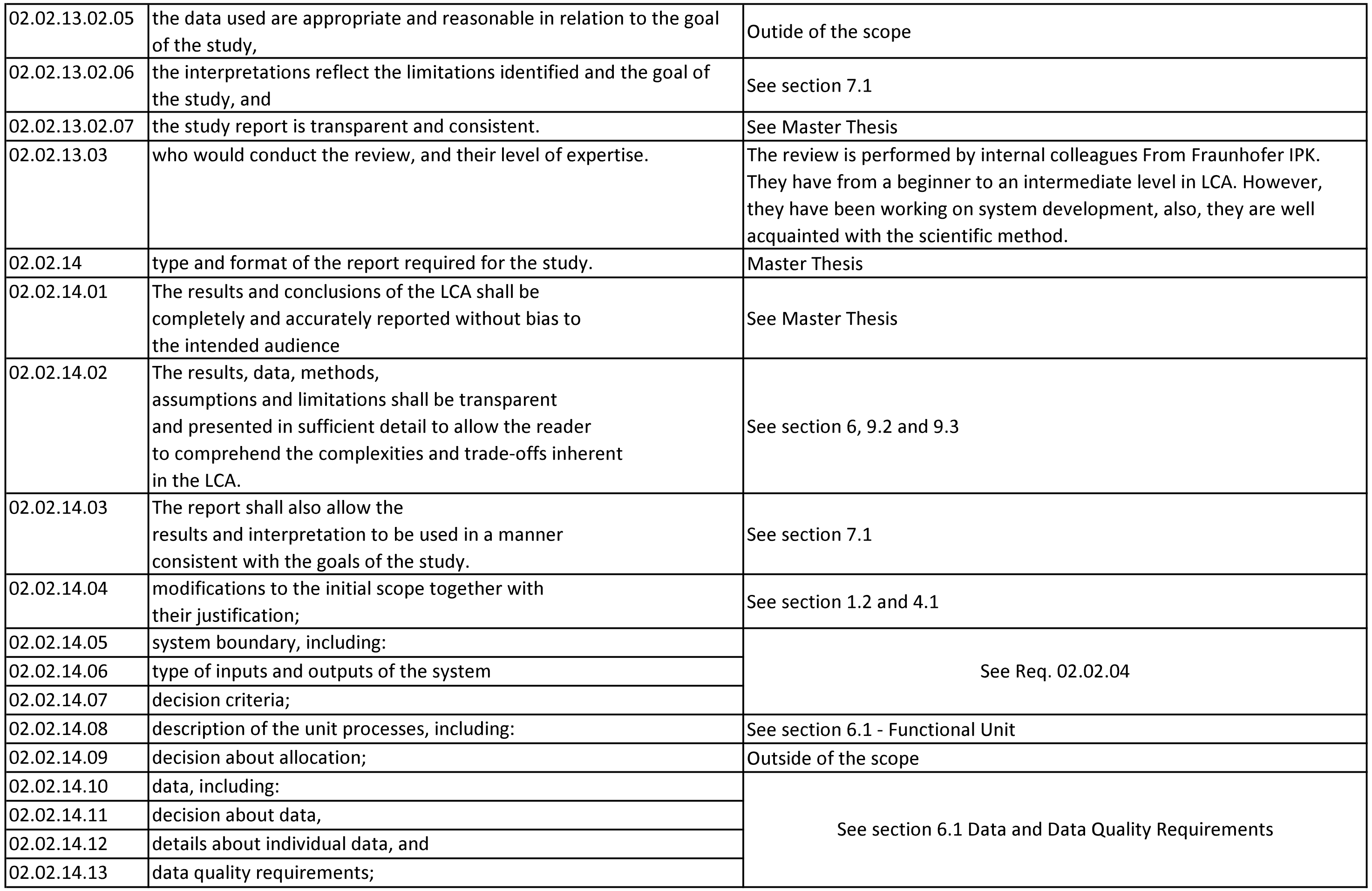


02.02.04	the system boundary;	Top Level: Fig. 6.1 System Specification: Fig. 6.5 Use: Fig. 6.7 Raw Material Processing: Fig. 6.9 Transportation: Fig. 6.13
02.02.05	allocation procedures;	Outside of the scope
02.02.06	LCIA methodology and types of impacts;	Outside of the scope
02.02.07	interpretation to be used;	It is kept outside of the scope because the data used in this work is only based on assumptions.
02.02.08	data requirements;	See section 6.1 - Data and Data Quality Requirements
02.02.08.01	data may be collected from the production sites associated with the	
02.02.08.02	In practice, all data may include a mixture of measured, calculated or estimated data.	
02.02.09	assumptions;	See section 6.1 - Assumptions
02.02.10	value choices and optional elements;	Outside of the scope
02.02.11	limitations;	See section 6.1 - Limitations
02.02.12	data quality requirements;	See section 6.1 Data and Data Quality Requirements
02.02.12.01	time-related coverage: age of data and the minimum length of time over which data should be collected;	Outside of the scope
02.02.12.02	geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;	Outside of the scope
02.02.12.03	technology coverage: specific technology or technology mix;	Outside of the scope
02.02.12.04	precision: measure of the variability of the data values for each data expressed (e.g. variance);	Outside of the scope
02.02.12.05	completeness: percentage of flow that is measured or estimated;	Outside of the scope

Figure 9.23: LCA requirements and their fulfillment

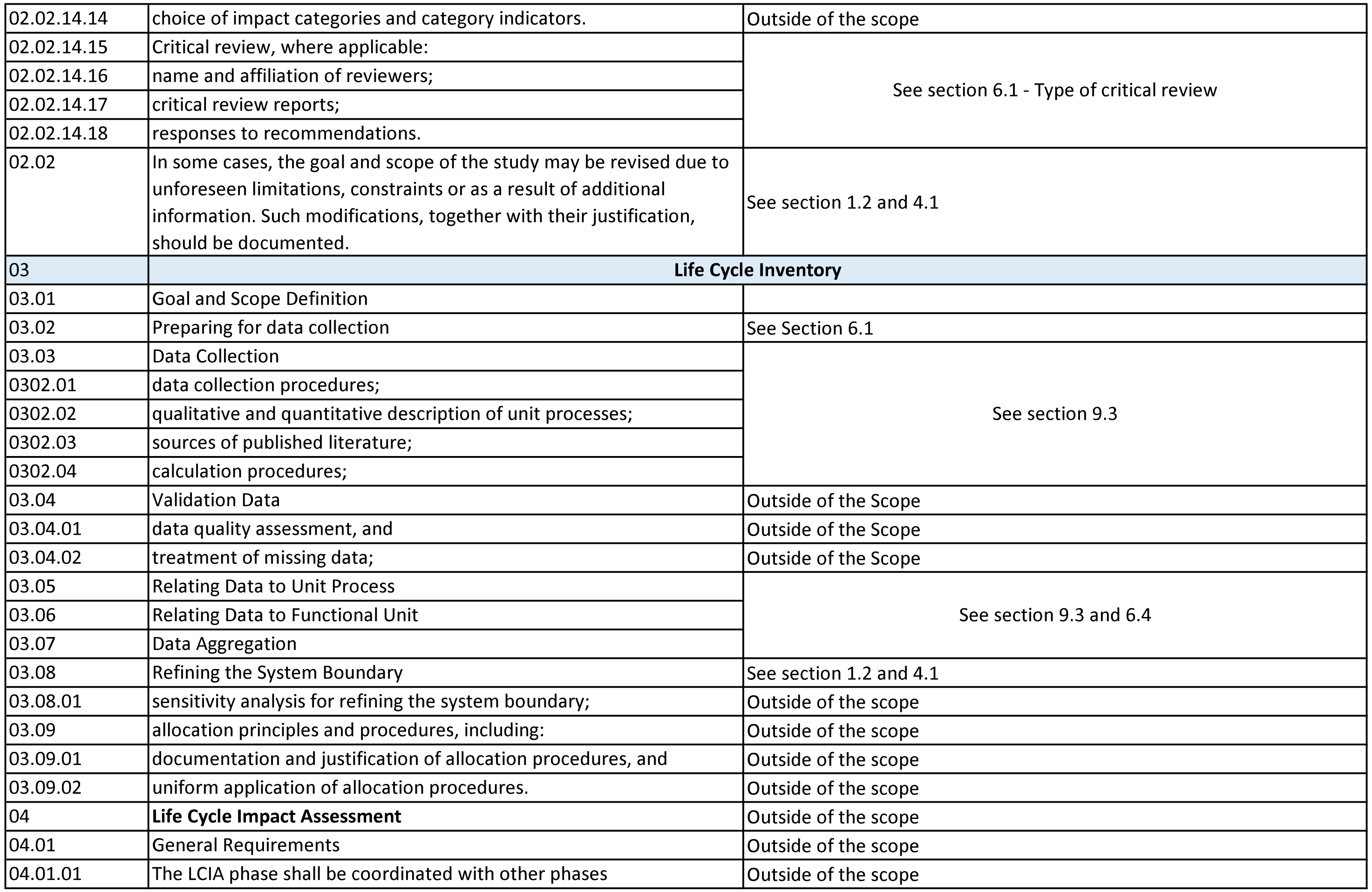
02.02.12.06	representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);	Outside of the scope
02.02.12.07	consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;	See section 6.1 Data and Data Quality Requirements
02.02.12.08	reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;	See chapter 6 as well as section 9.2 and 9.3
02.02.12.09	sources of the data;	See section 9.3
02.02.12.10	uncertainty of the information (e.g. data, models	Outside of the scope
02.02.12.11	Treatment of missing data	Outside of the scope
02.02.12.12	Comparison between systems	Outside of the scope
02.02.13	type of critical review, if any; The scope of the study shall define	The review was performed after drawing conclusions
02.02.13.01	whether a critical review is necessary and, if so, how to conduct it,	Not necessary, but desirable. The review will be perfomed before submitting the master thesis
02.02.13.02	the type of critical review needed (see Clause 6), and	Critical review by internal colleagues from Fraunhofer IPK
02.02.13.02.01	A critical review may be carried out by an internal or external expert. In such a case, an expert independent of the LCA shall perform the review.	internal colleagues with moderate knowledge in LCA and an expertise in product development and scientifc method
02.02.13.02.02	The review statement, comments of the practitioner and any response to recommendations made by the reviewer shall be included in the LCA report.	Outside of the scope
02.02.13.02.03	the methods used to carry out the LCA are consistent with this International Standard,	Yes. This is demonstrated in this table
02.02.13.02.04	the methods used to carry out the LCA are scientifically and technically valid,	Yes. This is demonstrated in this table

Figure 9.23: LCA requirements and their fulfillment



02.02.13.02.05	the data used are appropriate and reasonable in relation to the goal of the study,	Outide of the scope
02.02.13.02.06	the interpretations reflect the limitations identified and the goal of the study, and	See section 7.1
02.02.13.02.07	the study report is transparent and consistent.	See Master Thesis
02.02.13.03	who would conduct the review, and their level of expertise.	The review is performed by internal colleagues From Fraunhofer IPK. They have from a beginner to an intermediate level in LCA. However, they have been working on system development, also, they are well acquainted with the scientific method.
02.02.14	type and format of the report required for the study.	Master Thesis
02.02.14.01	The results and conclusions of the LCA shall be completely and accurately reported without bias to the intended audience	See Master Thesis
02.02.14.02	The results, data, methods, assumptions and limitations shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA.	See section 6, 9.2 and 9.3
02.02.14.03	The report shall also allow the results and interpretation to be used in a manner consistent with the goals of the study.	See section 7.1
02.02.14.04	modifications to the initial scope together with their justification;	See section 1.2 and 4.1
02.02.14.05	system boundary, including:	See Req. 02.02.04
02.02.14.06	type of inputs and outputs of the system	
02.02.14.07	decision criteria;	
02.02.14.08	description of the unit processes, including:	See section 6.1 - Functional Unit
02.02.14.09	decision about allocation;	Outside of the scope
02.02.14.10	data, including:	See section 6.1 Data and Data Quality Requirements
02.02.14.11	decision about data,	
02.02.14.12	details about individual data, and	
02.02.14.13	data quality requirements;	

Figure 9.23: LCA requirements and their fulfillment



02.02.14.14	choice of impact categories and category indicators.	Outside of the scope
02.02.14.15	Critical review, where applicable:	See section 6.1 - Type of critical review
02.02.14.16	name and affiliation of reviewers;	
02.02.14.17	critical review reports;	
02.02.14.18	responses to recommendations.	
02.02	In some cases, the goal and scope of the study may be revised due to unforeseen limitations, constraints or as a result of additional information. Such modifications, together with their justification, should be documented.	See section 1.2 and 4.1
03	**Life Cycle Inventory**	
03.01	Goal and Scope Definition	
03.02	Preparing for data collection	See Section 6.1
03.03	Data Collection	See section 9.3
0302.01	data collection procedures;	
0302.02	qualitative and quantitative description of unit processes;	
0302.03	sources of published literature;	
0302.04	calculation procedures;	
03.04	Validation Data	Outside of the Scope
03.04.01	data quality assessment, and	Outside of the Scope
03.04.02	treatment of missing data;	Outside of the Scope
03.05	Relating Data to Unit Process	See section 9.3 and 6.4
03.06	Relating Data to Functional Unit	
03.07	Data Aggregation	
03.08	Refining the System Boundary	See section 1.2 and 4.1
03.08.01	sensitivity analysis for refining the system boundary;	Outside of the scope
03.09	allocation principles and procedures, including:	Outside of the scope
03.09.01	documentation and justification of allocation procedures, and	Outside of the scope
03.09.02	uniform application of allocation procedures.	Outside of the scope
04	**Life Cycle Impact Assessment**	Outside of the scope
04.01	General Requirements	Outside of the scope
04.01.01	The LCIA phase shall be coordinated with other phases	Outside of the scope

Figure 9.23: LCA requirements and their fulfillment

04.01.02	b) whether the system boundary and data cut-off	Outside of the scope
04.01.03	c) whether the environmental relevance of the	Outside of the scope
04.02	The LCIA phase shall include the following mandatory	Outside of the scope
04.02.01	– selection of impact categories, category indicators	Outside of the scope
04.02.02	– assignment of LCI results to the selected impact	Outside of the scope
04.02.03	– calculation of category indicator results (characterization).	Outside of the scope
04.03	For each impact category, the necessary	Outside of the scope
04.03.01	– identification of the category endpoint(s),	Outside of the scope
04.03.02	– definition of the category indicator for given category endpoint(s),	Outside of the scope
04.03.03	– identification of appropriate LCI results that can be assigned to the	Outside of the scope
04.03.04	– identification of the characterization model and the characterization	Outside of the scope
04.04	the following recommendations apply to	Outside of the scope
04.04.01	the impact categories, category indicators and	Outside of the scope
04.04.02	the impact categories should represent the aggregated	Outside of the scope
04.04.03	value-choices and assumptions made during	Outside of the scope
04.04.04	the impact categories, category indicators and	Outside of the scope
04.04.05	the characterization model for each category	Outside of the scope
04.04.06	the extent to which the characterization model	Outside of the scope
04.04.07	the category indicators should be environmentally	Outside of the scope
04.05	The environmental relevance of the	Outside of the scope
04.05.01	the ability of the category indicator to reflect the	Outside of the scope
04.05.02	the addition of environmental data or information	Outside of the scope
04.06	Assignment of LCI results to the selected	Outside of the scope
05	**Life Cycle Interpretation**	
05.01	General Requirements	
05.02.01	identification of the significant issues based on	See section 7.1
05.02.02	an evaluation that considers completeness, sensitivity and consistency checks;	Outside of the scope
05.02.03	conclusions, limitations, and recommendations.	See chapter 8

Figure 9.23: LCA requirements and their fulfillments

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Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Gemäß der Allgemeinen Prüfungs- und Studienordnung ist zusammen mit der Abschlussarbeit eine schriftliche Erklärung abzugeben, in der der Studierende bestätigt, dass die Abschlussarbeit „– bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit [(§ 18 Abs. 1 APSO-TI-BM bzw. § 21 Abs. 1 APSO-INGI)] – ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich zu machen.“

Quelle: § 16 Abs. 5 APSO-TI-BM bzw. § 15 Abs. 6 APSO-INGI

Dieses Blatt, mit der folgenden Erklärung, ist nach Fertigstellung der Abschlussarbeit durch den Studierenden auszufüllen und jeweils mit Originalunterschrift als letztes Blatt in das Prüfungsexemplar der Abschlussarbeit einzubinden.
Eine unrichtig abgegebene Erklärung kann -auch nachträglich- zur Ungültigkeit des Studienabschlusses führen.

Erklärung zur selbstständigen Bearbeitung der Arbeit

Hiermit versichere ich,

Name: Bassam

Vorname: Hamza

dass ich die vorliegende Masterarbeit bzw. bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit – mit dem Thema:

Modelling and Simulation the CO2-Emissions of a Product (from Cradle to Grave) early in Design

ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

- die folgende Aussage ist bei Gruppenarbeiten auszufüllen und entfällt bei Einzelarbeiten -

Die Kennzeichnung der von mir erstellten und verantworteten Teile der -bitte auswählen- ist erfolgt durch:

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