Development of an MBSE Enabled Ecodesign Approach at Thales NL

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THALES

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Summary

The increasing importance of environmental sustainability has driven organizations to adopt ecodesign practices to minimize the environmental impact of their products. However, integrating ecodesign into existing engineering processes remains a challenge, particularly in complex systems engineering contexts. This thesis addresses this challenge by proposing a novel ecodesign approach that leverages Model-Based Systems Engineering (MBSE) to support environmental analysis and decision-making during the early phases of system development for Thales Netherlands. The approach builds on the ARCADIA methodology and the Capella tool, central to Thales' MBSE environment, enabling the identification and analysis of environmental hotspots at the system architecture level. The approach focuses on calculating carbon footprints of individual components and linking these to system functionalities, offering a clear perspective on key design trade-offs. An application study involving a Thales radar system was conducted to validate the approach, demonstrating its potential to identify and address environmental impact during the early stages of system development. Key results from the study indicate that the proposed approach effectively integrates environmental considerations into Thales's development process by levering MBSE to integrate and assess how non-functional aspects of system design can be addressed during the early development phases. This enables Thales to optimize the architecture early in its development based on customer and business needs beyond functional performance. The thesis concludes with practical recommendations for further embedding ecodesign into Thales's engineering processes. This work contributes to advancing MBSE capabilities for sustainability goals and provides a foundation for future research and development in this field.

Contents

1 Introduction

In today's rapidly evolving world, the essence for sustainable product design has become increasingly evident due to growing environmental challenges such as climate change, resource depletion and pollution. These environmental challenges necessitate a transformative approach in the way products are designed and manufactured, emphasizing the integration of environmental considerations throughout the product lifecycle to enable a sustainable future. Ecodesign is a lever for enabling sustainable product design by focusing on environmental considerations. The ecodesign principle can be defined as the set of activities aimed at integrating environmental considerations into product design throughout the entire lifecycle without compromising other criteria and specifications such as functionality or appearance [1].

Simultaneously, businesses operate in an increasingly competitive global market where sustainability is not just a regulatory requirement, such as those set forth by the European Union's Ecodesign for Sustainable Products Regulation (ESPR) [2], but has become a key differentiator. Although environmentally friendly design and manufacturing may not always be the most cost-effective strategy in the short term, modern companies are increasingly investing in ecodesign for products and processes due to concerns about environmental pollution. This long-term investment not only yields environmental benefits but also influences public opinion about the company and helps with meeting customer and political requirements [3]. As today's consumers become more environmentally conscious, businesses that adopt ecodesign principles can gain a competitive edge and enhance their brand reputation. Furthermore, ecodesign practices can not only enhance an organization's image with various stakeholders such as environmental groups, neighboring communities, suppliers and the general public, but can also lead to an increase in its profitability [4].

As a result, ecodesign can improve competitiveness by incorporating environmentally friendly practices. It influences green purchasing, requiring manufacturers to source from suppliers with environmentally friendly systems and processes. Additionally, ecodesign can positively impact manufacturing performance, enabling the development of competitive products designed to minimize waste and environmental impact. This approach results in products that are more sustainable and meet environmental standards, ultimately contributing to the manufacturer's market position and operational efficiency [5].

However, despite these advantages, the practical implementation of ecodesign remains complex. There are important barriers to overcome to fully implement environmentally friendly product design, such as an unclear link to profitability within companies, difficulties in handling design trade-offs and a lack of management support and integration of sustainable design into organizational strategy [6]. Introducing a new methodology often requires significant changes in habits, pushing designers out of their comfort zones and necessitating the learning of new tools for ecodesign. This can complicate the successful integration of environmental criteria within development teams [7].

Thus, it seems that despite the advantages of implementing ecodesign in enhancing sustainability, stakeholder perception, and competitiveness, its widespread adoption remains a challenge. Companies often struggle with aligning environmental objectives with business priorities, facing barriers such as organizational resistance, design trade-offs, and the integration of new tools and methodologies. This tension between the potential benefits of ecodesign and the difficulties in its implementation reflects a broader conflict regarding the implementation of ecodesign initiatives by companies.

1.1 Thesis Context

The broader conflict regarding the potential benefits of ecodesign and the barriers to adopting an ecodesign mindset have been acknowledged by numerous organizations, including Thales Nederland B.V. (later referred to as Thales). This thesis project is conducted within the context of Thales located in Hengelo, the Netherlands. Thales is a subsidiary of the French multinational Thales Group and has significant presence in the Netherlands with multiple locations. Thales focuses on high-tech, defense and security systems, which are utilized by navies and defense forces worldwide. Their operations include the design, development, production and integration of sophisticated high-end radar and combat management systems. Thales not only operates as a system developer, but also functions as a key systems integrator of the solutions they supply, allowing their systems to interact seamlessly with other means. Additionally, Thales provides full operational support of their solutions, including upgrades and decommissioning. This means that Thales has a stake in all lifecycle stages of their products, which are shown in Figure 1.

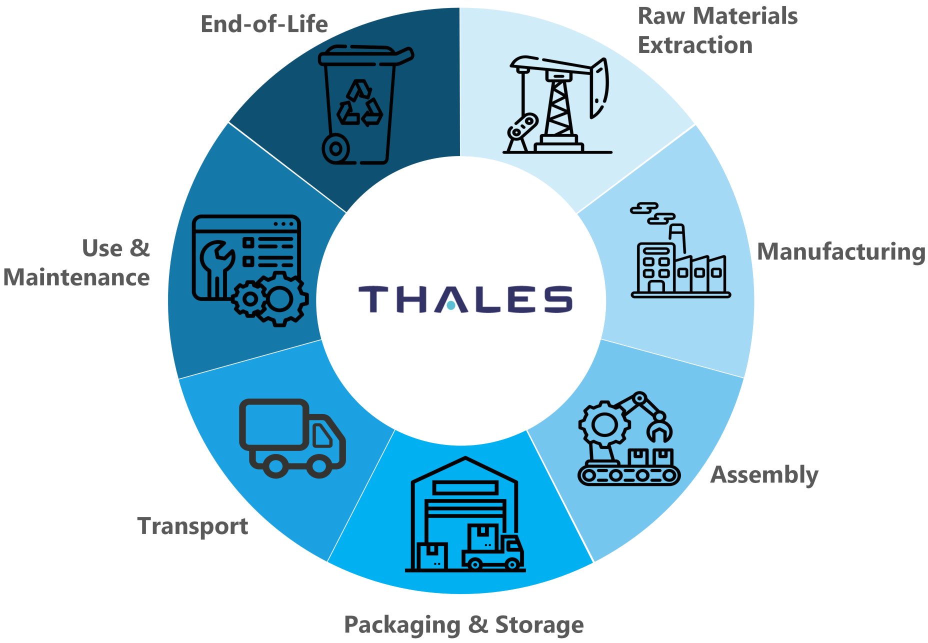


Figure 1: Generic product lifecycle stages of Thales products.

Thales is starting to take environmental considerations into account as it sees the potential benefits of pursuing ecodesign activities and acknowledges their responsibility as a major supplier their industry [3], [5]. However, with these new initiatives also come challenges that resemble those documented by Dekoninck et al. [7], such as forcing changes in habits for design teams and implementing new methodologies. To better understand the motivation for this thesis project at Thales, we can take a look at what they are trying to achieve and why they have struggled to successfully implement ecodesign initiatives in the development process.

Environmental targets

Environmental impacts can take many forms and may concern different parts of nature; climate change, toxicity, biodiversity loss, water pollution, ozone depletion and many others. Thales considers reducing their environmental impact from green house gas (GHG) emissions of their products as its first step towards becoming more sustainable and is looking for ecodesign approaches that are aligned with this view. Thales measures their GHG emissions by estimating their emissions expressed in CO_2-equivalent, which will therefore be the main parameter for evaluating environmental impact in this thesis.

As part of the Group's global strategy to reduce GHG emissions, Thales has introduced various high-level initiatives and targets that align with the Paris Climate Agreement which aims to limit the global temperature rise well below 2°C compared to pre-industrial levels. On the Group's strategic level, considerable attention is already given to increase environmental awareness throughout the entire organization and foster a climate in which every employee contributes to the reduction in GHG emissions. To put words into action, Thales has committed to achieve the following by 2030, using 2018 as a reference:

- A 50.4% reduction in absolute carbon emissions related to its operational processes and energy consumption on all Thales sites (scope 1 and 2 emissions).
- A 15% reduction in absolute carbon emissions related to the supply chain and and use of Thales's products by its clients (scope 3 emissions).

Company GHG emissions are classified into 3 scopes, defined by Green House Gas Protocol, which is an organization that helps companies measure and report their GHG emissions. These scopes are designed to ensure that all relevant emissions are accounted for, both from direct and indirect activities across the value chain.

Scope 1: Direct emissions
Scope 1 includes all GHG emissions from sources and assets that are controlled or owned by the organization. For example, the emissions related to company owned vehicles.

Scope 2: Indirect emissions
Scope 2 includes all GHG emissions from the generation of purchased energy. For example, the emissions produced for generating electricity or extracting gas to that is used to light or heat an office building. These emissions occur at the site of the energy production and not where it is used, but are attributed to the organization that consumes the energy.

Scope 3: Other indirect emissions
Scope 3 includes all other indirect GHG emissions that occur in the value chain, both upstream and downstream. Examples of upstream emissions are those from the production of procured goods and services, waste generated in operations and upstream distribution. Downstream emissions come from the use of sold products, the end-of-life treatment and the downstream distribution of products.

Addressing scope 3 emissions is often complex, as tackling these emissions involves engaging with suppliers and customers to measure, report and reduce emissions across the value chain. However, scope 3 often accounts for the largest portion of an organization's total GHG emissions, as is the case for Thales. On Thales operations, just 2% of GHG emissions belong to scope 1 and 2 combined and 98% belongs to scope 3. Addressing upstream and downstream emissions on all lifecycle stages is therefore a crucial focus for reducing emissions.

The implementation of ecodesign principles is viewed as a key driver of reducing emissions related to Thales products, which will help them address scope 3 emissions. The ecodesign initiative seeks to embed sustainability into the core of Thales's development process, ensuring that products are designed with minimal environmental impact throughout their lifecycle while maintaining superior functionality and performance. Additionally, there is a growing emphasis on the integration of environmental considerations early in the product development process.

Development process
Given the high-tech nature of the systems that Thales develops and integrates, systems engineering is one of the core disciplines that help manage system complexity throughout the devel-

opment process. Sophisticated technological solutions face intricate challenges to ensure that all components of a system work seamlessly together to meet requirements. Systems engineering provides a streamlined, interdisciplinary approach that oversees the design, development, integration, verification, validation and qualification (IVVQ) of complex systems. It helps manage complexity, reduce risks, and ensure that all subsystems function cohesively within the larger system architecture.

Traditionally, systems engineering has relied heavily on document-based processes. However, the increasing complexity of high-tech systems has driven the adoption of Model-Based Systems Engineering (MBSE) in many large organizations, including Thales. According to the International Council on Systems Engineering (INCOSE) [8]: *"MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."* MBSE enhances the capabilities of traditional systems engineering by using models to support each step in the development process of a system. This model-centric approach enables better simulation, visualization and management of highly complex systems.

The Thales Group is a front-runner in the application of software engineering and MBSE tools and practices to deal with complexity during different stages of a product's development process. The Thales Group developed its own open-source MBSE tool called Capella. Capella allows the system engineer or architect to develop the system architecture and capture the model views following the ARCADIA framework. The ARCADIA framework serves as both a modeling language and method, since it describes how elements should communicate and how relationships should be made, but also describes the method for developing the systems architecture.

Since systems engineering supports product development activities, this discipline is also tasked with translating environmental targets into specific ecodesign requirements and ensuring that these requirements can be met through engineering practices. Thales had identified MBSE as a key enabler for integrating ecodesign activities into the product development processes. As a result, the work performed in this thesis must ensure that MBSE capabilities are used to further develop and integrate ecodesign practices in product development. Thales views that leveraging MBSE can help them address some of the current challenges with ecodesign integration.

Ecodesign integration challenges
While Thales has established high-level environmental objectives, they have yet to be translated into actionable engineering practices following a dedicated ecodesign approach. Whilst some ecodesign activities and tools have been developed, they have yet to be established within the product development process. The current inability to effectively integrate ecodesign into the product development process leads to inefficiencies, resulting in limited support from engineering teams to contribute to ecodesign.

This limited support from product development teams to not actively contribute to ecodesign, is strengthened by the fact that environmental performance of their systems is not the main priority. Thales products distinguish themselves for providing superior performance and functionality, which remains the key focus. The systems that Thales develops are used by defense forces around the world, environmental considerations are generally secondary to other aspects of the system such as the need for superior performance, system availability and costs. So far, Thales's current ecodesign efforts are not comprehensive enough to address these factors. As a result, they are looking to develop an ecodesign approach that implements ecodesign activities and tools into their product development processes.

Thales recognizes MBSE as a key enabler for ecodesign, and looks to leverage its capabilities to develop an ecodesign approach that translates high-level environmental goals into actionable engineering activities. Introducing MBSE allows an ecodesign approach to consider the systems architecture and performance related aspects. However, Thales recognizes that there are conflicting challenges for integrating MBSE in ecodesign. Incorporating environmental considerations across a product's lifecycle introduces challenges, as most environmental requirements are not directly functional. Furthermore, additional complexity stemming from environmental aspects is not yet explicitly integrated in MBSE [9].

This situation at Thales reflects the broader global conflict between the recognized benefits of ecodesign and the barriers to its integration. While Thales has recognized ecodesign as a key initiative for reaching its environmental targets, its implementation within Thales faces resistance due to unclear ecodesign workflows and the lack of direct functional links between environmental and performance requirements. Recognizing that superior functionality and performance take precedence in Thales's product development, ecodesign efforts are typically initiated during product redesign processes. Thales has recognized MBSE as a potential enabler for implementing ecodesign during this development process, but it still faces the challenge to establish how MBSE can be leveraged for thus purpose. Addressing the broader conflict in Thales requires a structured approach that bridges the gap between environmental initiatives and practical engineering activities, ensuring that ecodesign becomes an integral part of product development, instead of an isolated initiative.

1.2 Problem Definition and Thesis Objectives

In essence, the central problem that Thales is facing is how to effectively bridge the gap from the high-level incentives on ecodesign to tangible engineering activities that are enabled through MBSE. Specifically, Thales is looking for a standardized approach to ecodesign that considers the architecture of the system early in the product development process, when design changes can still be made. In order to effectively contribute to bridging the gap between the high-level incentives on ecodesign and the development process, this thesis establishes a main objective that is supported by multiple sub-objectives.

Objectives
The main question that this thesis aims to answer is: *How to mitigate the gap from Thales's high-level incentives on ecodesign to practical engineering activities by leveraging MBSE-enabled capabilities?*
Consequently, the main objective of this thesis is to mitigate that gap, by developing an ecodesign approach consisting of actionable engineering activities that are enabled by MBSE and integrated into the early phases of the standard product development process. In order to support and break down the main objective of this thesis into manageable parts, the following sub-objectives have been established:

1. Understand the role and maturity of MBSE in product development at Thales.
2. Understand Thales's current ecodesign initiatives and challenges.
3. Identify the stakeholder needs for improving ecodesign within Thales.
4. Establish how Thales's current ecodesign needs and knowledge gaps can be addressed through the integration of MBSE in early-stage product development.
5. Develop an MBSE enabled ecodesign approach suited to Thales based on the established needs and lessons learned.
6. Validate the developed ecodesign approach through an application study.

Key result
This thesis develops an ecodesign approach for Thales, which includes an ecodesign analysis designed to identify key architectural system elements for improvement based on functionality and carbon footprint. By utilizing MBSE information models, the ecodesign approach connects the system architecture to environmental performance, making ecodesign activities more tangible for engineers. The approach will be applied to an existing Thales radar system, ensuring its relevance and practicality. While the use case is specific to the radar system analyzed, the approach is designed to be generic across similar product redesign projects with ecodesign goals.

1.3 Report Outline

An in-depth analysis into Thales is presented in Chapter 2, aiming to address the first three sub-objectives. To develop the ecodesign approach, the thesis draws on an analysis of Thales's current ecodesign activities, tools, and processes, alongside lessons learned from prior ecodesign projects. Furthermore, an examination of Thales's product development and MBSE workflows ensures that the proposed ecodesign approach aligns seamlessly with existing practices. Stakeholder requirements from disciplines such as systems engineering, product teams, and ecodesign are assembled to assess organizational needs and interests for the ecodesign approach.

The literature review presented in Chapter 3 supports the thesis by addressing knowledge gaps related to integrating ecodesign into engineering workflows. The review covers topics such as ecodesign, systems engineering, MBSE, product development processes, and conceptual design. It identifies best practices, challenges, and opportunities for incorporating environmental considerations into early development stages. Specific attention is given to the use of MBSE and to determine how it can support ecodesign activities early in the product development process, supporting the fourth sub-objective. Insights from the literature support the development both the ecodesign approach and engineering activities.

In Chapter 4, the ecodesign approach is proposed, and relates to the fifth sub-objective. The insights from the literature are filtered through the context of Thales's specific needs and stakeholder requirements to develop an ecodesign approach that ultimately aligns with the existing ecodesign workflow. The proposed approach includes the development of an ecodesign analysis tool, designed to identify hotspots for ecodesign in a system's architecture. Every activity in the ecodesign approach is materialized into actionable steps that help to bridge the gap between general ecodesign incentives and engineering practices.

The thesis culminates in a practical implementation of the proposed approach through a use case involving an existing fire control radar from Thales in Chapter 5, addressing the sixth sub-objective. Using Capella architecture models, product specifications, and carbon footprint data, the analysis identifies opportunities for architectural improvements by highlighting ecodesign hotspots in the systems architecture. These ecodesign hotspots are related to the component functions and system capabilities to provide a functionality based assessment to ecodesign. The ecodesign approach is validated through stakeholder feedback, with lessons learned and improvement opportunities documented for future improvement.

Given globally increasing environmental awareness and Thales's commitment to reducing its environmental footprint, this research is not only timely, but also contributes to aligning systems engineering practices with environmental goals. Through this approach, the thesis will provide actionable insights and a methodology for integrating ecodesign into organizational engineering practices, ultimately contributing to mitigate the broader conflict in implementing ecodesign.

2 Thales Development Process

This chapter aims to provide the full operational context and development process of Thales in which the ecodesign approach must be integrated, relating to sub-objectives one, two and three. Understanding this context is crucial for developing an ecodesign approach that can be integrated into the existing engineering landscape of Thales. This helps identify the constraints in the current development process and addresses needs for the integration of the ecodesign approach. Section 2.1 describes the general product development process at Thales at a high level, and puts it into a systems engineering context. Section 2.2 aims to address sub-objective one, by outlining how MBSE is integrated into the general product development process, explaining how it contributes to the development of systems. Furthermore, it details what tools are used to support MBSE related activities, which helps to understand the capabilities of these tools and highlight the potential for leveraging them in ecodesign activities. Section 2.3 analyzes the current ecodesign initiatives from Thales and their alignment with the product development process, supporting sub-objective two. The analysis highlights key gaps in the current ecodesign approach and activities. These gaps are identified in collaboration with the involved internal stakeholders of Thales. Section 2.4 describes both the involvement of the internal stakeholders in this thesis, as well as their specific requirements for the development of a MBSE supported ecodesign approach, addressing sub-objective 3.

2.1 Thales Product Development Process

This section outlines the product development processes at Thales to construct a comprehensive view of the engineering environment in which ecodesign activities need to be integrated. System engineering is one of the core engineering activities at Thales due to the nature of their complex products, generally referred to as solutions. The systems engineering discipline is integral for the management of complex systems ensuring that Thales systems are delivered efficiently whilst meeting customer requirements and expectations. The information presented in this section will help construct the overall picture of the development process in which the developed ecodesign approach needs to fit.

The Thales systems engineering process can be understood as a structured, interdisciplinary approach that encompasses a wide range of activities in the development process, from the initial requirements and concept development phase through to the final solution delivery and support phase. Systems engineering tasks are performed throughout all phases of the a product development process, and can be represented in the form of a standard systems engineering V-model. Figure 2 shows the Thales systems engineering V-model, which acts as a framework during Thales's standard development processes.

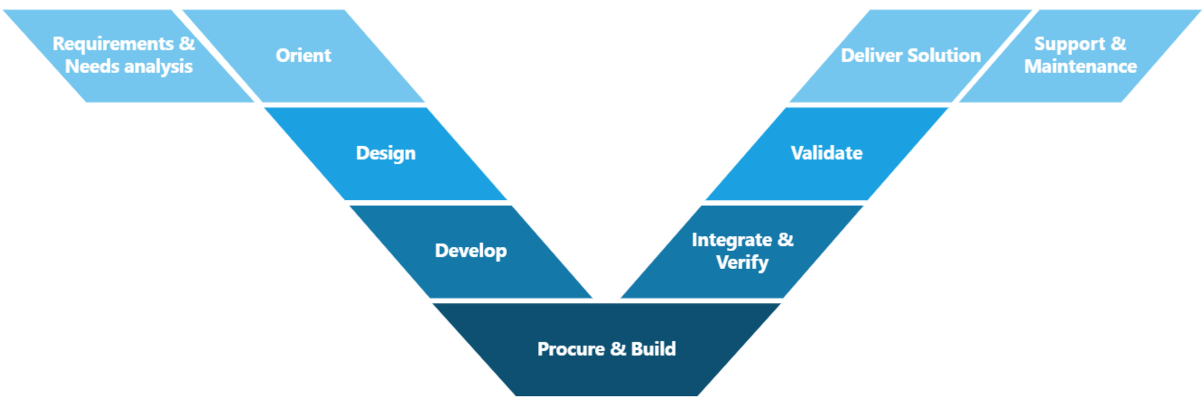


Figure 2: Thales systems engineering V-model framework and development phases.

The V-model framework organizes the development process in sequential phases that are paired with corresponding verification and validation activities. This approach ensures that clear expectations are set and potential limitations are identified early in the development process, without the need for a completed system. It emphasizes the importance of continuous validation throughout the development cycle to meet stakeholder requirements.

This continuous validation is reflected in Thales's development process phases. For example, during the design phase, attention is given to whether the system being designed aligns with the previously defined customer requirements, ensuring that the 'right system' is being developed. Similarly, during the development phase when the design of the solution is fully defined and consolidated, you consider if the system is build right and implement the right functions correctly. This could be done by performing various simulations and analyses individual system components, such that technical specifications of the system are in line with expectations. By describing the further the objectives, main activities and connection between the standard process development phases in Thales, a good understanding of the environment where ecodesign needs to be included is build.

2.1.1 Development Phases

The development phases in the first half of the V-model are the main focus of for this thesis, as this is where the system is designed and ecodesign activities can be implemented. Consequently, activities such as testing or qualification of the solution are disregarded. For each of the considered development process phases, the main activities and outputs relevant to the context of this research are analyzed and documented. Figure 3 details a comprehensive overview of the outputs of each of the standard development phases considered in this analysis.

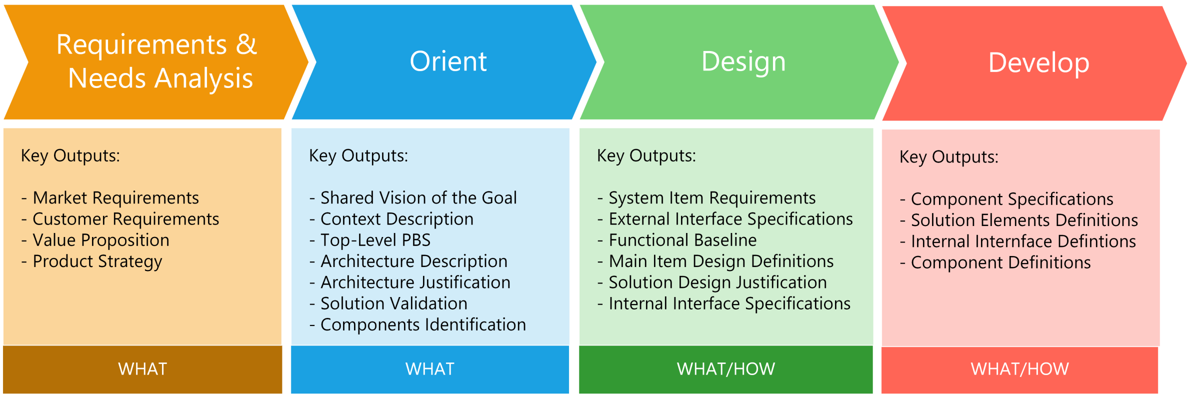


Figure 3: Outputs of the system engineering solution development phases.

Requirements & Needs Analysis

This phase marks the beginning of the systems development. It can be initiated by two primary means; Either by external drivers such as customer demand, or internal drivers like the pursuit of product improvement through internal development initiatives. The main activities in this phase include identifying stakeholders, understanding the context and needs by defining top-level system requirements based on market and customer requirements, and building the product development strategy. Essentially, the most important aspect of this phase is to understand what the users of the system need to achieve, including potential environmental performance aspects. One of the main outputs of this phase is the Operational Concept Description (OCD), which provides the value proposition. This ensures that every stakeholder is on the same page with regards to the system.

Orient phase
During the orient phase, you consider what the system has to achieve for the customer such that they can achieve their mission goals specified in the previous phase. This means that a shared vision of the to be developed system needs to be established. A top-level Product Breakdown Structure (PBS) of the system will be constructed including all of the major architectural elements of the system, which is the combination of any equipment, equipment element, building block and component depending on the context. Subsequently, the first architecture description can be developed and justified, already partially validating that the system has a high chance of achieving its objectives. Environmental stakes of the system such as the its total expected carbon footprint are documented in the environmental performance file. Concluding this phase, a major review of the system architecture is conducted. The objective of this review is to approve the developed conceptual architecture and development strategy to ensure that a value proposition is achieved. Any consideration must be made with regard to risks, costs and stakeholder satisfaction. The review is performed on the scope of the target architecture with full involvement of the hardware and software engineering disciplines.

Design phase
During the design phase, you formalize exactly how the system will operate to meet system requirements and what functions individual components must perform. Subsystem requirements can be specified based on the outputs of the previous phases, such as the architecture description and system requirements. These requirements include any environmental component requirements. The purpose of setting requirements is to agree on the specification of the components and design used to achieve the intended purpose of the solution. One major milestone within this phase is the requirements review. This review results in the full definition and specification of the external interfaces and the systems main design items. The specifications define the requirements concerning the functional and technical characteristics, whilst taking into account the design and production constraints. This amounts to the development of the internal interface specifications, solution design and justification. This phase concludes with a functional system review, which justifies that the design is compliant with the solution requirements and specifications.

Development phase
In the development phase, all of the requirements and design specifications identified in the previous phase are refined down to a complete definition of all the solution elements. All the individual Hardware (HW) and Software (SW) components are consolidated in respect to these requirements, which includes environmental requirements. Once the solution is fully defined, a preliminary design review of these components ensures that the requirements are met. All internal interfaces between components designed. This results in the complete technical design and definition of the HW/SW components and solution elements. This definition consist of a Bills of Materials (BOM), technical drawings, interface definitions, electronic circuits definitions etc. All of these engineering artifacts are stored in the Product Lifecycle Management (PLM) software. The final design review confirms that the detailed design of the solution or the solution element and its interfaces, including integration with all other components, meet the solution requirements.

2.1.2 Product Solution Hierarchy

Thales develops solutions at different scales and levels of complexity. These solutions are structured across multiple hierarchical levels to manage complexity and ensure a clear flow of requirements, design, and verification activities during the product development process. Engineering redesign projects, like ecodesign projects, can be initiated for any solution element within this hierarchy, so it is is important to consider the type of solution element beforehand. The levels can be represented in a breakdown structure, like the one in Figure 4, which indicates the standardized breakdown structure of Thales solutions. The Thales solution levels are:

Mission System:
At mission system level, solutions are developed that have to fulfill a certain mission by integrating and connecting various Thales developed equipment solutions, as well as the integration of systems from other suppliers. This level defines a solution that fulfills top-level missions through the combination of multiple types of equipment.

Equipment:
At the equipment level, solutions are developed that are completely under Thales's control, such as their own developed radar systems. This can be seen in most companies as the system level, where the first standardized system variants also arise. Equipment at Thales are comprised of Equipment Elements, Building Blocks, and Components.

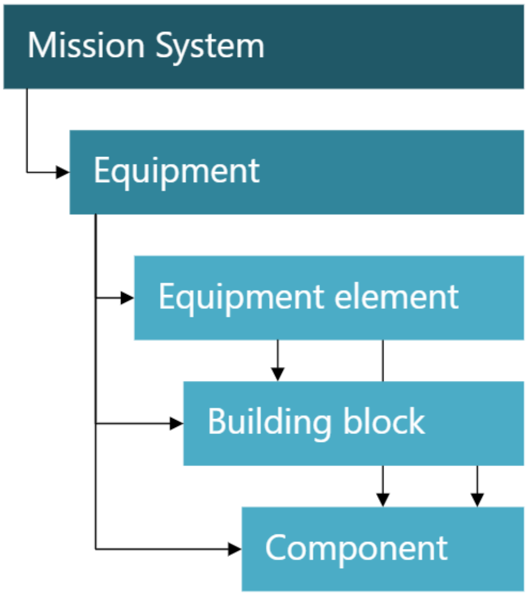


Figure 4: Vertical breakdown structure of Thales solutions.

Equipment Elements:
The equipment elements are standardized high level subsystems that can be used to develop equipment in combination with building blocks and components.

Building Blocks:
Building blocks are standardized modules often consisting of standard components that can be used to develop equipment in combination with equipment elements and components. Building blocks do not belong to a specific product, but can be used across projects and products.

Components:
Components are the lowest level in the standardized set of the Thales solutions breakdown structure. These components are often Commercial Of The Shelve (COTS) items that are managed within the Thales procurement portfolio, but can also be internally developed and designed components.

Each level in a product breakdown structure is developed by different teams who are responsible for the management of variants, the design, procurement etc., all tailoring to a customers needs. For any development process, it is important to considered what the scope of the project is by defining what type of solution is being developed.

This concludes this section outlining the development process at Thales from a general perspective and detailing the type and complexity of the solution elements developed by Thales. The following sections explore the contribution of MBSE to the development of solutions and ecodesign maturity within Thales. By analyzing Thales' MBSE and ecodesign workflows within the overall product development context, this thesis will identify gaps and potential integration points for new activities, setting the stage for the exact ecodesign approach proposed in this thesis.

2.2 MBSE in Thales

This section describes the maturity and use of MBSE within Thales. The integration of MBSE enabled capabilities is a requirement for this thesis, so this section outlines how the MBSE support the development process environment and identifies the tools used to conduct systems engineering activities. The benefit of MBSE lies in the ability to share information digitally between all of these tools through a modeling environment that acts as the single source of truth. Thales uses the Capella software tool for capturing information digitally into models and developing the systems architecture. Capella is the main source for sharing and documenting information, but the full range of software tools required for MBSE integration in Thales is much greater. The MBSE landscape and the way Thales uses it is during product development is detailed in this section.

2.2.1 MBSE in the Development Process

MBSE support the development process by building a shared view of the system from concept to final design. It does this by using models to capture the most important aspects of the system, such as the system's requirements, design and behavior. In order to structure the process of MBSE, a methodology must be used during the development of systems. Thales uses Capella for capturing the system models, which is a software tool that implements the ARCADIA methodology.

The aim of the ARCADIA methodology is to create a clear and shared understanding of the system architecture, enabling better communication among stakeholders and more efficient system development processes. The ARCADIA methodology is based on four layers that help to describe and design the system with increasing level of detail. The four layers consist of; (1) Operational analysis [OA], (2) System Analysis [SA], (3) Logical Architecture [LA] and (4) Physical Architecture [PA]. Each of the phases consists of constructing multiple system views within Capella. The activities and key outcomes of each layer are:

- **Operational Analysis:** Identifies the stakeholders, operational context and scenarios. Defines what the users of the system need to accomplish.
- **System Analysis:** Specifies functional and non-functional requirements and interactions, along with system boundaries. It concludes in a full definition of the contribution expected from the system to meet the needs of the users. It specifies how the system interacts with its environment. It is not yet specified how the system works and what components are included in the system to fulfill specified functions.
- **Logical Architecture:** The principles of the underlying system behaviour are defined. It describes how the system will operate to meet expectations and what components are used to perform the specified functions. However, it does not provide detailed interface specifications.
- **Physical Architecture:** Describes how the system will be developed and built. Fully defines the design and interface specifications.

A holistic system architecture is developed consisting of multiple system views at different levels of detail depending on the development and ARCADIA phases. The four layers of the ARCADIA methodology can be aligned with the standard product development phases detailed in Section 2.1.1, as shown in Figure 5. The first architecting activities start during the Requirements & Needs phase, where the goals is to establish what the users of the system need to accomplish, which aligns with the Operational Analysis of the ARCADIA methodology. The

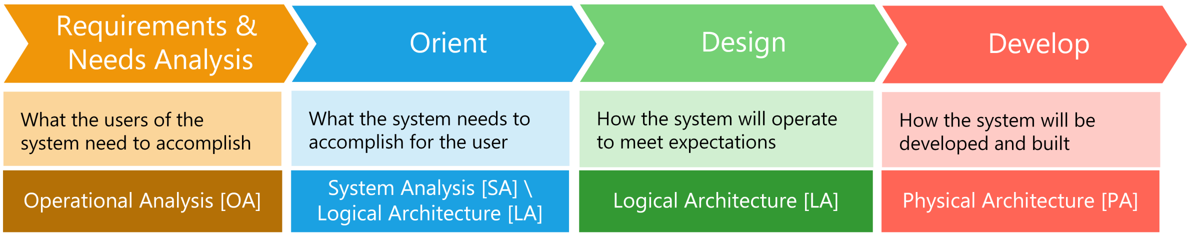


Figure 5: ARCADIA framework aligned with standard development phases.

Orient development phase aligns with both the System Analysis, as the goal is to first establish exactly what the system needs to accomplish for the users to complete their objectives, and Logical Architecture, since top-level components included in the architecture are defined. Furthermore, the Design phase also aligns with the definition of the Logical Architecture in Capella as it is defined how the system will meet its expectations by formalizing requirements. Lastly, the Development phase aligns with the definition of the Physical Architecture, where the entire solution is specified and all internal interfaces are defined. Additional information on the ARCADIA methodology can be found in Appendix A.

2.2.2 Thales MBSE Software Framework

Through modeling, MBSE enables the capture of critical information about a system, including operational scenarios, system states, functions, and capabilities in a structured way. In order to manage the complexity and dissect different systems engineering activities, a set of software tools is integrated into the MBSE framework at Thales. This MBSE framework of tools is shown in Figure 6, which indicates tools dedicated to different disciplines and activities such as requirements management, product line management, IVVQ management, document generation, configuration management, and change management. All tools within the MBSE framework can interact with each other to exchange information and data artifacts. With growing modeling maturity, better understanding, accessibility and consistency is achieved. The MBSE tools are essential for managing requirements and handling design trade-offs, and the framework allows for automatic model validation, greatly supporting the development process.

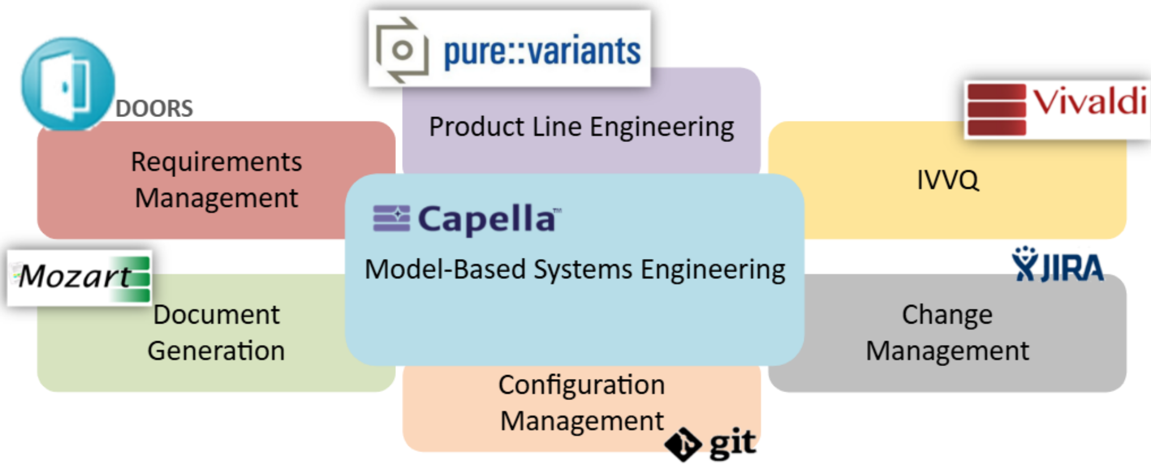


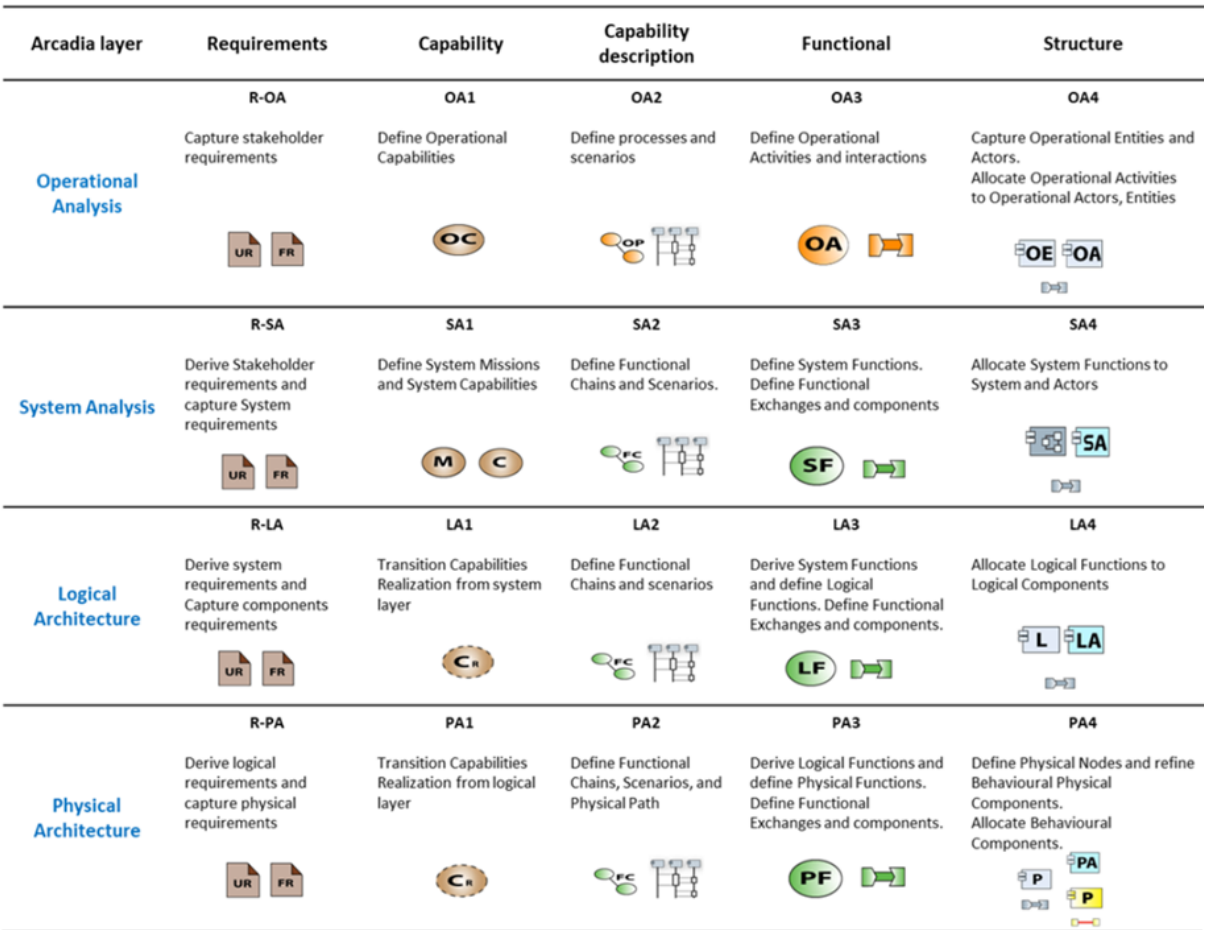
Figure 6: Overview of software tools within the Thales MBSE framework.

Capella is the primary tool used in this context, it adopts the ARCADIA methodology and dictates the design and development of systems. Capella therefore acts as the main information database regarding the design information throughout the development process. Capella's capabilities enable early-stage evaluations of architectural concepts, supporting feasibility studies and performance assessments.

Capella will be used in this thesis to support ecodesign activities, because it acts as the key technical information source throughout the development of the system and its elements. Crucially for this thesis, the system models captured in Capella can be leveraged to conduct environmental analyses at the architectural level, making it a powerful tool for embedding ecodesign early in the design process. Therefore, it is important to consider what elements are modeled in Capella for Thales developed systems, to understand how it might be used to contribute to ecodesign activities.

2.2.3 Capella Modeling Elements

Following the ARCADIA methodology, the four different layers ([OA], [SA], [LA], [PA]) are modeled in Capella to define the systems architecture during the development process. The information modeled in Capella by consists of multiple information categories that are modeled in different diagrams. The main information categories that Thales uses to define their systems are: Requirements, Capabilities, Capability descriptions, Functional, and Structural. These information categories are reflected in every layer of the ARCADIA methodology. The key modeling elements and activities for every ARCADIA layer, in respect of the information categories are detailed in Figure 7.



Arcadia layer	Requirements	Capability	Capability description	Functional	Structure
Operational Analysis	R-OA Capture stakeholder requirements	OA1 Define Operational Capabilities	OA2 Define processes and scenarios	OA3 Define Operational Activities and interactions	OA4 Capture Operational Entities and Actors. Allocate Operational Activities to Operational Actors, Entities
System Analysis	R-SA Derive Stakeholder requirements and capture System requirements	SA1 Define System Missions and System Capabilities	SA2 Define Functional Chains and Scenarios.	SA3 Define System Functions. Define Functional Exchanges and components	SA4 Allocate System Functions to System and Actors
Logical Architecture	R-LA Derive system requirements and Capture components requirements	LA1 Transition Capabilities Realization from system layer	LA2 Define Functional Chains and scenarios	LA3 Derive System Functions and define Logical Functions. Define Functional Exchanges and components.	LA4 Allocate Logical Functions to Logical Components
Physical Architecture	R-PA Derive logical requirements and capture physical requirements	PA1 Transition Capabilities Realization from logical layer	PA2 Define Functional Chains, Scenarios, and Physical Path	PA3 Derive Logical Functions and define Physical Functions. Define Functional Exchanges and components.	PA4 Define Physical Nodes and refine Behavioural Physical Components. Allocate Behavioural Components.

Figure 7: Thales adaptation of ARCADIA architecture layers, activities and modeling elements in Capella [10].

Figure 7 also provides an overview of how modeling in Capella, following the ARCADIA methodology, helps design the system throughout the development process. Even though, the level of detail and scope increases for the subsequent layers, the overall process for developing the system views in each layer is similar.

Defining and modeling the requirements is the first step in developing the system views. Capabilities are derived from the requirements, as they specify what the system or components must be able to do, to fulfill the requirements. A capability description details how a capability can be realized by completing a path of activities or functions in different scenarios. That means that these activities or functions must also be specified individually. These activities and functions must be allocated to a certain entity within the system being developed. Depending on the development phase, this entity can either the system or an operational actor during the Operational Analysis [OA], or single component during the development of the Physical Architecture [PA].

The Capella models in the Physical Architecture [PA] layer contain the most detailed information of the system, and provides a complete overview of the structure of the system. The system breakdown structure shows what components are physically present in the system, and how they are embedded in their relative subsystems and work together to fulfill system level capabilities. The modeled physical components can contain specifications and technical attributes such as mass or power consumption data.

This subsection detailed not only how MBSE supports the design of new system through the development phases, it also detailed what elements and aspects of the system are modeled by Thales currently. This understanding is crucial for the development of an ecodesign approach that aims to integrate MBSE, as it highlights the information that is available from the architecture during the various stages of product development. The next subsection will discuss the current ecodesign maturity in Thales, highlighting the current ecodesign activities conducted during development processes of systems.

2.3 Ecodesign in Thales

This section documents the current ecodesign state-of-the-art within Thales NL and aligns it with the development phases outlined in Section 2.1. This subsection aims to provide a complete understanding of Thales's current ecodesign initiatives and challenges, aligning with sub-objective 2. To achieve the sub-objective, first the high-level ecodesign initiatives are outlined, which will help define the overall strategy to reducing environmental footprint. Secondly, the materialization of the ecodesign initiatives into ecodesign activities is outlined, highlighting what is actually being done during the development process. The last part of this section will focus on the challenges and lessons learned by Thales, based on their experience working with the current approach in the one ecodesign pilot case they have concluded so far.

2.3.1 Thales's Ecodesign Initiatives

The ecodesign initiatives that Thales implements are ultimately designed to help them achieve their environmental targets to limit overall GHG emissions. To steer the overall ecodesign process that Thales wants its development teams to follow, they have introduced five fundamentals for conducting ecodesign. These fundamentals are general directives that support the implementation of ecodesign practices in the development process. Figure 8 shows how the five fundamentals align with the product development phases. The fundamentals are explained next, as this will provide the necessary insight into how Thales steers the development process of products with ecodesign in mind.

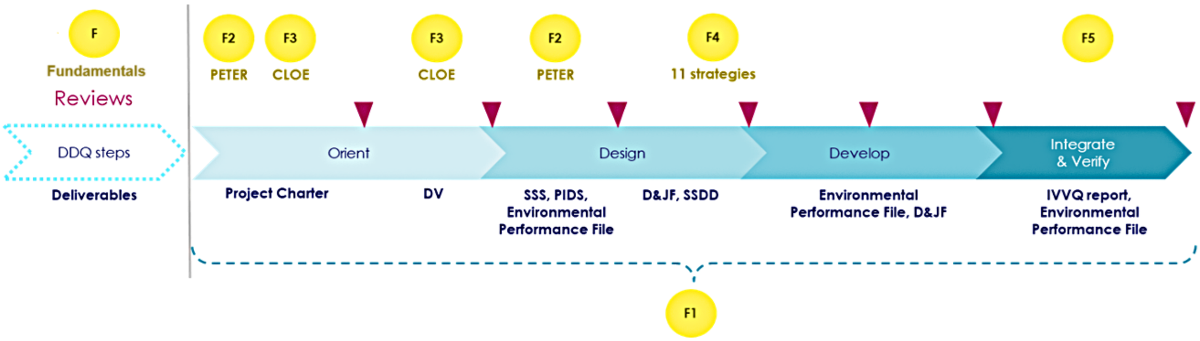


Figure 8: Ecodesign fundamentals aligned with the development process and deliverables.

Fundamental 1: Specify how to deal with ecodesign
For each project, it must be clearly specified how to deal with ecodesign. Ecodesign initiatives are encouraged throughout the project by introducing environmental awareness at each stage of the product design phase. An ecodesign path is outlined incrementally throughout the project, aiming to manage the ecodesign process throughout every development phase.

Fundamental 2: Get environmental stakes
Each project is subject to an environmental evaluation. The product carbon footprint is estimated before development launch, at the start of the orient phase, based on footprint knowledge of previous iterations of standardized solution elements. Multiple lifecycle phases of the product shall be covered to get an indication of a products total carbon footprint. For this purpose, an internally developed tool called PETER should be used, which considers the material selection, manufacturing, testing, use and end-of-life phases of the product's lifecycle. Thales considers these as the most important lifecycle phases for their products, and thus focusing on these phases. PETER can also be used later in the development process when trying to estimate carbon footprint of newly designed solution elements or components.

Fundamental 3: Set the course on the right track
For each project, ecodesign needs shall be addressed using ecodesign strategies to steer the engineering development course. These needs can be addressed with an internally developed checklist-based tool, called CLOE. This tool helps teams to specify ecodesign orientation strategies that help to focus ecodesign efforts. The ecodesign strategies should support engineers to focus on specific areas for improvement when ecodesigning a solution, as they have a strategy in mind. This step should be finalized at the end of the orient phase of product development.

To support this process, Thales has specified eleven ecodesign strategies centered around the three ecodesign themes; Frugality, Innocuity, Circularity. Frugality implies that engineers should design according to the actual customer need and be efficient with the available resources. Innocuity implies that solutions should be as harmless as possible. Circularity implies that solutions are designed with end-of-life in mind, and that the lifecycle loop is closed. The eleven strategies can be found in Appendix B.

Fundamental 4: Implement ecodesign strategies
The selected ecodesign engineering strategies for frugality, innocuity and circularity shall be used to support the ecodesign orientations. The ecodesign strategies are of descriptive nature and are not a list of requirements. Thus the strategies must be quantified into direct goals, which will help to form product requirements that are centered on ecodesign. During the development phase, the design of the system must be consolidated against these targets.

Fundamental 5: Build the footprint profile
Each project shall be characterized at the end of development and the actual performance shall be recorded. The environmental characterization relies on physical measurement or calculation.

This concludes the overview of Thales's current efforts to support ecodesign during the development process through the five fundamentals, which is a high-level initiative on how ecodesign should be performed. This initiative shows the level of maturity in ecodesign in Thales, which is a strategic outline of what ecodesign should look like. The next section details how this view materializes itself into actual ecodesign engineering activities throughout the development of products.

2.3.2 Current Ecodesign Approach

This subsection explores how Thales's initiatives on ecodesign and translate into concrete engineering activities related to ecodesign. Exploring these activities gives a good understanding of the current ecodesign maturity in the physical engineering domain, providing a good view of the current ecodesign process. This view is constructed based on the only pilot case that has been performed related to ecodesign during the time-frame of this thesis. This pilot case was conducted with a radar product team in collaboration with the environmental team. By analyzing the activities that were performed during this pilot, a baseline ecodesign approach was established with these stakeholders. This approach aligns with the product development process phase and is structured by following the five fundamentals. Figure 9 depicts this baseline ecodesign approach that is to be followed at during product development.

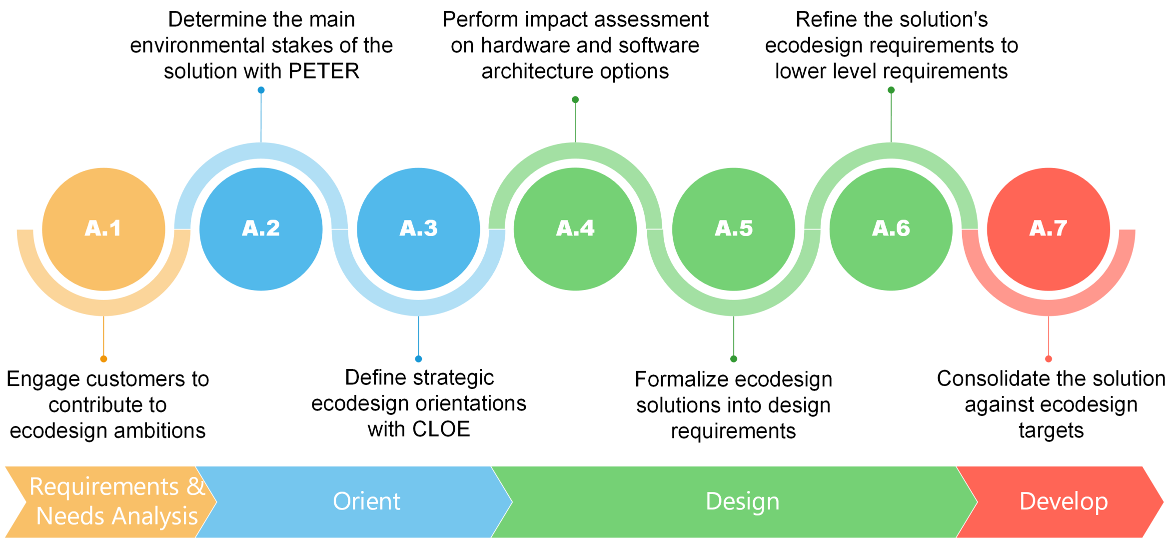


Figure 9: Current ecodesign activities aligned with the standard development process phases in the baseline ecodesign approach.

By comparing Figure 8 with Figure 9, is becomes clear how the fundamentals provide the necessary directions for the baseline ecodesign approach, during early the product development phases. Activity A.1 in Figure aims at providing the necessary backing for ecodesign and allows teams to specify how to deal with ecodesign as defined by fundamental 1. Next, environmental stakes and needs should be identified as early as possible during product development, which aligns fundamental 2 in Figure 8 with activity A.2 in Figure 9. Identifying the environmental stakes helps to define the strategic orientations of ecodesign. The architecture of the previous version is used as the baseline to perform a preliminary environmental study with PETER.

This preliminary environmental study provides some insight into the carbon footprint breakdown of the system. Emission reduction strategies should be defined with CLOE (A.3) in order to target specific aspects, as defined by fundamental 3. After approving the strategic ecodesign orientations, impact assessments must be performed on various elements within the architecture based on the teams knowledge and best judgement in the design phase (A.4). The appropriate resources are allocated to address them in the planned development and generate solutions. Subsequently, the ecodesign solutions are translated into engineering requirements (A.5) and are refined to all levels of the architecture (A.6).

During the development phase, a solution is developed in compliance with the ecodesign requirements at every level of the solution architecture (A.7). The solution's environmental performance is verified by assessing if the ecodesign requirements are met. The full validation of the solution follows after a detailed analysis of the real performance and the environmental performance is validated by the environmental stakeholders of the project.

This ecodesign process paints the picture that ecodesign is well matured into the processes at Thales. However, there is still a mismatch between the strategic directives to introduce ecodesign at every stage of the development process and the practical implementation in engineering practices. The only ecodesign pilot case in which a product team has tried to actively reduce its footprint following the outlined ecodesign approach has revealed some key gaps and challenges. The next subsection will discuss the challenges that the development team experienced when following the current ecodesign activities, and outline the direct lessons learned for the development of a better ecodesign approach.

2.3.3 Ecodesign Pilot Challenges

This subsection highlights the challenges that the radar product team encountered during the ecodesign pilot. By first analyzing what the focus of the ecodesign pilot was and exploring the challenges with the ecodesign approach, a comprehensive understanding of gaps in the engineering activities is made. This amounts in key lessons learned which and highlight what is needed to improve on the current ecodesign approach.

The steps that were followed to improve the carbon footprint of the radar in the pilot, were only related to the orient and design perspective. The engineering activities coincide in general terms with the activities A.2 to A.5 from the baseline ecodesign approach displayed in Figure 9. These activities included:

1. Analyzing the current product footprint based on existing carbon footprint data of the product's latest design iteration. This helped identify in what lifecycle stages of the system are responsible for the largest impact on the total lifecycle carbon footprint, aligning with activity A.2.

2. Emission reduction strategies aimed at reducing carbon footprint in the significant lifecycle stages were defined, aligning with activity A.3. Emission reduction estimates were generated to help the team get an indication how certain carbon reduction strategies impact the carbon footprints.

3. Conducting multiple brainstorm sessions to generate ideas that could reduce the carbon footprint of the radar system. All ideas were subsequently analyzed with a feasibility study in terms of projected cost and carbon footprint reduction, aligning with activity A.4.

4. The effect on emission reduction and the costs of developing and integrating the additional design complexity was analyzed. The team was able to identify what proposed

solution would work most effectively using a cost and effect metric. Given the targeted solution, new requirements were made at a system level so that the design solution was substantiated, aligning with activity A.5.

Although a conclusive redesign proposal for a single component was realized that should improve on the lifecycle carbon footprint of the product, there is not a structured workflow in place on how to conduct the individual ecodesign activities in practice. The lack of a description of the activities in turn made the project lengthy, unstructured and not directly repeatable. To expand on this aspect, there was no standardized method or tool for finding alternative solutions that reduce GHG emissions. This means that repeatability of success depends more on the experience and expertise of individual engineers than on data-driven decisions. This highlights the gap between overall strategy and set in stone engineering tasks. However, also some good practices that should be considered for the future became apparent. The lessons learned from analyzing the most developed use of ecodesign are summed up below.

Lessons learned:

1. If available, carbon footprint data of an existing iteration of a system should be used for preliminary footprint evaluation. It gives indications on where possible improvement can be made most efficiently.

2. Is is best to introduce ecodesign practices and tools early in the development process. During the early phases, changes in design will be less costly to develop than later in the final design stages.

3. It was difficult to generate technical solutions based on the information available early in the process and just an overview of product carbon footprint. The solution space was too large to select ecodesign strategies and generate technical solutions with the limited information on product carbon footprint. A method should be established for pinpointing aspects of the system that have large potential in reducing emissions, beyond just the overall carbon footprint evaluation.

4. It is useful to quantify expected footprints and costs of alternative solutions. A standardized analysis metric should be used to evaluate technical solutions.

5. A technical solution that results in reduction of carbon emissions must not negatively impact the performance of the system. This link is currently not visible, however would provide key insight to help develop and assess technical solutions.

6. In general, the current ecodesign activities are descriptions of what must be done, but do not specify how they must be performed and what exact results must be achieved. This concrete definition of the activities should be established for clarity.

These lessons raise questions on how to implement ecodesign activities effectively and standardize the process of ecodesign. Hence, the need for this research has emerged for developing and implementing a standardized ecodesign approach, integrated into the development process of new systems supported by systems engineering. Thales seeks a solution where it can make use of its existing tools and systems engineering practices to make ecodesign and environmental evaluation more convenient to engineers. Thales has identified the opportunity to support ecodesign through their MBSE capabilities to help solidify the ecodesign approach in engineering product development. This means that it is important to consider what the relevant internal stakeholders in this thesis project are and what there expectations are for the development of an ecodesign approach which utilizes MBSE.

2.4 Stakeholder Involvement

This section discusses the involvement of key stakeholder disciplines, whose requirements and expectations play a crucial role in shaping this thesis. The emphasis will be on understanding the specific needs and objectives of each discipline and why their involvement is essential to this thesis, addressing sub-objective 3 stated in the introduction. The internal stakeholders are essential to balance ecodesign objectives with system performance and feasibility, as their insights support the integration of ecodesign with MBSE. By analyzing their needs and requirements, this section provides the necessary foundation for the MBSE based ecodesign approach proposed in this thesis. It supports a more effective integration of ecodesign by validating the value of the developed approach in this thesis against the stakeholder expectations.

2.4.1 Stakeholder Disciplines

There are three key discipline areas involved in this project which are; environmental, systems engineering, and radar product team representatives. Each of these disciplines contribute in their own way. A stakeholder register can be found in Appendix C, detailing the general concerns and exact roles of the individual stakeholders of this thesis. The three stakeholder disciplines are involved because they either provide input and set constraints and may be impacted by the outcome of this research project. The roles and concerns of the key discipline areas within Thales are explained below.

Environmental:
The expertise provided from the environmental discipline is crucial in understanding the current ecodesign trajectory and ensuring that this project is in line with the targeted objectives for embedding ecodesign into the engineering processes. This discipline is also responsible for setting constraints on how environmental calculations must be done to be in line with current footprint calculations and where necessary provide the necessary means or environmental data used in this thesis. This discipline consists of a single ecodesign spokesperson who will also validate the benefits from the proposed approach developed in this thesis in light of the overall direction ecodesign is going in the organization.

Systems Engineering:
Their technical understanding of systems engineering and modeling is necessary for understanding complex system architectures and the information available during various lifecycle stages. They provide insight on the potential use of various tools and the information available to support ecodesign decision-making. The MBSE team ensures that the system architecture and functional descriptions are properly defined or can evolve to a state that captures essential system behaviors and specifications required to support ecodesign. The specific roles are people who directly contribute to the advancement of MBSE within Thales and view ecodesign as another step toward a complete integration of MBSE within the organization.

Radar Product Team:
The product team's experience with the current ecodesign workflow is key to identifying desired capabilities of the proposed ecodesign approach developed in this thesis. Their input is crucial for developing the use-case for one of the existing radars under their control. They are directly involved in providing the means to gather product data required for conducting ecodesign studies on the radar. They are also responsible for validating the added value of this thesis, ensuring that the proposed approach aligns with practical needs and delivers the desired benefits.

2.4.2 Stakeholder Needs

With an understanding of the roles and rationale behind each stakeholder discipline's involvement, the next step is to outline their specific expectations and needs. These needs represent the inputs from the involved stakeholder disciplines and will shape the development of the ecodesign approach and highlight key gaps for which answers need to be found. By addressing these needs, the aim is to ensure that the work from this thesis helps to advance ecodesign within Thales through the use of MBSE. The list of key stakeholder expectations centered around an MBSE enabled ecodesign approach is shown in Table 1. These needs were established through internal discussions and interviews with relevant stakeholder discipline representatives.

Table 1: List of stakeholder expectations and needs for developing and defining an ecodesign approach.

List of Stakeholder Needs		
Discipline	**#**	**Stakeholder Needs**
Environmental	1	An approach must be constructed that mitigates the gap between ecodesign directives and engineering activities, to support the use of ecodesign during development. A clear definition of the ecodesign practices must be made available.
Environmental	2	An approach must align with the already in place ecodesign approach and general directives. This means that any new activity must fit into the established ecodesign approach and use the information that is provided by the current activities and calculate carbon footprint according to Thales's standards.
Environmental/ Radar Product Team	3	Ecodesign should not be limited to carbon footprint assessments alone but should also consider the architectural aspects of a system. This requires an approach that enables engineers to assess environmental impacts in relation to system functionality, performance, or other design parameters.
Radar Product Team	4	An ecodesign approach needs to provide more information that highlight areas for environmental improvement in the system's architecture, which will make it easier to orient on technical solutions. A quantifiable means of assessing improvement opportunities is needed to improve repeatability.
Radar Product Team	5	Ecodesign should build on existing product carbon footprint knowledge as much as possible. The latest product and component specifications should be used during carbon footprint analyses.
Radar Product Team	6	Any new activity or analysis must be conducted in a commonly accessible platform or tool, such that engineers do not need to learn new software.
Radar Product Team/ Systems Engineering	7	The ecodesign approach must consider the systems architecture and as many modeled components for which technical data is available in the Capella models. Significant level of detail is required to validate any ecodesign approach in practice.
Radar Product Team/ Systems Engineering	8	Any ecodesign activity must adhere to the component information that is available during different development stages and ensure consistency and traceability with the Capella models.
Systems Engineering	9	Ecodesign activities need to be integrated into MBSE architecture models or must utilize the system information available in Capella.

These needs highlight the importance of aligning with existing ecodesign practices, ensuring compatibility with MBSE, and practical usability for product teams. These stakeholder needs help ensure that both environmental and technical limitations are considered. The convergence of these needs highlight the importance of developing ecodesign activities that not only support the goal to meet environmental targets, but also adheres to technical constraints.

These technical constraints have been pointed out by the stakeholders, such as the need to use the tools and processes already established across disciplines to be incorporated into the ecodesign approach as much as possible. Furthermore, stakeholders emphasize the importance of integrating ecodesign principles early in the development process, where they can have the greatest impact. A summary of the key points from this chapter that must be considered by the ecodesign approach is presented in the next section.

2.5 Summary of Key Needs

Concluding this chapter is a summary of the key points that need to be considered by the ecodesign approach. This chapter was aimed at addressing the first three sub-objectives stated in the introduction. These sub-objectives were aimed at understanding the role of MBSE within the development process, the current ecodesign initiatives and challenges, and the stakeholder needs. This resulted in a list of lessons learned from the ecodesign pilot case, outlined in Section 2.3.3, and the stakeholder expectations from Section 2.4.2. Summarizing these provides a set of key points that are critical for the development of the ecodesign approach in this thesis.

1. Transforming high-level ecodesign directives into practical engineering activities
There is a need for an approach that integrates ecodesign into engineering workflows, ensuring alignment with existing Thales methodologies and directives. As such, any new ecodesign activity must be compatible with the baseline ecodesign approach, using existing carbon footprint reporting standards. Crucially, the current ecodesign approach describes what should be done but not how to do it or what results must be achieved, which must be also addressed.

2. Leveraging existing product data and ensuring accessibility
Ecodesign activities should make use of available product data for the given development stage. Additionally, new activities or analyses should be conducted within commonly accessible engineering platforms, minimizing the need for engineers to learn new tools.

3. Integrating ecodesign through MBSE
To ensure traceability and consistency, ecodesign activities should utilize information from Capella. This means that the approach must be compatible with existing MBSE practices and leverage modeled components and technical data at different stages of development. However, it is still unclear how MBSE can best support ecodesign practices for Thales and thus requires more research.

4. Expanding on decision-making factors beyond carbon footprint calculations
The current ecodesign approach made it difficult to generate technical solutions. A method must be developed that highlights key architectural areas for environmental improvement, making it easier to orient on technical solutions. A quantifiable and standardized means of assessing environmental impacts is needed to improve repeatability. Technical aspects such as the system requirements, performance, functionality or other technical aspects should be included to help engineers evaluate options identify the most effective improvement strategies. What decision-making factors are best to include is not determined yet, but must be compatible with the existing product data in Capella, as stressed by the previous two points.

5. Supporting early-stage decision-making
Since design decisions made in early development phases have the highest impact, ecodesign must be introduced as early as possible. However, early-stage assessments must be detailed enough to guide engineers toward viable solutions without overwhelming them with unnecessary complexity. Although the baseline ecodesign approach spans all development phases, there is a need for a better and more structured and streamlined approach due to the challenges that the radar product team encountered in the ecodesign pilot regarding solution orienting. It is unclear how this can be improved and what challenges may arise.

These points form the main conclusion into the analysis of Thales's product development and ecodesign needs, and specify clear directions that should be followed to advance the integration of ecodesign while utilizing MBSE. The points also highlight important gaps in knowledge that the literature review should focus on, such as how to include technical aspects of the system beyond carbon footprint in an ecodesign approach, and what methods or tools can support such ecodesign activities. The opportunity to use MBSE capabilities to support ecodesign activities also requires significant attention. The literature review will also support whether the lessons learned from the current Thales ecodesign pilot are justified by other sources, which will help align the opportunities and practices found in literature with the needs Thales and its internal stakeholders have.

3 Literature Review

This chapter reports on the literature review conducted for this thesis. The literature review focuses on the integration of MBSE enabled ecodesign activities during the early product development phases, aiming to address Thales's needs and support sub-objective 4. The focal points of the literature review are derived from the analysis of Thales's development process and the challenges associated with implementing ecodesign, which culminated into a list of key points described in Section 2.5. Especially points 3-5 highlighted critical gaps in knowledge that need to be addressed to increase the chance of developing a successful MBSE enabled ecodesign approach for Thales. In order to get the information needed to mitigate the knowledge gaps, the literature review aims to provide answers to the following questions:

- How can ecodesign practices be adapted to suit different types of systems and companies?
- What are the most prominent ecodesign tools for early conceptual design, and what are their strengths and limitations?
- How can MBSE support ecodesign practices, and what are the opportunities and challenges of its integration?
- What are the key decision-making factors for ecodesign during the early stages of product development?
- What are the challenges and best practices for integrating ecodesign into early product development phases?

Answering these questions will reduce the gaps in Thales's current ecodesign process and activities and help introduce MBSE capabilities for ecodesign while considering the stakeholder expectations. This chapter starts by detailing the approach to the literature review, by mapping the research landscape and explaining the search queries that were used to identify articles aimed at answering the research questions. Next, the selected literature will be addressed, critically reviewing their content by identifying suitable practices and challenges for implementing ecodesign tools or methodologies in the conceptual or early product design phases. Where possible, as much attention will be paid to works that employ a methodology that integrates ecodesign in a systems engineering context, specifically MBSE. The chapter concludes by presenting the main findings and answering the literature research questions.

3.1 Literature Approach

Considering that the research landscape on environmental engineering is vast, it is important to set some boundaries for the literature review. Similar words are used in literature that discuss the concept of environmentally friendly development. For example, the European Union defines ecodesign as a framework to establish requirements for the environmental performance of energy-related products in its Ecodesign Directive (Directive 2009/125/EC [11]). However, Ecodesign, Design for Environment (DfE) or Design for Sustainability (DfS) are all terms that are frequently used in the context of environmentally friendly design.

DfS is considered as the most multidisciplinary methodology within the 'Design for X' framework centered on environmentally friendly development. The focus of DfS is not only on environmental design, but considers the entire socio-technical system from three perspectives; environmental, economic, and societal [12]. The other terms mostly or only consider environmental stakes in the development process. For instance, Fiksel [13] describes DfE as a holistic methodology that integrates environmental considerations into the design and development of products and processes.

In a sense, ecodesign is a subset of DfE since its focus is more dedicated to the design and development of a product only. However, the terms are sometimes used as synonyms in literature. This literature will therefore include both the terms "ecodesign" and "Design for Environment" as synonyms for everything related to ecodesign. This limits the literature review to articles that have a specific focus on environmental design and should filter out articles that focus on broader aspects such as societal impacts of design choices. Societal aspects are not as important in this research since Thales is specifically looking for ecodesign solutions that are centered on mitigating GHG emissions of their products.

The literature review is conducted using the Scopus database, as it gives a comprehensive overview of high quality peer-reviewed research articles. The Scopus search queries must be designed to find information that overlaps coincides with the key topics that are conveyed in the literature research questions. For this literature review, there are three key topic areas, consisting of ecodesign practices, MBSE and early product development. Figure 10 sketches the knowledge landscape of the literature review that is conducted in this thesis. The term conceptual design is used as it is found in many studies related to general design activities during the early product development process and therefore aligns with Thales's needs for an improved ecodesign approach during the earlier phases of the development process.

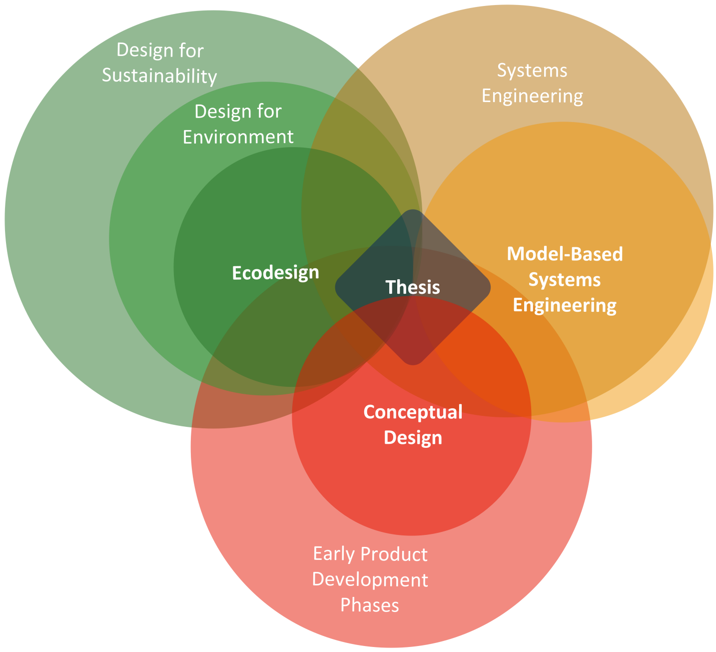


Figure 10: Venn diagram of the key topics coinciding with the literature research questions.

A good search query should incorporate every meaningful word that represents the topics or fields of interest. In this review, a search query should ideally retrieve more than thirty but fewer than five hundred articles, to provide a large enough but also limited scope. The keywords inserted into the search queries are searched within the article title, abstract and keywords. The strategy to limit any given number of retrieved articles, to articles related only relevant subject areas was to use the Scopus filter functions to limit the subject areas to Engineering, Computer Science, Energy, and Environmental Science, and only includes English articles.

Even when limiting the scope of the articles retrieved in Scopus, not all articles will be able to provide the answers to the literature questions. As a result, the scope of the literature review will be limited by carefully reading the title and abstract of the thirty 'most cited' and 'newest' articles retrieved from each search query, and making a selection of the most promising articles for further reading. By selecting articles in this way, it ensures that both the best or most commonly used approaches, as well as recent and novel approaches and ideas are included in the review, whilst maintaining a manageable scope.

This selection of the most promising articles for further reading is made based on a set of criteria. Since we want to use the found research articles for input of this thesis, they should provide answers to the questions posed in the introduction of this chapter. It is helpful if the articles provide a case study, describe best practices and pitfalls, map the state-of-the-art or outline the direction any of the three main literature topics is heading towards. In short, articles will be selected for further reading if they adhere to at least one of the following criteria:

- The article provides guidelines or maps the strategies for integrating ecodesign into the product development process.
- The article gives an overview of how to implement ecodesign considerations in a systems engineering environment, documenting best practices and challenges.
- The article develops a case study on how to implement ecodesign considerations in the early or conceptual design process, ideally from a systems perspective.
- The article describes how MBSE tools can be used to support product development.
- The article describes how MBSE tools can be used to support ecodesign activities.
- The article develops a case study or proposes a framework on how to implement MBSE tools to support ecodesign or to support the product development processes.

The article selection process is depicted in Figure 11. The criteria were also used to verify whether the search query itself was good to begin with. If, after reading the title and article of the thirty most cited articles, none were deemed useful for further reading, then the search query was altered.

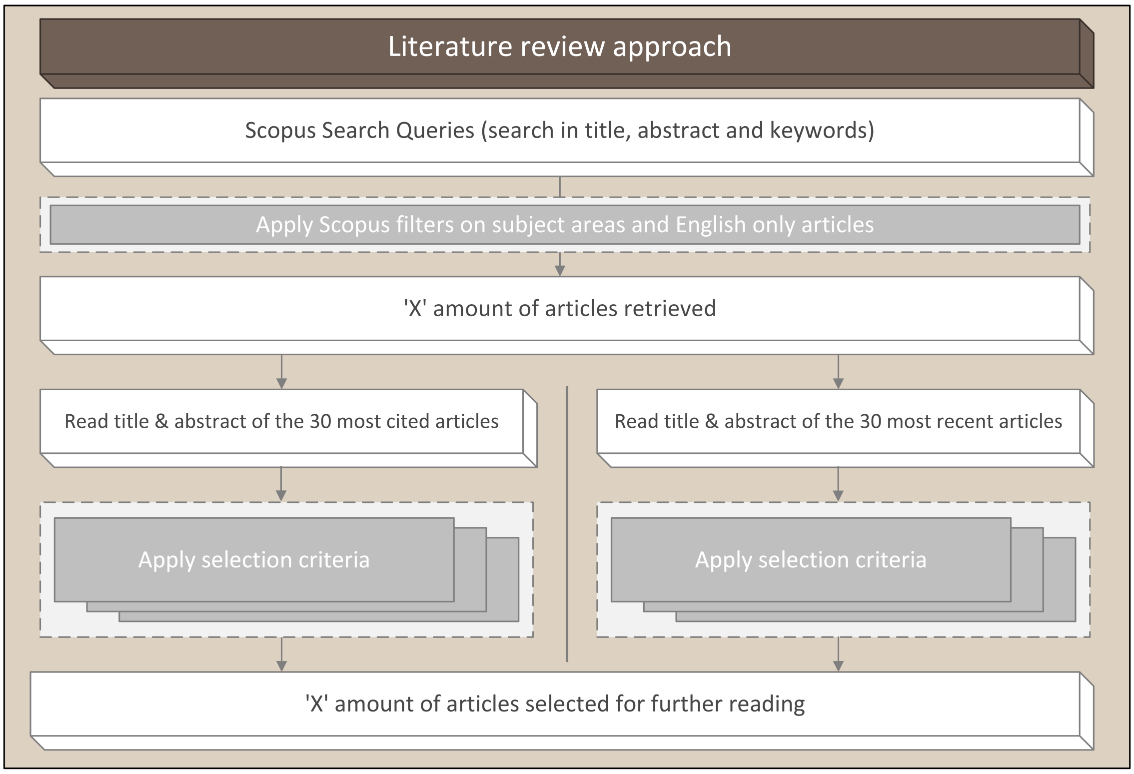


Figure 11: Literature review article selection approach.

3.1.1 Search Queries

The search queries used in this literature review relate to the subject areas of Figure 10. It is most interesting to look for the intersection points of the subject areas in published research articles. By reviewing the intersection points, it will reveal how MBSE and ecodesign can be integrated during the early product development phases. This in turn, will highlight articles that have a high chance of helping to answer the literature review research questions. The search queries used for this thesis are detailed next.

The search query *("eco-design" OR "ecodesign" OR "Design for Environment" OR "DfE")* retrieves over seven thousand articles on Scopus, and the query *(mbse OR "model-based systems engineering")*, retrieves over three thousand. However, the combination of both the topics in Scopus, *("eco-design" OR "ecodesign" OR "Design for Environment" OR "DfE") AND (mbse OR "model-based systems engineering")*, only retrieves nine articles. Furthermore, adding the other topic area of conceptual design to the search query, *("concept design" OR "conceptual design" OR "early design phase")*, retrieves zero articles. It indicates that even though there is a large body of knowledge of the topics individually, the combination of these topics is still considered a novelty. Of these nine retrieved articles on MBSE and ecodesign, only three were selected for further reading based the process depicted in Figure 11, as they highlight the use of MBSE tools to support ecodesign activities.

As the combination of the knowledge areas in ecodesign and MBSE is very limited, the combination of ecodesign in systems engineering in general would also provide valuable information. The search query *("eco-design" OR "ecodesign" OR "Design for Environment" OR "DfE") AND ("systems engineering")* retrieved 57 documents related to the topics areas. Of the retrieved articles, sixteen articles have been selected for further reading. The selected articles develop and integrate frameworks or methodologies in support of developing ecodesign from a systems perspective. The lessons learned from these articles will help guide the thesis into a direction where the various activities in systems engineering can be used to support ecodesign.

The search query *("eco-design" OR "ecodesign" OR "Design for Environment" OR "DfE") AND ("concept design" OR "conceptual design" OR "early design phase")* retrieved 259 documents. Seventeen articles have been selected for further reading as they include specific examples or case studies of incorporating ecodesign considerations in the conceptual design process, describe the impact of implementing ecodesign in the conceptual design process, or present best practices and challenges of implementing ecodesign early in the design process.

The search query *("MBSE" OR "model-based systems engineering") AND ("concept design" OR "conceptual design" OR "early design phase")* retrieved 163 documents. Ten articles have been selected for further reading. These articles will provide detailed descriptions and identify opportunities on how MBSE can be used to support the conceptual design phase of product development.

3.2 Review of the Literature

The findings from the literature review are presented in this section. The literature is categorized in separate subsections. Each subsection will detail specific topics related to the questions that the literature review should help answer. It starts by reviewing literature that addresses tools that are used to support ecodesign in the early development. Next, the integration of MBSE in ecodesign is explored. This section ends with a comprehensive review of literature addressing ecodesign in the early product development phases.

3.2.1 Ecodesign Tools in Early Development

This section addresses the most commonly used ecodesign guidelines and tools to support ecodesign during the early conceptual development of products. It is often reported that 80% of the environmental impact is determined after just 20% of the designing activity, putting great emphasis on the importance of the conceptual design phase [14]. The attention to environmental performance in early product development has heightened as environmental concerns have increased over the last decades. This has led to the development of many different guidelines, tools and frameworks that try to deal with ecodesign in the early development phase. There exists a large amount of literature that attempts to address ecodesign, but with various levels of detail. This results in a dispersed set of guidelines and tools that make it difficult for those ecodesign principles to be used in a universal context.

There have been attempts to formalize and categorize a compilation of ecodesign guidelines into one set of guidelines that provide a common foundation for all ecodesign activities. One of the earlier attempts comes from Luttropp and Lagerstedt [15], who have composed a set of ten golden rules for ecodesign. More recently, Telenko et al. [16] have compiled a list consisting of 76 DfE guidelines following a detailed literature study within the field of environmental engineering. These guidelines have been organized into the most important lifecycle categories(e.g. resources, production, transportation, use, and end-of-life). Their motivation comes from the fact that guidelines are more useful in the early design phases of product development compared to quantitative tools which require more data that is usually only available at a detailed design stage.

Likewise, the architecture of the system to be developed is often finalized at the detailed design phase. The authors support the idea that guidelines are a great tool in the early design phases helping designers generate concepts, decide on ecodesign orientations or used to set up into criteria for evaluation. However, they also point out that the guidelines lack quantitative measures for the environmental impact of products. If quantitative measures are included in guidelines, then they mostly rely on the knowledge of experts or design authorities.

These (semi-)quantitative ecodesign measures can typically be grouped into three categories: checklist-based tools, LCA-based tools, and tools that use quality function deployment (QFD) [17]. Checklist-based tools and guidelines are among the most widely used ecodesign approaches in industry, as is the case for Thales. Generally they are the most easy to develop as they essentially don't have to rely on quantitative data to be used. Conversely, these strength of these tools introduces a limitation; the outcomes of such tools tend to be more subjective and open to interpretation, as they depend heavily on expert knowledge rather than data.

QFD is a methodology that is used to translate market or customer requirements into engineering design specifications and plans. It is customer driven product development methodology that is very much design oriented. The strength of the approach is that costumer feedback drives product design from the early design stages to achieve customer satisfaction [18]. A QFD approach developed for ecodesign is the QFD for the Environment (QFDE) tool [19], that can be used to support environmentally friendly products.Their approach is carried out in four phases; the first two phases focus on identifying environmentally outstanding aspects of the product and the latter two phases focus on choosing and evaluating alternative designs.

However, QFD is often regarded as loosely defined which can make the implementation difficult. The information needed to use the QFD is often very subjective and coming from multiple sources in order to construct the full picture of customer needs. Not only, is a lot of time spent on representing the needs of the customer, it has to be done right as it form the foundation of the method [20]. There have been attempt trying to solve this problem, for example by means of a fuzzy model approach [21], but a large mathematical models has to be developed and input from customers and experts stil form the foundation of the approach due to the nature of QFD.

One of the most widely known and objective tools for environmental evaluation follow a LCA method. However, as Ramani et al. [22] point out, there are some serious obstacles to integrating LCA in the product design development stage. These include the lack of information available at the early design stages, the process of setting up a LCA being costly and time-consuming, LCA not being naturally being design-oriented but assessment-oriented and that most LCA databases generally do not contain specific process information. That does not mean that the integration of LCA cannot provide benefits, as LCA can provide invaluable information for design teams once it is set up properly, given the amount of data it provides. Exploring the framework upon which LCA is based or finding ways to streamline LCA integration into product development could yield important insights for an ecodesign approach aligned with MBSE.

In conclusion, there are four commonly used tools for supporting ecodesign activities during the early product development, each with different strengths and characteristics. The next section delves into the potential for integrating ecodesign practices early in the development process, with MBSE capabilities in mind. It will reveal the best practices for incorporating ecodesign into product development processes by exploring frameworks and methodologies in more detail.

3.2.2 Ecodesign in Model-Based Systems Engineering

The literature review highlighted the novelty of trying to use MBSE to directly support or be fully integrated into an ecodesign approach. So far, only limited work has been done to enable ecodesign practices through MBSE tools. The most promising findings can be classified in two distinct approaches; (1) Direct MBSE application for ecodesign and (2) Development of MBSE frameworks for ecodesign. The first approach, by Bougain and Gerhard [9], focuses on utilizing MBSE to directly support the ecodesign process. They apply SysML, a system modeling language [23], to represent and analyze the environmental impacts across various stages of a product's lifecycle. By modeling these impacts in SysML, their approach integrates sustainability considerations directly into the design process.

The second approach used by Eigner et al. [24] focuses on the development of a model-based lifecycle development framework that considers sustainability aspects throughout a system's lifecycle. Their work culminates in the development of a lifecycle management framework that supports sustainable product development. Rather than directly using MBSE to model environmental factors, it works on developing methods and processes that can enable ecodesign through MBSE.

Bougain and Gerhard's research focuses on the integration of environmental considerations into the MBSE process using SysML. While modeling the system, architects would have to implement environmental parameters in the model, like material and weight. This happens already at the earliest stages of the product development, but should be updated throughout the development. By linking the software with multiple databases that provide environmental data on different lifecycle stages such as material extraction or recycling, they were able to calculate in their case the greenhouse gas potential of the solution, categorized per lifecycle stage. Furthermore, when development is finished and CAD models are fully defined, Product Data Management System could update the part data (material and weight) to overwrite the model. Then the environmental analysis could theoretically stay up-to-date.

The authors clearly express the potential of using MBSE to integrate ecodesign. Integrating environmental impacts from different lifecycle stages early in the product development project supports ecodesign decision-making by design engineers. By making environmental information available and up-to-date, it facilitates the integration of new ecodesign methods and initiatives such that engineers can take action as early as possible in the development process. Furthermore, is would be helpful for an engineer to know how much energy consumption is tied to a particular part or system function. The latter would be enabled by MBSE as different models are created that model different viewpoints of the system, including behavioral models. If the environmental data is adequately stored, they can be used subsequent projects in order to improve early estimations on their environmental impact [25].

However, Bougain and Gerhard also mention some clear drawbacks for the implementation of MBSE to support ecodesign. To model the complexity of the systems, there was need for a network of models. Issued concerning traceability between the various models appeared by modeling the environmental impacts in SysML. The result was that properties were not considered if not properly linked in different parts of the models. On top of that, the ability for companies to integrate the proposed method into their engineering workflows would require great effort because of the need to link different data management systems.

Eigner et al. [24] present a framework for the model-based development of cybertronic systems. System Lifecycle Management can contribute to ecodesign of products by making information from downstream lifecycle stages available earlier in the development process of new products. It provides traceability to the early development phases where most of the product impacts are defined. In their approach, the focus was on the usage phase. The considered system, in their case an excavator, was modeled in SysML. The modeling methodology is similar to ARCADIA in the sense that it addresses the development of the system by modeling in different layers, starting at a contextual level and developing to the technical solution level. Using behaviour models, all of the different use-cases of the excavator were modeled. Information on the functional behaviour of the system, can be used by engineers to conduct environmental analyses. Given the traceability of the system models, the engineer can identify and redesign system components and functions that are related to use-cases with the highest emissions, or redesign parts and functions that have the least impact on other parts and functions.

Despite the benefits, there are challenges involved with integration such a process. First of all, the need for harmonization between various tools to ensure traceability poses difficulties. The implementation of the approach is therefore very resource-intensive. Secondly, the environmental analysis considered in the paper only focuses on a single environmental parameter. The example considered only fuel consumption of the engine over the various behaviors during the usage phase of the excavator's lifecycle, such as lifting, idling, or traveling. The authors do not explain a clear reason for this approach, but it shows that the scope of the environmental analysis was fairly limited. It is unknown how much complexity will arise if a broader system level environmental analysis would be conducted, so the full extent of the usefulness is unknown.

Given the lack of literature addressing the use of MBSE to support or directly integrate ecodesign practices, it is necessary to look broader into ecodesign approaches that are not directly implemented or enabled by MBSE, but still in a systems engineering context. Other methods and guidelines for implementing ecodesign into the early product development process with systems engineering in mind are investigated below.

3.2.3 Ecodesign Implementation in Systems Engineering and Early Development

Strategies for implementing ecodesign in the development process are plentiful. There exist a large range of various ecodesign or DfE activities that a company could pursue, but these activities cannot always be applied directly. Ecodesign guidelines and activities must suit the company and should be in line with the strategic objectives of the company, in this case Thales. The list of DfE guidelines that Telenko et al. [16] propose for example, summarizes activities centered around seven strategies to reduce environmental impact. The guidelines can be used to support the definition of the technical solution, rather than to support the environmental analysis of the considered system.

These guidelines are helpful only once it is clear for a designer what part of the system is considered for redesign concerning environmental performance. In fact, the authors stress that the first step in performing ecodesign activities should always be to understand the environmental footprint of the system under consideration. The advancement of ecodesign within a company should follow a strategy and build on the already in place activities.

Ecodesign maturity
It is therefore good to understand the level of advancement in a company such that suitable strategies can be followed. In the work of Pigosso et al. [26], a framework is proposed to support ecodesign implementation, following a diagnosis of a company's ecodesign maturity profile. The maturity model is based on five levels that describe the current state of ecodesign within a company. The model aims to help companies build a roadmap of ecodesign practices and improvement projects from a managerial standpoint that guides them to the next level of maturity. It works by analyzing the current product development processes and the current ecodesign evaluation of a company.

Applying the ecodesign maturity framework to Thales, its ecodesign maturity level is around level three. At this level, ecodesign is starting to be integrated into the product development process and the first steps are taken to structure an environmental approach based on the lessons learned from pilot projects. Following the framework, ecodesign practices would have to be systematically incorporated into the product development process for Thales to transition to the next level of ecodesign maturity. To achieve that, the authors describe that the influence of ecodesign in the company has to grow in both managerial and technical areas.

To expand on ecodesign improvement opportunities, functionality or requirement analyses can be performed with environmental analyses to keep satisfying stakeholders whilst improving environmental performance. Ecodesign analyses of the current products and processes should be incorporated company wide. In order to get a better understanding on how to conduct various analysis on ecodesign, the remainder of this section will outline examples from literature that show how ecodesign analyses can be implemented in product development.

Understanding carbon footprint
The work of He et al. [27] focuses on modeling the carbon footprint of the product throughout the sustainable supply chain. The developed framework and calculation model is able to measure and analyze carbon emissions at each stage of the supply chain. This information is useful to understand where the carbon footprint of the product originates, which can be used as input for redesign activities with ecodesign strategies in mind. If the model is expanded then the information on supply chain emissions could show what suppliers or contractors emit the most, and a strategy to minimize emissions can be developed.

However, their work also indicates that the model and therefore product carbon footprint could be influenced a lot during the design stage, and information over the entire supply chain is necessary for the model to work. Furthermore, true supply chain analysis requires input from all parties in the supply chain. This puts the robustness of their model into question and thus the call for future research. Other works try to approach ecodesign differently, focusing on single lifecycle stages of the product under consideration.

An adaptation of DfE, called Design for Energy Minimization (DfEM) is presented in the work of Seow et al. [28]. They introduce a design framework that integrates energy efficiency considerations into the early design stages with a specific focus on reducing energy consumption during the manufacturing phase. Unlike many LCA methods that only consider the mass of materials used in a product, their framework also includes the processing time required by each manufacturing operation. The framework consists of an energy simulation engine, an energy database and a decision support matrix. The energy database is the knowledge base of their framework and can be sourced from known databases or built up to be more company specific by means of advanced energy metering systems.

The authors stress that applying this methodology is most beneficial for non-energy consuming products and systems, like furniture, as most of the emissions and environmental impact of these products can be attributed to the manufacturing and material extraction phase of the product lifecycle. However, this work indicates how a methodology based on a relatively simple framework can help conceptual designers limit the environmental impact during the manufacturing stage and therefore reduce total lifecycle emissions of their product.

A study by Santolaya et al. [29] tries to achieve something similar, by combining ecodesign and Life Cycle Sustainability Assessment (LCSA) with a quantitative assessment. The focus is on the improvement of a product's sustainability during the production stage, comprised of three steps; sustainability assessment, redesign and comparing designs. In their framework, the sustainability assessment is used to assess the initial product as well as redesigned alternatives. The designs are then compared on various important environmental, economic and social metrics that indicate in what areas a product has been improved.

Other examples also highlight how focusing on a single lifecycle stage can be helpful in orienting on ecodesign efforts to reduce lifetime impact. For example, the work of Pigossa et al. [30] focuses on the End-of-Life (EoL) of the product. One of the key takeaways from these studies is that they highlight how understanding the product carbon footprint of only the most relevant lifecycle stage can help reduce environmental impacts by focusing efforts on that lifecycle. However, these works also stress that not only the most relevant lifecycle stage should be analyzed, but all significant lifecycle stages of products should be considered.

Multi-criteria decision-making

Romli et al. [31] developed an ecodesign decision-making methodology for the development of sustainable products. Key parameters for ecodesign analysis include material selection, energy consumption, emissions and lifecycle costs. The methodology involves a multi-criteria decision-making process that incorporates LCA, an ecodesign design process model and an ecodesign quality function deployment process. The effectiveness of their model is shown with the help of a use case of a simple product and a single material change.

Unfortunately, the work falls short in realizing that a lot of products from the largest manufacturers are complex systems. Using the ecodesign decision-making methodology on larger complex systems would require intensive effort from designers. Despite the simplicity of their case-study, lessons can be learned from the methodology. The authors were able to effectively introduce an ecodesign cost analysis into the decision-making methodology, based on the eco-cost model initiated by Vogtlander et al. [32].

Costs are always one of the main concerns for any company embarking on ecodesign projects. Orji and Wei developed a cost model specifically oriented on the impact of green manufacturing [33]. Although their model requires a extensive cost database for the manufacturing activities, it did showcase again how useful it is to consider costing into the development of products. In this case entirely focused on a methodology for costing of green manufacturing at the early design stage. Their model showed that the total life cycle cost of product in green manufacturing is lower than that of same product in conventional manufacturing.

These works showcase how eco-costs could be introduced in the ecodesign decision-making process in a successful way. In more general terms, it highlights how other criteria or aspects of the system can be considered in ecodesign other than just carbon footprint, and how that provides valuable insights to engineers or managers. It helps engineers to make more informed decisions during the development process of products.

Standardized indicators

Lacasa et al. [34] propose a product development methodology that combines traditional design criteria with sustainability requirements. An analysis into an LCA is conducted on the material flows exchanged by an industrial installation throughout the production process. The environmental impact is evaluated both by global warming indicators as well as the EI99 indicator.

Their work is based on three phases that have to be undertaken for sustainable product development: (1) identify the inputs and outputs of the production process and inventory; (2) assess engineering metrics for sustainability; (3) redesign the product. The obtained results illustrated the effectiveness of the used metrics and indicators to assess the product sustainability and product redesign improvement validated by two independent use case analyses. This work again indicates how the use of multiple criteria, in this case transformed into indicators, can be used to conduct sustainable design practices.

Data integration

For all approaches described in this literature review, it is important to obtain the relevant data and integrate the methodology into the product development process. Favi et al. [35] developed a life cycle model based on ISO standards and a data framework related to the early phases of shipbuilding design. The goal was to support the decision-making process for various sustainability practices such as material selection, assembly and manufacturing processes, maintenance, use and end-of-life disposal. Their model includes both the LCA and the Life Cycle Cost Analysis (LCCA) with an approach to retrieve and collect data for the analyses. The Global Warming Potential (GWP100) was used to indicate the contribution to global warming, which is based on the ReCiPe LCIA method. Figure 12 shows how the data framework is connected to the life cycle model and how the results of the life cycle model can result in design changes if unfavorable environmental impacts or costs are calculated.

The main finding is that the authors clearly show how their approach integrates into the product development process. Initially, project or product data is collected from various engineering documents. This data is organized in their data framework, which divides all of the relevant data according to the relevant lifecycle stages that will later be considered in the LCA and LCCA. This structured method streamlines the integration of environmental analyses into the product development process.

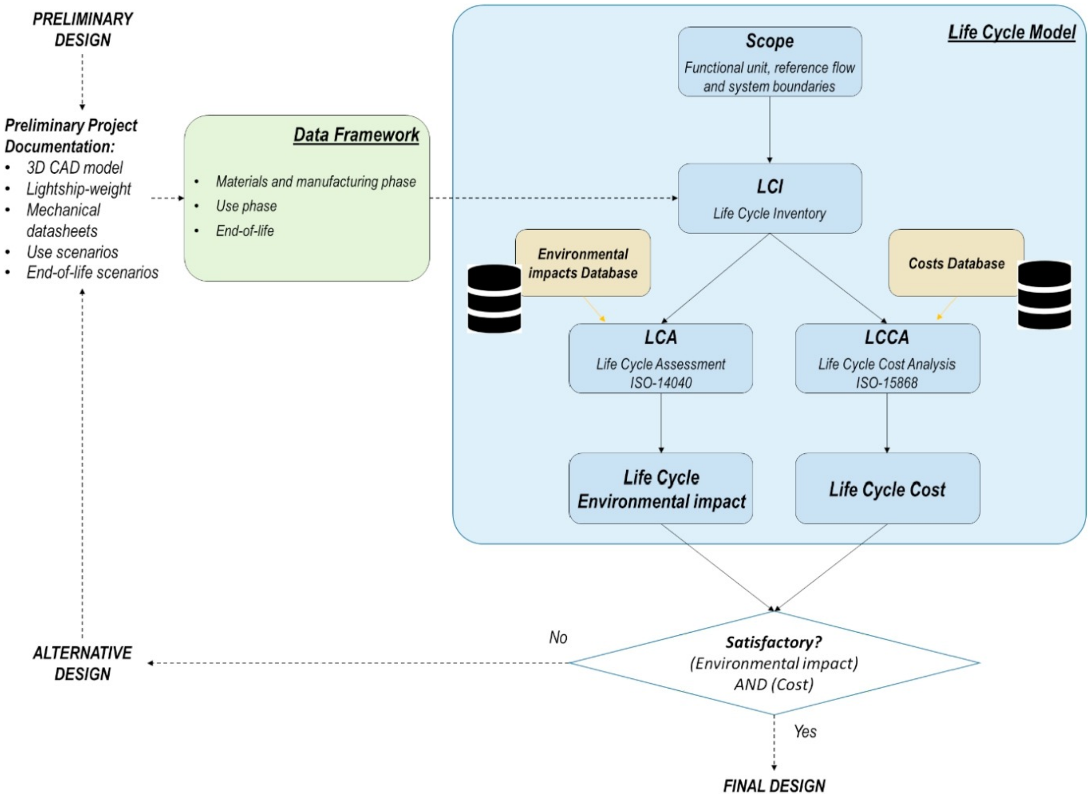


Figure 12: Data framework and life cycle model integration in the product design loop [35].

3.3 Summary of Key Findings

This section summarizes the key findings from the literature review, and provide answers to the five literature review questions posed in the introduction. These questions were formed to fill the knowledge gaps and identify suitable practices centered around the key points for Thales's ecodesign development through MBSE, stated in Section 2.5. The answers to these five questions will provide key input for the development of an ecodesign approach that can be integrated at Thales.

1. Adapting ecodesign to general systems and companies
The first step to answer the question:*"How can ecodesign practices be adapted to suit different types of systems and companies?"* is to take into account and understand the system and the companies in question [26]. It is essential to assess and understand a company's maturity to ecodesign to develop strategy that builds on existing activities and push toward the next level. Creating roadmaps and expanding ecodesign practices from pilot projects to company-wide integration can support the gradual integration of ecodesign in the product development process.

Secondly, adapting ecodesign requires a complete understanding of the product's lifecycle carbon footprint. This makes it possible to target efforts on the most impactful lifecycle phases of the system as discussed by [27–30]. Standardized approaches can further ensure that practices are tailored to diverse systems while maintaining consistency across projects [34].

2. Suitable ecodesign tools
The answer to the question: *"What are the most prominent ecodesign tools for early conceptual design, and what are their strengths and limitations?"* is that the most prominent ecodesign tools are either descriptive, such as guidelines, or (semi-)quantitative, like checklists, QFD and LCA [17]. In summary, several ecodesign tools and guidelines have been developed to support

environmentally conscious decision-making during the early conceptual design stages, each with distinct strengths and limitations.

Checklist-based tools and guidelines are widely used due to their simplicity and minimal data requirements, but they often rely heavily on expert knowledge, leading to them being open to interpretation. QFD-based methods offer a structured approach to integrating customer and environmental requirements into the design process, yet their implementation can be complex and time-intensive due to their reliance on a very strong foundation of customer requirements. Lastly, LCA provides a highly quantitative evaluation of environmental impacts, but its integration into early design phases is hindered by a lack of available data and its assessment-oriented nature rather than design oriented. These findings highlight the importance of balancing simplicity, usability, and data availability to effectively integrate ecodesign into the early product development phases. As pointed out by the answer to the previous question, an ecodesign tool must be tailored to the needs of the company and the ecodesign approach that is carried out.

3. MBSE ecodesign integration
To answer the question: *"How can MBSE support ecodesign practices, and what are the opportunities and challenges of its integration?"*, we can look at the two approaches from Bougain and Gerhard [9] and Eigner et al. [24]. In summary, both approaches show the potential of using MBSE to support ecodesign in very different ways. Were one approach directly uses SysML to model environmental aspects of the system, the other approach uses the SysML models to analyze the behaviour of the system, with which an environmental analysis can be performed.

Both approaches show that MBSE should be used to retrieve information from the architecture that can be used to evaluate how much energy consumption or carbon footprint is tied to a particular component or function. This helps engineers to identify specific components or system functions that can be considered for redesign, as they are related to the highest emissions and have the least impact on other parts and functions.

However, both approaches also stress the difficulty involved for companies to integrate the approaches given the effort required to link various tools and systems. It appears that there is difficulty in performing environmental analysis if a complex system is considered or if multiple environmental parameters are considered. Modeling ecodesign aspects and parameters in MBSE can therefore become a complex and time-consuming task if the right information is not already available. Furthermore, integrating these models with data management systems may present challenges.

4. Decision-making factors
To answer the question: *"What are the key decision-making factors for ecodesign during the early stages of product development?"*, we can start by revisiting the work from Pigosso et al. [26] again. It discusses the importance of integrating additional dimensions, such as functionality or stakeholder requirements, into the decision-making process. These dimensions help ensure that ecodesign activities align with broader system objectives and satisfy key stakeholder priorities, which is particularly crucial during the early design stages when critical decisions are made.

Similarly, the discussion on frameworks like the ecodesign decision-making methodology by Romli et al. [31], which incorporates life cycle assessment and cost analysis, and the work of Orji and Wei, which introduce a cost model oriented on green manufacturing, help answer this question. It highlights how multi-criteria decision-making processes can be used to evaluate trade-offs between environmental and economic impacts during early design stages.

Adding to this, the methodology proposed by Lacasa et al. [34] highlights the importance of quantifying environmental impacts through standardized indicators, enabling designers to make informed choices during early development phases. These attributes to support decision-making should ultimately be incorporated with the findings to the previous three questions to develop an ecodesign approach suited to Thales.

5. Ecodesign practices in early product development phases
Lastly we have the following question: *"What are the challenges and best practices for integrating ecodesign into early product development phases?"* One major challenge is the complexity of assessing the environmental impact at different stages of the lifecycle, especially early in the product development phase. Challenges like data availability and integration have been widely recognized [22, 31], but accurate and reliable data is essential for any quantitative analysis on ecodesign. Furthermore, the integration of data into ecodesign approaches requires a robust framework to ensure consistency [35]. Managing how to integrate and use data consistently is crucial to overcoming barriers to implementation. Therefore, having a consistent and reliable source for any ecodesign analysis should be a priority.

Beyond overcoming challenges to integrating ecodesign in early product development, it is also important to establish suitable practices that should be followed during early product development. There were common approaches in the literature centered around the following objectives: (1) approaches focused on environmental analysis of products, (2) approaches focused on ecodesign solutions to improve environmental performance of products, and (3) approaches focused on the combination of performing environmental analyses and developing technical solutions. A general workflow to ecodesign can be constructed by considering the answers to the previous research questions and the common activities between these literature approaches [27–31, 34]. Figure 13 highlights how an ecodesign approach should be structured during the early development stages of product.

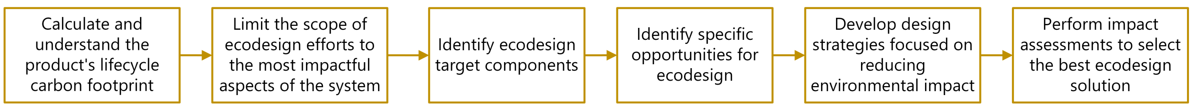


Figure 13: Ecodesign workflow during early stages of product development following literature approaches.

The process shown in Figure 13 indicates that first, development teams should calculate and understand the carbon footprint of the considered product. By analyzing the carbon footprint profile of the product, the most impactful technical characteristics and lifecycle stages can be identified. The scope of the ecodesign efforts should be limited to the most impactful aspects of the system, which aids the development team by focusing on the aspects with the largest improvement potential.

With the scope of the ecodesign study clearly defined, is would be good to identify ecodesign target components. These target components must show great potential for design changes that can lead to environmental improvements. Once specific ecodesign targets are identified, improvement opportunities can be developed. These steps align greatly with Thales's need for a more structured approach that highlights architectural areas for environmental improvement. Additionally, Eigner et al. [24] highlight how MBSE can contribute to these steps by providing the right technical information from the system architecture models.

The last two activities of the workflow indicates that only once a clear aspect of the system or lifecycle are identified for improvement, should a development team perform ecodesign activities that are focused on developing a technical solution that reduces carbon emissions. The ecodesign workflow during the early development stages concludes with performing impact assessments on ecodesign solutions.

The next chapter will detail the developed ecodesign approach for Thales. The approach is constructed by filtering the key findings from this literature review and aligning them with the key points from the stakeholders. This ensures that the current state of ecodesign and MBSE in literature are considered for the approach and that the expectations from the stakeholders are taken into account.

4 Ecodesign Approach Proposal

This chapter develops the adapted ecodesign approach based on the key stakeholder needs from Thales, discussed in Section 2.5, and the key findings from literature, discussed in Section 3.3, and addresses sub-objective 5. The proposed ecodesign approach aims to mitigate the gap between the strategic objectives that Thales has set out and the realization of those objectives through engineering activities. The approach includes the development of the specific engineering tasks to be followed for engineering decision-makers, and offers a clear rationale for adopting MBSE to support ecodesign.

Section 4.1 explains the rationale for the proposed ecodesign approach, which is deduced from the lessons learned from the literature review, filtered through the context of Thales to align with the stakeholder needs. This rationale culminates in a list of key elements that should be implemented to improve the ecodesign approach of Thales. The improved ecodesign approach for Thales is introduced in section 4.2. This approach is tailored to integrate with the existing ecodesign workflow of Thales, and introduces key activities based on the rationale. As the integration of MBSE is integral to this thesis, part of this section is dedicated to discuss specifically how MBSE will contribute to the proposed ecodesign approach developed for Thales. It details what specific MBSE data is integrated to conduct the ecodesign activities proposed in this thesis.

The specific engineering steps that must be followed to achieve the objectives of the ecodesign activities in the approach are introduced in Section 4.3. Individual subsections will provide a detailed description of each of the engineering steps in the ecodesign approach. Key inputs and outputs of the steps will be highlighted. By providing this stepwise approach to Thales, it will help to bridge the gap between general ecodesign directives and engineering activities.

4.1 Ecodesign Approach Rationale

This section relates the lessons learned from the literature review, described in Section 3.3, to Thales's ecodesign needs discussed in Section 2.5. The rationale presented in this subsection provides the key input for the development of the ecodesign approach in this chapter. Important stakeholder needs are briefly discussed before substantiating the use of specific findings from literature and adopt them to develop an ecodesign approach suited to Thales's needs.

4.1.1 Stakeholder Needs

The stakeholder groups discussed in Section 2.4 (environmental, product development teams, and systems engineering) emphasize the importance and need for further developing ecodesign activities in the early development phases, where they can have the greatest impact on the design. A short summary of the key needs discussed in Section 2.5 is detailed below as a quick reference for the rationale behind the ecodesign approach proposed in this chapter. Integrating these needs will help to achieve the ultimate goal of the project, which is to mitigate the gap between high-level ecodesign directives and detailed engineering activities while leveraging MBSE.

1. **Transforming high-level ecodesign directives into practical engineering activities**
   The approach must align with Thales's existing methodologies, providing clear guidance on how to implement ecodesign within engineering workflows.

2. **Leveraging existing product data and ensuring accessibility**
   Ecodesign activities should utilize available product data at each development stage and be integrated into commonly used engineering platforms and existing tools.

3. **Integrating ecodesign through MBSE**
   MBSE practices should support ecodesign by ensuring traceability, consistency, and alignment of available data in Capella system models.

4. **Expanding decision-making factors beyond carbon footprint calculations**
   Environmental assessments should incorporate additional technical considerations and be able to highlight environmental improvement opportunities, to enhance decision-making early in the development process.

5. **Supporting early-stage decision-making**
   Ecodesign should be embedded early in the development process with a structured approach that balances detail and usability.

4.1.2 Key findings from literature aligned to Thales needs

The literature review culminated in a list of key findings presented in Section 3.3 that will aid the advancement of the ecodesign efforts within Thales. By aligning the key needs listed in Section 2.5 with these key findings, a clear rationale for the development of an improved ecodesign approach is provided. This rationale begins with the broader aspects for the ecodesign approach and then provides the rationale for more specific aspects that should be implemented.

Structured approach to ecodesign
The first key need emphasizes that any newly developed ecodesign approach or activity must integrate seamlessly into existing ecodesign and engineering workflows, with better descriptions of activities. Literature reinforces this need by highlighting the importance of understanding a company's ecodesign maturity to build upon existing practices, as summarized in the first key finding. Learning from pilot projects further supports the gradual integration of ecodesign into product development. Standardized approaches ensure that ecodesign remains adaptable across different systems while aligning with engineering workflows, supporting ecodesign integration.

Thales's ecodesign pilot project revealed key challenges, such as the difficulty design teams faced in generating technical solutions. This underscored the need for a structured method to identify improvement opportunities within the system. This gap in Thales's current ecodesign approach is reflected by key needs 4 and 5. To fill this gap and provide more structure to the ecodesign efforts and early stage decision-making, we can draw from the ecodesign approach constructed from literature works in Figure 13. This approach clearly emphasizes on identifying target components in the system and subsequently formulating specific opportunities during the early stages of product development, an aspect that is absent in Thales's current ecodesign approach (Figure 9). Adopting this strategy reduces effort spent on solution-orienting though more streamlined decision-making, which improves the structure of the ecodesign approach.

Thus, by implementing these activities into an ecodesign approach, the need for a structured approach that is able key areas for improvement can be addressed. This means that the existing ecodesign approach will be expanded by two activities that single out environmental improvement areas and derive clear ecodesign opportunities. In other words environmental hotspots in the system must be identified, by environmentally assessing the system's architecture and individual components. Since these activities focus on system assessment rather than immediate solution development, they should be incorporated into the orient phase of product development. Careful consideration is required to determine how these activities integrate into the existing ecodesign approach and how they materialize, as emphasized by the first key need.

Materializing ecodesign hotspot assessment
A crucial need was a clear description of the activities. Additionally, the stakeholders stressed the need to provide a quantifiable and standardized means of assessing environmental impacts by introducing additional decision-making factors. To give substance to the activities of identifying environmental hotspots and assessing them, we can draw from the literature findings on ecodesign tools. There are various strategies or tools that can be followed to achieve emission reductions. The literature indicated that there are four major categories for ecodesign tools: guidelines, checklist-based tools, QFD-based tools, and LCA-based tools.

Thales is already implementing guidelines and a checklist-based tool (CLOE) to guide ecodesign orientation, which revealed the need for more quantitative approaches. Inherently, QFD as a tool is more focused on solution orienting and transforming customer requirements into design specifications, which does not align with the identified need for identifying hotspots through environmental assessment of the system.

An approach that incorporates an adaptation of a LCA, more simplified and line with Thales information availability, can be developed. Furthermore, LCA are assessment oriented and not inherently design oriented. To ensure compatibility with existing carbon footprint assessing and reporting standards, the method for assessing carbon footprint to identify ecodesign hotspots adhere to the assessment method behind the existing PETER tool.

Quantifying ecodesign hotspots
Thales's existing ecodesign tools focus on carbon footprint assessments but fail to integrate broader technical and functional attributes. Literature findings indicate that effective ecodesign decision-making requires incorporating factors such as functionality, system performance, and stakeholder requirements. By considering these attributes, engineers can balance environmental objectives with system requirements, making ecodesign activities more actionable within Thales's engineering environment.

Furthermore, to ensure consistency and repeatability, ecodesign hotspots should be assessed using standardized indicators. Literature findings emphasize the necessity of clear, quantifiable metrics to improve the robustness of ecodesign analyses. Integrating these technical characteristics into the ecodesign approach through MBSE is not only supported by literature, but also ensures that a key stakeholder need is addressed. Additionally, only existing product data that is modeled through MBSE should be considered to ensure accessibility to engineers.

Ecodesign data integration through MBSE
The use of MBSE in ecodesign can also introduce challenges. The literature on MBSE integration highlighted the importance of data availability and limiting the complexity of assessing environmental impact at different stages of the lifecycle, especially early in the development. This requires a robust data framework in order to model ecodesign aspects. However, given the traceability between the modeled components, Capella models can act as a reliable and consistent source of information for ecodesign, and provide structure to the ecodesign approach.

The stakeholder have expressed their need to incorporate a functionality or performance parameter, as the functionality of the system may not be compromised. The integration of functionality will be enabled through MBSE, as this information is currently available in models (Section 2.2.3). MBSE should be employed to extract functional system data from the architecture models, enabling the assessment of emissions tied to specific components and functions. This approach will help development teams identify key aspects of the system architecture that should be considered for ecodesign during redesign projects.

4.1.3 Key elements for ecodesign approach

Based on the rationale outlined in this section, a summary of the key elements for the development of the ecodesign approach is shown as a conclusion. These elements are be reflected in the ecodesign approach, proposed in Section 4.2 and the subsequent development of the specific engineering steps in 4.3. The key elements that are integrated in the ecodesign approach are:

1. The ecodesign approach should introduce key activities during the orient phase of product development: (1) Identifying ecodesign hotspots through the assessment of the system's components, and (2) Deriving clear improvement opportunities by evaluating the hotspots.
2. The integration of the new activities in the orient phase should align with and build on the existing practices established by Thales.
3. The identification of ecodesign hotspots must be made through quantifiable decision-making metric. Standardized indicators must be used to identify and evaluate hotspots.
4. The decision-making metric should include a functional aspect linked to the components, which is enabled through data provided by MBSE models.
5. MBSE should provide the key information for conducting environmental analyses. It shall be used to provide data for calculating carbon footprint related components and provide the link to functionality, showing functions and components with the highest emissions.
6. Current carbon footprint assessment methods will be integrated into the new ecodesign activities, which is based on the existing PETER tool calculations.
7. Ecodesign activities will be clearly described based on how they must be performed and what the expected outcome of each step is.

4.2 Improved Ecodesign Approach

This section discusses the proposed ecodesign approach, which introduces key activities into the existing ecodesign process of Thales, enabled through MBSE. These activities aim to refine and enhance the current process by integrating deeper architectural and functional analyses, building on the key findings from literature aligned with the key needs from Thales stakeholders. The proposed ecodesign approach, shown in Figure 14, is developed from the implementation of the key elements provided by the rationale in the previous section, and thus introduces two new ecodesign activities in the orient phase of product development:

- A.3: Identify ecodesign hotspots in the system's architecture.
- A.4: Derive ecodesign opportunities based on the ecodesign hotspots.

The adapted approach aligns with expectations from the stakeholders and incorporates key lessons from literature, which were discussed in Section 4.1. The two introduced ecodesign activities were developed based on the ecodesign workflow found in literature, shown in Figure 13. Specifically, that ecodesign hotspots are identified from a system perspective (A.3) and these are used to derive ecodesign opportunities (A.4).

By putting a greater emphasis on identifying the so-called environmental hotspots in the systems architecture, it allows teams to narrow their focus to specific ecodesign opportunities earlier in the development process. This leads to a more structured and targeted ecodesign approach, leading to a more efficient ecodesign process during the remainder of the development process. The newly introduced activities fit well in between the existing ecodesign approach from Thales, shown in Figure 9 (where activity A.3 now becomes A.5), and even compliments them. To highlight the ease of their integration, an overview of the activities in the orient phase is provided.

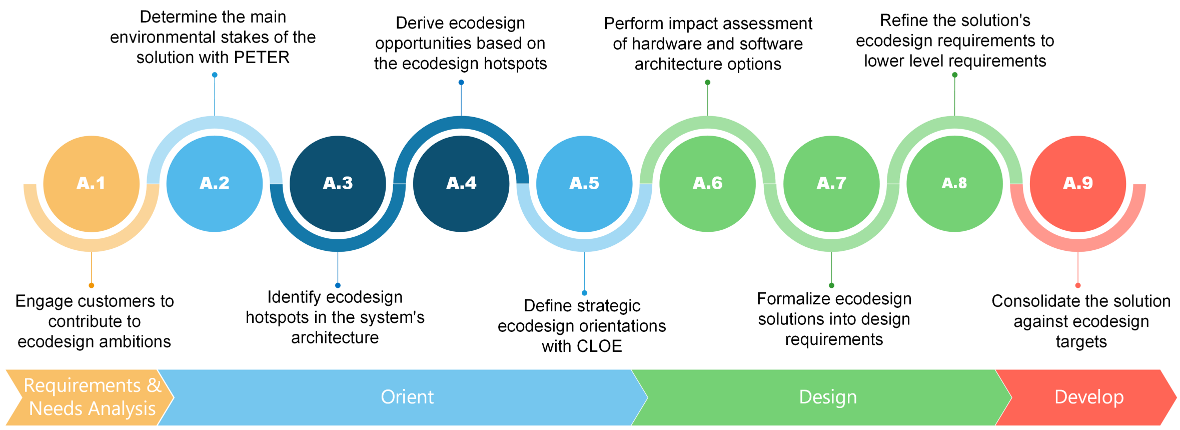


Figure 14: Improved ecodesign approach with new activities (dark blue) aligned with the in-place ecodesign activities in the development process.

A.2: Determining the main environmental stakes of the solution with PETER
The ecodesign workflow in Figure 13, indicated the importance of understanding the lifecycle carbon footprint of the product, and limiting the scope of further ecodesign efforts to the most impactful aspects of the system. The approach shown in Figure 14 combines these steps in one, by determining the main environmental stakes with PETER (A.2). The PETER tool, internally developed by Thales, facilitates the identification of key lifecycle stages and technical characteristics, by performing a preliminary carbon footprint calculation on the lifecycle impact of the entire product. Hence, PETER is used to determine which lifecycle stages require a more in-depth analysis of the product's carbon footprint, streamlining the ecodesign efforts.

A.3: Identifying ecodesign hotspots
The third step in Figure 13, details how ecodesign target components must be identified. In the proposed workflow, this is materialized by identifying ecodesign hotspots (A.3), through analyzing the carbon footprint of the system's architecture at a deeper level. This step is facilitated by limiting the scope of the carbon footprint analysis to the most impactful lifecycle stages. The hotspots are the components or aspects of the system that contribute disproportionately to the total product carbon footprint, relative to their contribution to system's functionality. Pinpointing these hotspots provides a foundation for targeted ecodesign efforts. The standardized metric used to identify ecodesign hotspots is provided in Section 4.3.6.

A.4: Deriving ecodesign opportunities
Once hotspots are identified, the next step is to carefully evaluate them and derive ecodesign opportunities (A.4), which also aligns with the fourth step shown in Figure 13. This evaluation should be on the role of the hotspot components in the system. These opportunities focus on specific technical characteristics and lifecycle stages of components where emissions can be reduced.

A.5: Defining strategic ecodesign orientations with CLOE
Following the two new activities in the ecodesign process, focus should be on defining strategic ecodesign orientations (A.5), which aligns with the fifth step shown in Figure 13. To support this process, engineers at Thales can still utilize the CLOE tool, designed to orient on strategies for improving the environmental performance of the system. In this new context, the use of CLOE is aided by first having derived specific ecodesign opportunities, ensuring a more structured focus on impactful areas with the highest improvement potential, instead of the general system oversight that was provided by PETER in the existing workflow.

4.2.1 MBSE integration into ecodesign approach

As pointed out by the rationale in the previous section, MBSE should be used to introduce functional data into the ecodesign decision-making process, which will advance ecodesign within Thales as additional technical aspects are considered. Thus, to meet the objectives of the added activities, MBSE is leveraged to provide the necessary information to identify architectural hotspots and translate them into ecodesign opportunities. Figure 15 illustrates how system information extracted from the Capella is integrated into the proposed ecodesign approach, specifically the information that is used to identify ecodesign hotspots in the system.

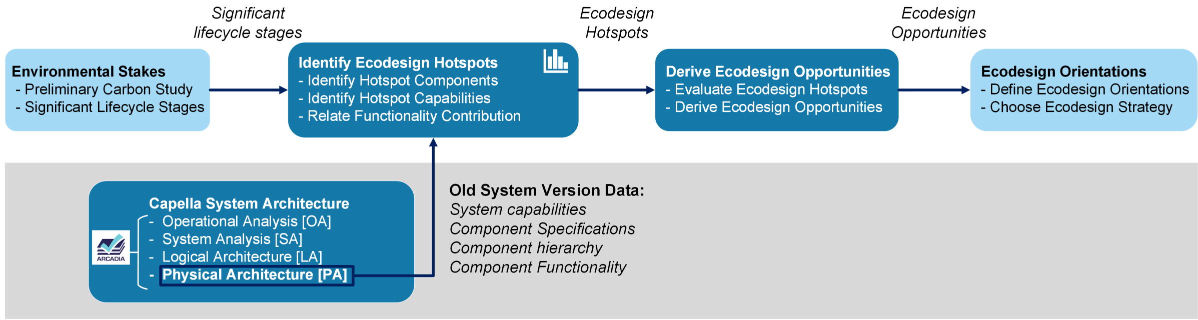


Figure 15: Information streams for completing the ecodesign highlighting the contribution of MBSE.

Following the Arcadia methodology, the four different layers ([OA], [SA], [LA], [PA] (Section 2.2)) modeled in Capella convey key technical information about the system, that can be used to conduct functional analyses beyond a general carbon footprint analysis of the system. As ecodesign is considered only during a system redesign, the ecodesign approach should make use of the most developed Capella models. It means that the existing system information is utilized for the development of new iterations of a system. The most detailed information exists in the Physical Architecture [PA] models in Capella.

Technical specifications of components and their functions will be used to calculate individual component carbon footprint and relate that to the components influence on the system. Using this information from the [PA] models in Capella, teams can pinpoint components with the highest emissions and evaluate their functional contribution to identify hotspots for ecodesign. Adding a capability perspective will allow teams to analyze which system capabilities are contributing most to the system's carbon footprint and help derive specific ecodesign opportunities.

The Capability realization (C_R), Physical Function (PF) and Physical component (P) elements from the Physical Architecture [PA] Capella models provide the data required for a detailed and traceable environmental analysis. This data is linked through direct traceability between the modeled elements and architecture diagrams in Capella, ensuring that relationships among system capabilities, functions, and components are clearly defined. This traceability is highlighted in Figure 16, where it shows the ratio of each model element in the Physical Architecture [PA] to each other, which is as follows:

- One Capability realization (C_R) is described by one Functional Chain (FC).
- One Functional Chain (FC) involves multiple Physical Functions (PF).
- Each Physical Function (PF) is allocated to one Physical behaviour (PA).
- Multiple Physical behaviours (PA) can be allocated to one Physical component (P), but also a single Physical behaviour (PA) can be allocated to one Physical component (P).

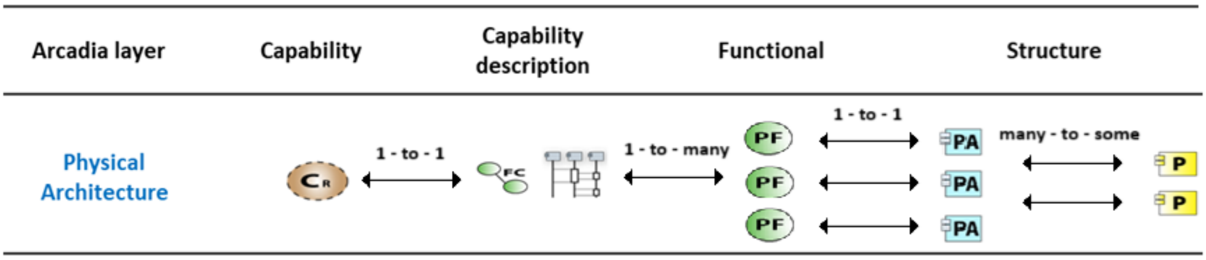


Figure 16: Physical Architecture [PA] traceability between modeled elements from Capability Realizations to Physical components.

The modeled Physical components (P) in the models must include detailed specifications and technical attributes such as mass, material composition and power consumption, which are essential for calculating the carbon footprint of the individual components. This information allows for the ecodesign approach to consider the carbon footprint of individual components and shows the carbon footprint composition throughout the system's component hierarchy.

The stakeholders stressed the need to consider how product data can be traced through the different Capella models, which is essential for detailing exactly how Capella can support ecodesign decision-making. Each Physical component (P) performs one or more Physical Functions (PF) that contribute to the realization of the system capabilities (C_R). Environmental data on components can be thus linked from individual component to system capabilities, enabling full traceability from the carbon footprint of individual components to the carbon footprint of the system's capabilities. By adding up all the carbon footprints of the individual components associated with a single capability, it allows to calculate the carbon footprint related to that capability.

Concluding this section is a summary of the key points in which MBSE will advance ecodesign. The integration of MBSE into ecodesign will support the approach in two ways:

1. The technical data associated to Physical components (P) shall be used to calculate individual component carbon footprint. This enables the identification of ecodesign hotspots, by considering the link to the components Physical Functions (PF).
2. The traceability between modeling elements, enables the calculation of carbon footprint for system capabilities. The required modeling elements include Capability realizations (C_R), Physical Functions (PF) and Physical components (P).

This covers the overall strategy to improve the ecodesign approach at Thales. In order to materialize the added activities in the ecodesign approach, a stepwise engineering workflow is developed in the next section. The engineering steps describe the specific tasks required to achieve the intended objectives of the added ecodesign activities.

4.3 Ecodesign Approach Engineering Steps

This section details the specific engineering steps for the completion of the ecodesign approach shown in Figure 14. The focus of this section is on detailing the steps in the orient phase of product development, highlighting the important inputs and outputs of the newly introduced activities in the ecodesign approach. The engineering steps detail every aspect that must be undertaken to complete the objectives of these ecodesign activities discussed in the previous section. For the proposed ecodesign approach, the orient phase ecodesign activities are:

- A.2: Determine the main environmental stakes
- A.3: Identify ecodesign hotspots in the system's architecture
- A.4: Derive ecodesign opportunities
- A.5: Define strategic ecodesign orientations

The ecodesign engineering steps, shown in Figure 17, detail specific ecodesign tasks belonging to each of the activities. In short, steps 1 and 2 focus on determining the main environmental stakes of the system. These steps identify the most impactful lifecycle stages and technical aspects of the system and determine the scope of the detailed carbon footprint calculation at the component level, which is needed to identify ecodesign hotspots.

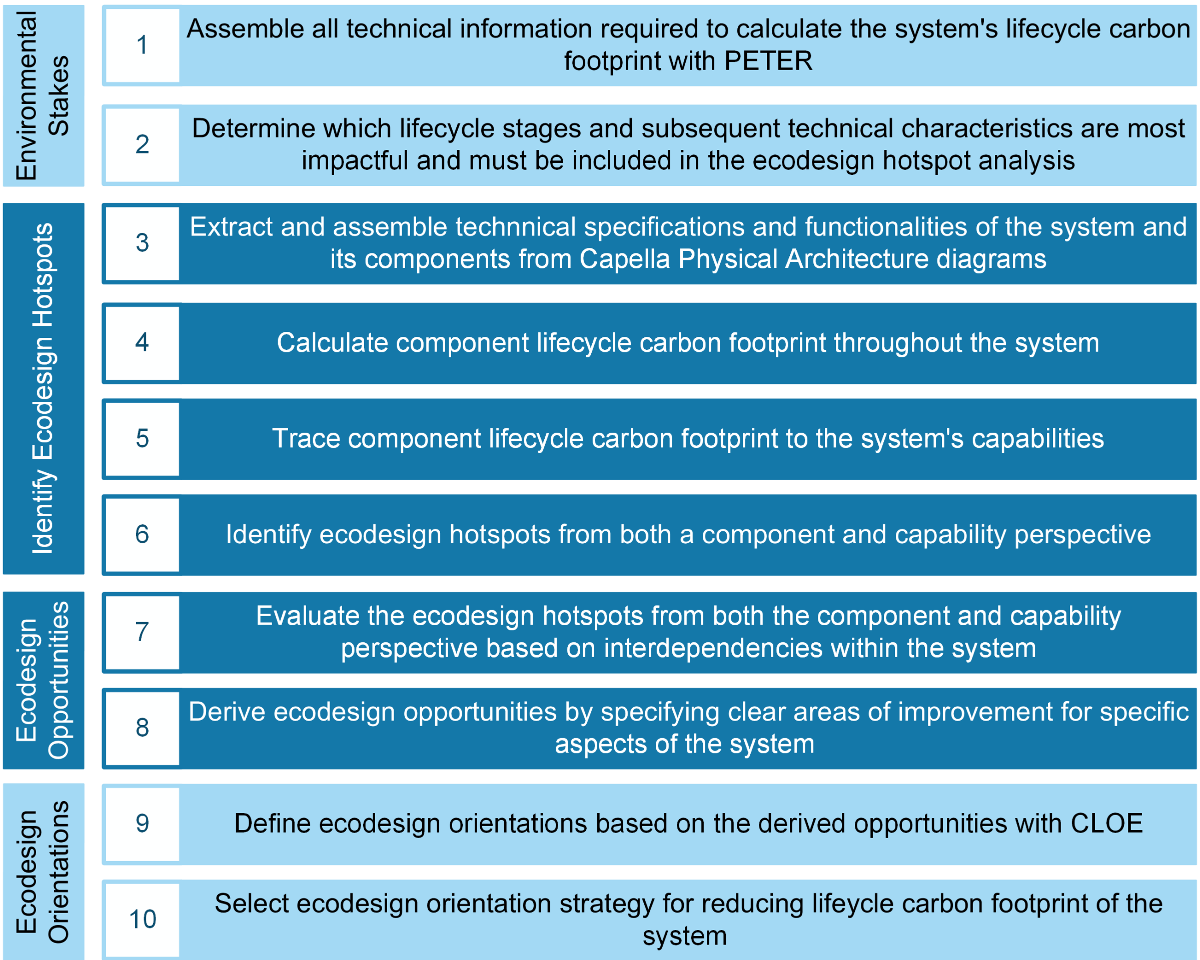


Figure 17: Engineering steps of the ecodesign activities in the orient phase of the proposed ecodesign approach.

The technical specifications needed for a component-level carbon footprint analysis are gathered in step 3. Among others, data such as mass, material composition, power consumption, and usage profiles are collected from Capella, for each component included in the analysis. Step 4 uses the collected data to calculate the lifecycle carbon footprint of individual components, which provides the foundation for identifying architectural hotspots. In steps 5 and 6, the component carbon footprints are analyzed in relation to their functionality and contribution to system capabilities, determining the carbon footprint related to system capabilities in the process. This provides the necessary information to identify ecodesign hotspots considering the entire system architecture.

From the identified hotspots, specific ecodesign opportunities can be derived as done in steps 7 and 8, by first carefully evaluating the hotspots. Lastly, steps 9 and 10 translate the identified opportunities into logical ecodesign orientations and design strategies. These strategies lead to technical solutions aimed at reducing the system's lifecycle carbon emissions.

The next remainder of this chapter will detail the specific tasks of each step in the orient phase of the ecodesign approach. As steps 1 and 2 are related to the activity of determining the main environmental staked with PETER (A.2), and steps 9 and 10 are related to the activity of defining strategic ecodesign orientations with CLOE (A.5), both of which are existing activities in the ecodesign approach, only the crucial inputs and outputs of these steps are detailed in this report. This provides enough information to understand the relation between these steps and the newly introduced steps (3 through 8) in the approach.

4.3.1 Step 1: Assemble technical system data

The first step in the ecodesign approach through the orient phase of product development is gathering the technical information required for the use of PETER, which calculates the systems lifetime carbon footprint. The following component lifecycle stages are considered in the PETER analysis, namely: (1) Manufacturing, (2) Use phase, and (3) End-of-Life. In short, PETER works on converting technical data on the system into a carbon footprint value, through carbon emission factors. These carbon emission factors come from a database that Thales has assembled specifically for this purpose. A more comprehensive overview of the emission factors relevant in the context of this thesis and the PETER tool in general can be found in Appendix D.

As the use of PETER is not a new activity introduced in this thesis, only the important input and output of this first step are discussed. As input, the scope of the system that is being studied is the most important. What that means is that beforehand it is determined whether the system is a Mission System, Equipment, an Equipment Element, a Building Block or even a Component.

The output of this step is the list of technical system parameters required to calculate the system's lifetime carbon footprint with PETER. These technical parameters are the:

- System lifespan
- System weight
- System's embedded platform type
- System mean power consumption
- System's power source
- System's recycling plan
- System's material breakdown by mass

These system parameters must be sourced from internal design documents, which are available in the Product Lifecycle Management (PLM) system. Once these technical parameters have been specified, it is possible to estimate the product lifetime carbon footprint and determine the most significant lifecycle stages, as described in the next step.

4.3.2 Step 2: Determine the most significant lifecycle stages

This aim of this step is determining the most significant lifecycle stages of the system being studied, which will narrow down the scope for the component level carbon footprint analysis used for identifying ecodesign hotspots. For this purpose, the PETER tool shall be used to perform the lifetime carbon footprint calculation, and provide a breakdown of the carbon footprint over the different lifecycle stages. More information on PETER can be found in Appendix D. The key input for this step is the list of technical system parameters, specified in step 1.

PETER will output a breakdown of the carbon footprint contribution associated to each lifecycle stage, which will reveal what the most significant lifecycle stages of the system are. The PETER tool will convert the list of technical parameters gathered in step 1, into carbon footprint equivalent values, through recognized emission factors. A graphical representation of the relative contribution of each lifecycle stage is shown in Figure 18. The lifecycle stages include Manufacturing of hardware mechanics and electronics, In-use mobility and power consumption, and End-of-Life recycling.

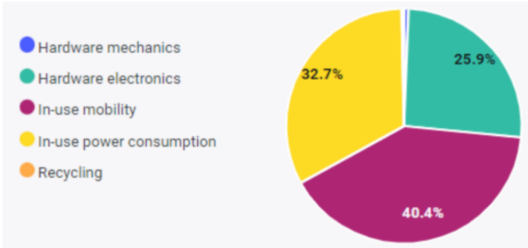


Figure 18: Pie chart of a lifecycle carbon footprint breakdown from PETER.

Subsequently, the development team will decide what lifecycle stages must be included into the detailed ecodesign hotspot analysis, where lifecycle carbon footprint will be calculated for each individual component in the system's architecture. The subsequent technical characteristics of the components belonging the most significant lifecycle stages must then be determined.

Determining what lifecycle stages must be included in the ecodesign hotspot analysis, is up to the development team to decide. The goal is to include at least the most impactful lifecycle stages of the product. It could be that the team decides to include all of the lifecycle stages in the analysis, if for example a relatively equal distribution of carbon footprint is calculated over all lifecycle stages. Conversely, a team may decide that a lifecycle stage is only included if it contributes at least 10% of the systems total lifetime carbon emissions, to reduce the working load in the next steps. As the approach described in this stage is general, the development teams have to determine what decision-making metric is used.

Most important, is that the development team specifies exactly what lifecycle stages will be considered for the ecodesign hotspot analysis, since this determines what technical specifications must be assembled on the components in step 3. Specifying the exact lifecycle stages is the main output of this step, and concludes the activity for determining the main environmental stakes with PETER (A.2).

4.3.3 Step 3: Extract and assemble component data from Capella

The third step of the ecodesign approach in the orient phase of product development is extracting and assembling component data from Capella. The aim of this step is to have a comprehensive dataset of the individual components in the system that are modeled in the Physical Architecture [PA] of Capella, and the technical parameters of these components that enable a carbon footprint calculation of each component and each capability. The exact data required is detailed in this section. This is the first step in the activity of identifying ecodesign hotspots in the system (A.3). The list of components, their hierarchy, technical specifications, list of functions, and the capabilities they relate to are extracted from the relevant Capella diagrams.

Assembling System Architecture Information from Capella
The information needed from an architectural point of view is both technical and functional. An overview of the key aspects from the Physical Architecture [PA] layer, modeled in Capella is shown in Figure 19. It shows both the traceability between the key information elements used for this analysis as well as the architecture diagrams that are used to capture the entire system. The Capability realization (C_R), Physical Function (PF) and Physical component (P) elements from the Capella models are the data elements that need to be extracted from Capella.

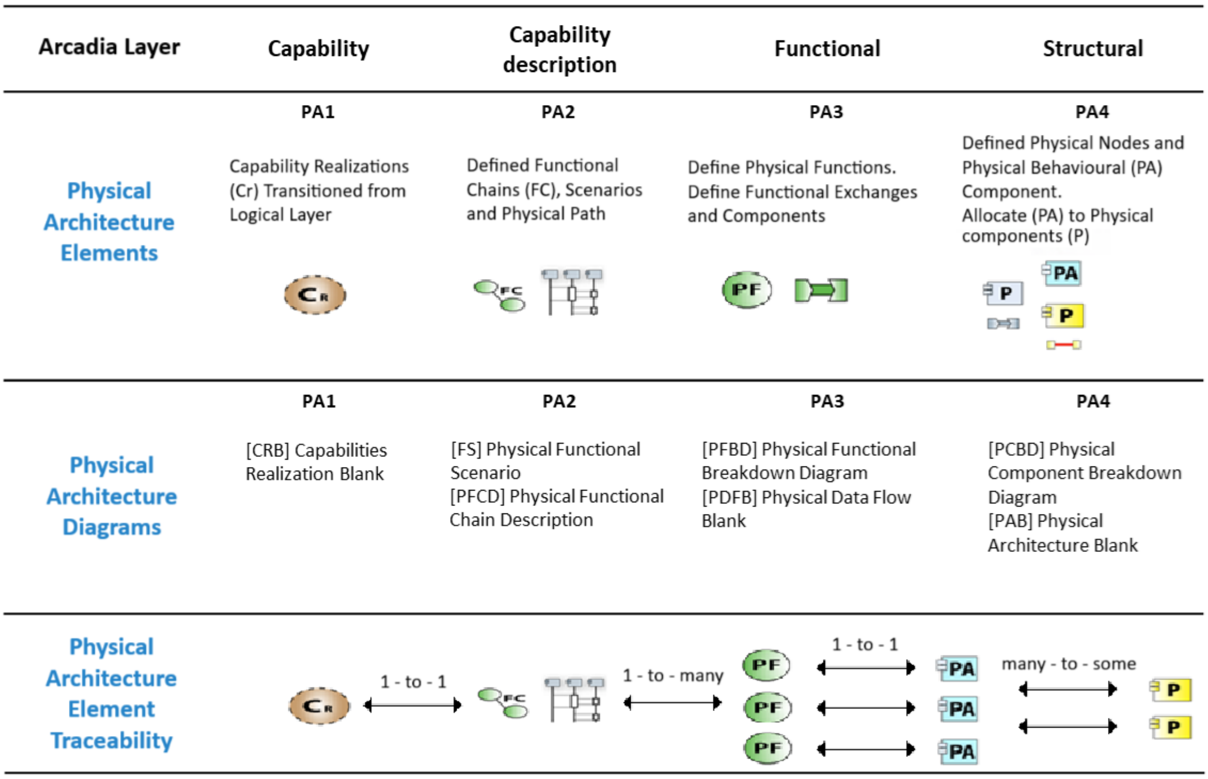


Figure 19: Physical Architecture [PA] overview of information categories and their characteristics.

From the functional perspective, both the Capability realizations (C_R) and Physical Functions (PF) must be extracted from Capella. The Capabilities Realization Blank [CRB] shall be used to extract the list of Capabilities in the system. The Physical Functional Breakdown Diagram [PFBD] shall be used to extract the list of functions in the system related to each component.

From the physical perspective, is important that the product hierarchy is respected. The product hierarchy shows how components are embedded in a larger subsystems. This product hierarchy can be extracted from Capella's Physical Component Breakdown Diagram [PCBD] in the Physical Architecture. Extracting this data provides a list of each Physical component (P) in the system and the hierarchy of these components.

Given the inherent traceability between all the modeled elements in Capella, a document must be constructed that provides the list of components, their functions, and their related capabilities. Additionally, the product hierarchy must be taken into account, thus for each component it must be visible in what larger subsystem it is embedded.

Assembling Component Technical Specifications
Each Physical component (P) in the system consist of a set of technical design specifications,

such as material and mass, that is required to calculate the carbon footprint of each component. This information should be inherent to the Physical components (P) elements in the Physical Architecture layer. The component related parameters should be extracted from either the [PAB] or the [PCBD] diagram in Capella. Not every technical parameter on the component has to be extracted. Step 2 determined what lifecycle stages should be considered in the ecodesign approach, which therefore also determines what technical parameters must be extracted from the Physical components (P) in Capella. In order to be general and inclusive, all component parameters that are needed to calculate component carbon footprint, considering each lifecycle stages, are included in the list below.

- Component Mass ($M_{component}$), expressed in [kg].
- Considering n materials in the component, the Mass of each Material ($M_{material}$) from material 1 through n in the component, expressed in [kg].
- Lifespan of the system (LS_{system}) expressed in hours [h].
- Lifespan of the component ($LS_{component}$) expressed in hours [h].
- Mean operational power consumption (P_{mean}) expressed in Watts [W].
- Component Duty Cycle ($DC_{component}$) expressed as a percentage of system lifetime [%].
- End-of-Life strategy of the component.

This information should be assembled in a single database, possibly arranged in a table, as shown in Table 2. With this data on the components it is possible to conduct an carbon footprint analysis based on Thales's current carbon footprint assessment method, considering the same lifecycle stages as PETER.

Table 2: Example list of individual technical specifications for every component.

Name	Parent	Mass	Material	$LS_{component}$	P_{mean}	DC	EoL
Component 1	None	97 kg	Steel	263.000 h	230 W	40%	Recycled
Component 2	Component 1	15 kg	Copper	175.000 h	125 W	40%	None
Component ...	...	...	...	...	...	...	...

The data on components and their technical specifications, shall be assembled into one common tool or program, up to the choosing of the company, such as Excel or Matlab. The list of functions and capabilities related to each component shall also be assembled into the same tool. The information will be used to calculate component carbon footprint in step 4, and capability carbon footprint in step 5.

4.3.4 Step 4: Calculate Component Carbon Footprint

This step relates to the calculation of the component carbon footprint (CFP). The total component lifecycle carbon footprint can be calculated with Equation 1. The total component lifecycle carbon footprint is the sum of all its individual lifecycle stages. Note that Equation 1 includes all possible lifecycle stages considered by Thales, however as defined by step 2, only the most significant lifecycle stages should be considered. The calculation is performed on every component considered in the analysis. The same carbon footprint assessment method as is currently used by Thales, which is embedded in PETER, is also used for this step, as stressed by key element 6 in Section 4.1.3.

$$CFP_{Lifecycle,component} = CFP_{Manufacturing,component} + CFP_{Mobility,component} + CFP_{Power,component} + CFP_{EoL,component} \; [kg\ CO_2\ eq.] \quad (1)$$

The technical specifications of each component have been assembled in step 3, in such a way that they relate to the carbon emission factors (EF) shown in Table 16 in Appendix D. The equations required to calculate the carbon footprint on every lifecycle stage of each component are detailed in this section. These lifecycle stages included in this thesis are: (1) Manufacturing, (2) Use phase, and (3) End-of-Life.

Manufacturing
The component emissions to the manufacturing lifecycle stage can be calculated by taking into account some specific information. As shown in Table 16, there are multiple materials that should be considered in the calculation. Often, a component is made of a distribution of various materials. Therefore, it is required that there is a breakdown of the materials by weight for every component. In order to calculate the carbon footprint during this lifecycle stage, the following data on the component is required:

- Material breakdown distribution by weight: Mass Material ($M_{material}$) from material 1 through n, considering n materials in the component.
- Lifespan of the system (LS_{system}) expressed in hours [h].
- Lifespan of the component ($LS_{component}$) expressed in hours [h]. Under the condition that ($LS_{component} \leq LS_{system}$) is always true. If the lifespan of the component is larger, then it must be set to equal the lifespan of the system.

The lifespan of the system and of the component is important to consider in the case that the component lifespan is shorter than the system lifespan. This indicates that the component will need repairs or replacement during the lifetime of the system. To account for a short component lifespan, the amount of carbon footprint related to the material and manufacturing is multiplied by the number of units used of that component during the lifetime of the system. We can calculate the number of units required by dividing the lifespan of the system by the lifespan of the component, rounded up to the next whole number if it does not equal one. Carbon footprint related to Manufacturing can be calculated for each component by Equation 2.

$$CFP_{Manufacturing,component} = Roundup(\frac{LS_{system}}{LS_{component}}) \cdot (M_{material,1} \cdot EF_{material,1} + ... + M_{material,n} \cdot EF_{material,n}) \ [kg\ CO_2\ eq.] \quad (2)$$

In-use Mobility
To calculate the emissions related to In-use Mobility, only the component mass ($M_{component}$) is important. Here it does not matter how the mass is distributed over the various materials. Furthermore, we need to know for the system on what type of platform it is embedded during its lifetime. This thesis only considers one type of platform which is the primary platform for systems developed by Thales, namely a naval vessel. Carbon footprint related to In-use Mobility can be calculated for each component as per Equation 3, as long as the systems lifespan is equal to the lifespan of the naval vessel considered.

$$CFP_{Mobility,component} = M_{component} \cdot EF_{mobility,vessel} \ [kg\ CO_2\ eq.] \quad (3)$$

In-use Power Consumption
To calculate the emissions related to In-use Power Consumption, we need to calculate the total power output of the component during the lifetime of the system, expressed in [kWh]. Non-power consuming components, like structural components, will not contribute to this lifecycle stage. In order to calculate the carbon footprint during for this lifecycle stage, the following data on the component is required:

- Mean operational power consumption (P_{mean}) expressed in Watts [W].
- Lifespan of the system (LS_{system}) expressed in hours [h].
- Component Duty Cycle ($DC_{component,\%}$) expressed as a percentage of system lifetime [%].

The DC is a factor that expresses how much the component is active during the systems lifespan, and as a result is consuming power. Even though peak loads through the component may be much higher than the mean operational power consumption value, this only lasts for a short period of time and is neglected in this study. Hence only the mean power consumption value of the components are required. The systems lifespan is a common factor shared by all components that is determined at the start of the study. As this thesis only considers one type of platform, the naval vessel, the only possible power source considered is the generator. The carbon footprint related to In-use Power Consumption can be calculated for each component as per Equation 4.

$$CFP_{Power,component} = (\frac{P_{mean}}{1000} \cdot LS_{system} \cdot DC_{component,\%}) \cdot EF_{power,generator}\ [kg\ CO_2\ eq.] \quad (4)$$

End-of-Life
Similarly to In-use Mobility, to calculate the emissions related to End-of-Life, only the component mass ($M_{component}$) is important. Secondly, the subsequent End-of-Life strategy needs to be assigned to the component. Either the entire system is recycled, or the system is considered to not be recycled. If the system is recycled, it only needs to be considered if the component is related to electronics or if it is related to cooling equipment. Structural equipment will belong into the electronics category in this instance. Carbon footprint related to End-of-Life can be calculated for each component as per Equation 5.

$$CFP_{EoL,component} = M_{component} \cdot EF_{EoL}\ [kg\ CO_2\ eq.] \quad (5)$$

The results of the calculations should be documented in the same common tool or program as the data assembled from step 3. Table 3 shows an example of how this information can be assembled in a table form. This will show the lifecycle carbon footprint for each component in the system, and also dissect it into each lifecycle stage.

Table 3: Example breakdown of component carbon footprint.

Component	Manufacturing [t CO2 eq.]	In-use Mobility [t CO2 eq.]	In-use Power Consumption [t CO2 eq.]	End-of-Life [t CO2 eq.]	Lifecycle Footprint [t CO2 eq.]
Component 1	70	120	170	10	370
Component 2	10	50	70	5	135
...	...	...	...	...	...

Once this information is documented in the same common tool as the assembled data from step 3, a link is made between the carbon footprint data of the components and their functions and capabilities. The next step details how to relate component carbon footprint to capabilities.

4.3.5 Step 5: Trace Component Carbon Footprint to Capabilities

In this step of the ecodesign approach, the component carbon footprints are associated to their capabilities, to determine the carbon footprint of all the capabilities of the entire system. Through the documented information from steps 3 and 4, it is possible to trace the carbon footprints of the Physical components (P) to their Capability Realizations (C_R), whilst adhering to the hierarchy of the components. The entire information chain is made possible through the integration of MBSE as the common source of information.

By definition, a subsystem always contributes to all capabilities that its underlying components also contribute to in Capella. Similarly, the total carbon footprint of a certain subsystem should always be at least as high as the sum of its underlying component carbon footprints. So we have to determine how to account for this data. Depending on how you define the link between component carbon footprint and capabilities in the hierarchy, there are various ways to calculate or take the carbon footprint of the capabilities since there are various aspects to consider.

In this ecodesign analysis, only the lowest level components that contribute to a capability are taken into account for the carbon footprint of the capabilities. This method used in this thesis and proposed to Thales is depicted in Figure 20, where an example is shown of a single capability that is completed by a two subsystems and their underlying components. Only the carbon footprint of the underlying components that contribute to the capability are accounted for in the calculation of the capability carbon footprint, and not the entire subsystem. The reason for this choice is that it reduces double accounting of the carbon footprints as much as possible and creates a more accurate picture of the carbon footprint of the capability.

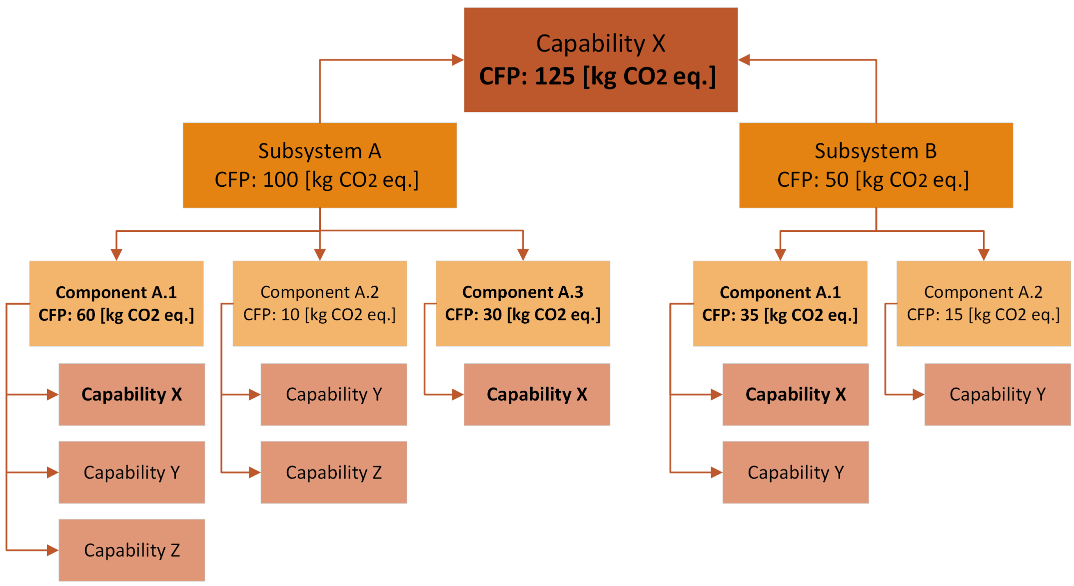


Figure 20: Tracing of component carbon footprint to capability in the hierarchy.

Secondly, the complete component carbon footprint is traced to the capabilities, even though the component may contribute to multiple capabilities. The reason behind this choice is that the component must still be present in the system in full, regardless if the system has the other capabilities or not. This is a limitation of the analysis with regards to calculating an actual carbon footprint related to the capabilities in the system. Ideally, there is a direct link between the usage of the component acting on a specific capability and its subsequent contribution to that capability's carbon footprint. As an example, a component may contribute to 2 system capabilities where it is actively supporting one capability for 80% of the operational life, and only supporting the other capability for 50% of the operational life. This is data is not yet available and is therefore not considered in this analysis.

In order to account for this limitation, a capability usage profile is introduced into the analysis. The capability usage profile is a factor that every capability in the system has, which expresses how much time a capability is utilized by the system throughout its lifetime as a percentage. This is expressed as a Capability Duty Cycle ($DC_{capability}$). With this in mind we can calculate the carbon footprint of capabilities as the sum of the component carbon footprint of all the lowest level individual components contributing to its completion, multiplied by its duty cycle. Equation 6 shows a representation of this calculation.

$$CFP_{Capability} = DC_{capability} \cdot \sum_{i=1}^{n} CFP_{Lifecycle,component,\, i} \tag{6}$$

The calculated carbon footprint of every capability has to be documented, so it can be used for the next steps of the ecodesign approach. This provides all of the required input to start the ecodesign hotspot analysis in the next step. The next section explains how to conduct the ecodesign hotspot analysis.

4.3.6 Step 6: Identify Ecodesign Hotspots

In this step of the ecodesign approach, the ecodesign hotspots in the system must be identified. The information assembled and calculated in the previous steps, make it possible to conduct the analysis of identifying ecodesign hotspots. It is important to consider exactly how hotspots in the architecture can be identified. The ideal targets are components with a high carbon footprint but limited contribution to system capabilities.

As stated in the list of key elements in section 4.1.3, standardized indicators should be used to quantitatively be able to assess the system for ecodesign hotspots. In order to identify hotspots quantitatively, a hotspot index (HI) is calculated for each component. Hotspot indexes are calculated by simply dividing the total carbon footprint of the component by a Function Factor (FF) of a component as shown in Equation 7. The equation includes a Function Factor (FF) term, which is used as a general term to account for the functionality of the components and how to rank them, which is further discussed later in this section. The higher the hotspot index value, the more inefficient a component is, and thus the components with the highest hotspot index values are the hotspot components. The cut-off point for what are and what aren't hotspot components has to be decided by the development team and depends on the studied product.

$$HI_{Component} = \frac{CFP_{Lifecycle,component}}{FF} \tag{7}$$

This information can be documented, and a key feature of the analysis is a graphical or tabular display of components and their hotspot index values. Once target components are identified, a more detailed breakdown of their carbon footprint across various lifecycle stages can be made available, offering insight into where emissions are concentrated.

Weighting of Functions
Equation 7 details how to calculate the hotspot index values. Depending on the system being studied in the analysis, it must be decided how functionalities will be ranked, indicating if certain functionalities are more important than other functionalities. This ranking could for example stem from the importance of certain capabilities relative to others. This is an aspect of the study that the development team has to consider and decide on how to approach, and can be different for every system being studied.

Depending on the needs and knowledge of the design team, there are multiple alternatives to rank functionalities. For clarity, three methods and corresponding reasons are given:

1. Not weighting functions: If the development team views all functions as equal or if the team does not know of another way for ranking functions fairly.

2. Weighting functions by number of capabilities: If the development team puts a heavy focus on the capabilities, the involvement of a function in multiple capabilities should be given a higher importance.
3. Weighting functions by category: If their is a clear distinction in the importance of certain functions by the category they have. A likely example could be that a function related to performance weighs more than a function for maintenance.

In the first example, the FF is simply equal to the number of functions as no weighting is applied:

$$FF_{equal\ weight} = n_{functions} \tag{8}$$

In Figure 21 there is an graphical example of finding hotspots components in the system following this first example. The graph shows the number of functions of a component against its total carbon footprint. There is a general trend for these components, where more functionality also relates to more carbon footprint. The hotspots component encircled in red are far below the general trend, meaning they are inefficient relative to the other components. They have a large contribution to the systems carbon footprint compared to the functionality they provide. As this is just an example with relatively few components, no threshold that determines whether or not a component is a hotspot or not, is truly defined. The figure displays a theoretical example in which the four most inefficient components have been highlighted.

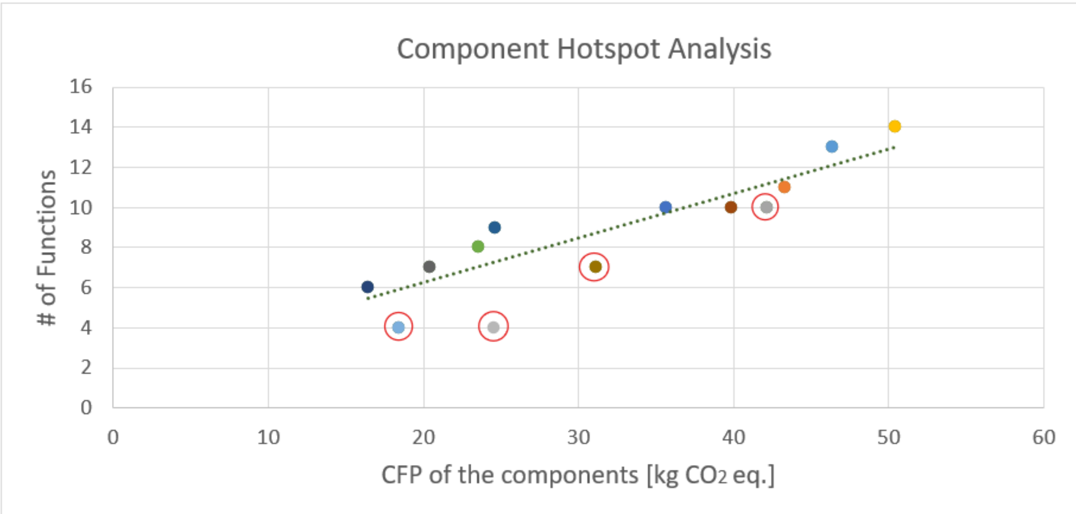


Figure 21: Graph highlighting hotspot components in a theoretical example.

In the second example, is slightly more complicated, as now each function is also multiplied by the number of capabilities it is involved in. Equation 9 shows how to calculate the FF for a component that has multiple functions and is weighted by the number of capabilities.

$$FF_{Capabilities} = Function_1 \cdot n_{Capabilities,1} + ... + Function_x \cdot n_{capabilities,x} \tag{9}$$

In the last example, when functions are weighted by their category, each functions would fall under a certain category. These could be operational, maintenance etc. Each category should be assigned a specific Weighting Factor (WF), and the FF can be calculated accordingly. Equation 10 shows how to calculate the FF for a component that has multiple functions and is weighted by the category of these functions.

$$FF_{category,weight} = Function_1 \cdot WF_{function,1} + ... + Function_x \cdot WF_{function,x} \tag{10}$$

Once the hotspot indexes are calculated according to the metric chosen by the development team, specific ecodesign candidates can be identified. It is important that the design team specifies exactly what the chosen ecodesign hotspots in the system are, since these ecodesign hotspots will be assessed in more detail in the next steps of the approach. It means that a list of ecodesign hotspot components must be made. By carefully evaluating each hotspot in the system, specific ecodesign opportunities can be derived. Evaluating and deriving ecodesign opportunities is part of steps 7 and 8 from Figure 17, which concludes this part detailing the ecodesign hotspot analysis (activity A.3 in Figure 14).

4.3.7 Step 7: Evaluate Ecodesign Hotspots

In this step, the identified ecodesign hotspot components from step 6 are evaluated in more detail. While the ecodesign hotspots work well in identifying improvement areas quantitatively, step 7 aims to put the calculated values into context. Examining the connections between components and their corresponding capabilities reveals the interdependencies within the system, which can subsequently discard certain hotspot components as best candidates for ecodesign. Consequently, the evaluation focuses on three key aspects: (1) functional contribution to capabilities, (2) functional system interdependencies, and (3) physical system interdependencies.

Functional contribution to capabilities
An overview of the hotspot components their functions and capabilities should be made. Relating the hotspot components not only to their functions but also to the contribution they have to the system capabilities, will reveal information on the importance of a component in the system. For example, a component contribution to just one function, but involved in all capability, indicates that the function is critical to the systems general operation. A representation of this information is displayed in Table 4, which highlights the number of functions, the functional description and the number of capabilities each hotspot component contributes to as an example.

Table 4: Example overview of hotspot components functionality and capability contribution.

Hotspot components	# PF	Function	# C_R
Component 1	1	function 1	2
Component 2	2	function 2, function 3	1
Component 3	1	function 4	8

In Table 4 it is clear that the third hotspot component is involved in eight capabilities, but only completes a single function. This means that this function is active in multiple functional chains, and likely acts as a critical and central function of the system. Hotspot components that contribute to fewer capabilities are prioritized because modifying them presents a lower risk to overall system functionality. This ensures that ecodesign changes do not disrupt critical system operations.

Functional system interdependencies
It should be made clear what the carbon footprint contribution of a component is to the carbon footprint of a capability. This means that the component's share of the environmental impact for the capabilities it supports must be visualized. This highlights the potential improvement step that can be made for each capability.

Additionally, hotspot components that support the same capability are closely related in the functional chain. If multiple hotspots contribute to the same capability, they present greater potential for combined redesign strategies, making ecodesign improvements more effective. This rationale aligns with Thales's current ecodesign principles by ensuring that functionality may be combined through design changes.

Physical system interdependencies
Secondly, for the hotspot components it should be considered what other components are part of its subsystem. If multiple hotspots components are part of the same subsystem, there is a greater potential improvement opportunity by tackling the hotspot components together through a single redesign process, making the process less disruptive to the system as a whole. As a result, it must be evaluated if multiple hotspot components are part of the same subsystem, showing how they relate to each other in the physical hierarchy.

If required, a selection of these components can be made for step 8, where specific ecodesign opportunities will be derived based on their characteristics. The key outcome of this step is a clear determination of which hotspot components represent viable ecodesign opportunities, ensuring that ecodesign improvements align with system functionality and engineering constraints. For Thales, hotspot components are prioritized for deriving ecodesign opportunities in the next step, if:

1. The component contributes to only a few system capabilities, meaning design changes forced by ecodesign are less likely to disrupt overall system functionality.
2. Multiple hotspot components are part of the same capability, as functional closeness allows for more opportunities and ecodesign strategies in the redesign process.
3. Multiple hotspot components are part of the same subsystem, as physical closeness allows for more opportunities and ecodesign strategies in the redesign process.

4.3.8 Step 8: Derive Ecodesign Opportunities

In step 8 of the ecodesign approach, specific ecodesign opportunities are derived from the selection of the hotspot components. By contextualizing the hotspot components by bringing the carbon footprint into context through assessing the operational modes and scenarios of the components, this step aims to provide the rationale for deriving ecodesign opportunities. By assessing how the functionality of the component is reflected in the carbon footprint, specific improvement areas will be identified. Depending on the complexity of the hotspot components and the number of them, this step can be relatively short or long.

A breakdown of the component over various lifecycle stages offers insight into where emissions are concentrated. For instance, if a target component's largest environmental impact stems from the manufacturing phase, which is determined by the materials, weight and lifetime of the component, it presents the opportunity to focus on strategies to reduce the weight, change the material or improve on the lifetime of the component. Opportunities like this can be created for each hotspot component, by understanding the carbon footprint and the technical parameters responsible for the large contribution in carbon footprint. As a result, the following must be done in this step:

1. Carbon footprint breakdown of the system over its lifecycle stages. (If only a single lifecycle stage was included in the hotspot analysis based on step 2, then this step is trivial.)
2. Relate the carbon footprint back to the technical parameters used to calculate the carbon footprint.
3. Relate the technical parameters to the operational modes and states of the component to determine if the relatively large carbon footprint contribution is justified given the operational conditions of the system.

Contextualizing the ecodesign hotspots in the way presented, key opportunities for ecodesign are derived. These opportunities can be worded as: *"Component X should improve/optimize/change technical aspect Y."*

By completing step 8, the use of the CLOE tool to orient on ecodesign strategies that tackle the derived opportunities in steps 9 and 10 is strengthened and streamlined, by limiting the possible solution space. Performing these steps addresses the need for a more structured and streamlined approach to focus on solution orienting. Formalizing the ecodesign opportunities based on specifying the areas for improvement marks the end of the fourth activity (A.4) in the ecodesign approach from Figure 14.

4.3.9 Step 9 & 10: Define Ecodesign Orientations

The last steps in the ecodesign approach are focused on defining specific ecodesign orientations, as described in step 9 and 10. These steps will address how to act on the presented opportunities that are derived in this step through Thales's established list of ecodesign orientation strategies. Ecodesign orientations can be defined with the help of the CLOE tool. As the use of CLOE and the associated activity of defining strategic orientations (A.5 in Figure 14 is not a new activity introduced in this thesis, only the important input and output is discussed for both steps. Both step 9 and 10 are existing steps within Thales's ecodesign process and are therefore mentioned separately, but are small enough and are exercised with the CLOE tool to be presented in one section.

Step 9: Define Ecodesign Orientations
Step 9 focuses on defining specific ecodesign orientations that will address the identified opportunities in the hotspot components of the previous step, with the use of the CLOE tool. Ecodesign orientations are product design orientations that aimed at reducing environmental impact. Thales defines these orientations based on their own established ecodesign strategies, which can be found in Appendix B for reference.

CLOE is a checklist-based tool that helps to define ecodesign orientations by going through a checklist. The tasks to define ecodesign orientations include:

1. Review the hotspot ecodesign opportunity.
2. Select suitable ecodesign strategy.
3. Select suitable product ecodesign orientation belonging to the selected strategy.

For example, if the opportunity states: The data processing servers should optimize their power consumption profile according to the needs. A possible ecodesign strategy should be #4: Adapt up and down. Consequently, CLOE presents a list of ecodesign orientations that are suited to this strategy, like; Implement elastic architecture by providing multiple states of use adaptive to the needs and conditions of the system.

The process of using CLOE to select ecodesign strategies and subsequent ecodesign orientations is greatly strengthened by the input from step 8. The clear definition of improvement opportunities leads to specific targets and makes it easier to define ecodesign orientations that will lead to significant environmental impact reduction, rather than going of the system carbon footprint breakdown that is provided by PETER in Thales's current ecodesign approach.

This step concludes by defining a list of possible ecodesign orientations for hotspot components, based on Thales's ecodesign strategies that lead to environmental improvement of the product.

Step 10: Select Ecodesign Orientation
It is possible that CLOE leads to multiple ecodesign orientations. Step 10 defines that the development team will decide on the best technical orientation. It is up to the design team to choose a selection of ecodesign orientation for further product development resulting in reduced carbon emissions.

This selection is based on ranking the ecodesign orientations on five criteria. This selection is also made within the CLOE tool, and is inherent to the use of CLOE. Therefore, the criteria are only stated in short:

1. Market differentiating aspect.
2. Reduced market price or total cost of ownership (TCO).
3. Technical and economical feasibility.
4. Visible environmental improvement for the user.
5. Actual environmental improvement.

The higher an ecodesign orientation scores on all five criteria, the better the orientation is. It may be the case that all strategies score relatively equal, and all will be evaluated in the design phase of product development. Most importantly, the development team decides on which technical design orientations to follow for the remainder of the product development process.

By defining key orientations for ecodesign that will lead to emission reduction, it will help the design team in the next phase of product development to focus on specific improvement areas. This concludes this chapter explaining the adapted ecodesign approach proposed to Thales in this thesis. In the next chapter, the approach is used on an existing radar system from Thales, highlighting its favorable impact on performing ecodesign.

5 Ecodesign Approach Application

The aim of this chapter is to demonstrate the practical application of the proposed ecodesign approach in Chapter 4, by implementing it on an existing radar product from Thales. This chapter serves as a proof of concept, validating the use of the ecodesign approach and highlighting its potential in a real-world context, addressing sub-objective 6. The chapter begins with a description of the product under analysis, including a breakdown of its components, its system capabilities and the information sources to establish the scope of this case. With the scope and technical characteristics of the radar fully established, the ecodesign approach can be applied to the STIR, by following the ten steps defined in Section 4.3. The focus is thus only on the activities in the orient phase of product development, as the newly introduced activities are integrated there. Following the steps, the results of the ecodesign hotspot analysis are presented, identifying critical areas of the radar system's architecture that show potential for significant improvement in emissions. Based on these identified hotspots, a set of actionable ecodesign opportunities are derived, considering their functionality and contribution to system capabilities. The ecodesign approach ends by defining ecodesign orientations for the radar. The chapter concludes with a validation of the approach by the stakeholders within Thales, reflecting on the utility of the approach.

5.1 Radar Product Description

The radar product chosen for this ecodesign study is the STIR (Signal Tracking and Illumination Radar). The STIR is a Fire Control Radar (FCR), known for its reliability during long missions and excellent stealth target detection capabilities. The STIR's radar antenna provides both I-band and K-band tracking capabilities to target stealth threats. The STIR variant under consideration for this study is the STIR 1.2 EO, shown in Figure 22, which beyond its radar tracking capabilities also provides Electro-Optical (EO) tracking and illumination capabilities by means of various EO sensors. The Figure 22 shows the above-deck equipment, like the radar antenna, stabilization platform and the EO sensors. The STIR has been a staple of Thales's product portfolio for several decades, having undergone various major improvement changes throughout the years. STIR radars are commonly deployed on frigates, destroyers, and corvettes. They often work in conjunction with surveillance radars to ensure situational awareness and defense readiness. A typical use case involves the STIR radar locking onto an incoming missile, illuminating it, and guiding a ship's missile to intercept it before it poses a serious threat to the vessel.

Figure 22: STIR - Tracking and illumination radar director.

This STIR was chosen for this ecodesign case due to its relevance and recent history with Thales's established ecodesign initiatives. It was the focus of initial ecodesign pilot study that was explored in Section 2.3.3. This provides a baseline for comparing the results of the proposed approach with prior efforts. Additionally, the team associated with this product is already familiar with ecodesign practices, facilitating support and communication with the product team. Beyond its suitability for this study, the STIR is also a significant product within Thales's portfolio, making it an important candidate for exploring environmental improvements.The remainder of this section provides more explanation on characteristics of the STIR that define the scope of its ecodesign study.

5.1.1 STIR Fire Control Radar Elements

The STIR radar consists of multiple major subsystems, like the director shown in Figure 22. The director is often regarded as the main element of the system, being placed above-deck and consisting of the radar dish. However, the STIR also includes other equipment that sits below-deck and out of sight. In this case, when referred to the STIR, both the above-deck and below-deck equipment are considered. The functionality of both types of equipment however, is different. This section provides a breakdown of the equipment elements typically used in a STIR, for which a full system hierarchy of the included components is shown in Figure 23.

Above-Deck Equipment Elements
The above-deck components handle signal transmission, reception, and initial signal processing. This includes the Director and the EO sensors shown in Figure 22, but also a cleaning unit and a junction box. The junction box is a component where all the wiring from below to above-deck equipment come together and power and signals are distributed to the corresponding components in the system. The director is the main component that includes the radar's antenna, a stabilized platform and rotational mechanisms to facilitates azimuth and elevation scanning for target acquisition and tracking. In summary, the major equipment elements include:

- Director (STDIR 1.2)
- Junction Box
- Infra-Red Camera (IR-C)
- Laser Range Finder (LRF)
- Tracking Investigation Unit (TIU)
- Cleaning Fluid Unit (CFU)

Below-Deck Equipment Elements
The below-deck equipment processes, analyzes, and integrates the data from the above-deck equipment into the ship's combat system. Other important subsystems include the cooling system and the air drying unit which reduces corrosive effects on the system by drying the air in the system. Given most equipment is used on ships, they are generally operating out at sea, with high humidity as a result. Other major elements are the Man Aloft and the Remote On-Off components. In summary, the major Equipment Elements include:

- Control Cabinet (SACC)
- Cooling Cabinet (CC)
- Liquid Filter Unit (LFU)
- Air Dryer (AD)
- Man Aloft
- Remote On-Off

The component hierarchy of the STIR considered in this case of application, shown in Figure 23, includes all the equipment elements mentioned above, but also some other key components that are embedded in their larger subsystems. This breakdown structure is important to keep in mind during the analysis, especially when comparing one component to another. It is also visible that not every equipment element has underlying components. This either has to do with limited data available or because those equipment elements simply do not have sub-components that can be specified. More information on these limitations are discussed in Section 5.1.3. The next sections will discuss the system capabilities realized by the STIR, which is an important element of the ecodesign approach.

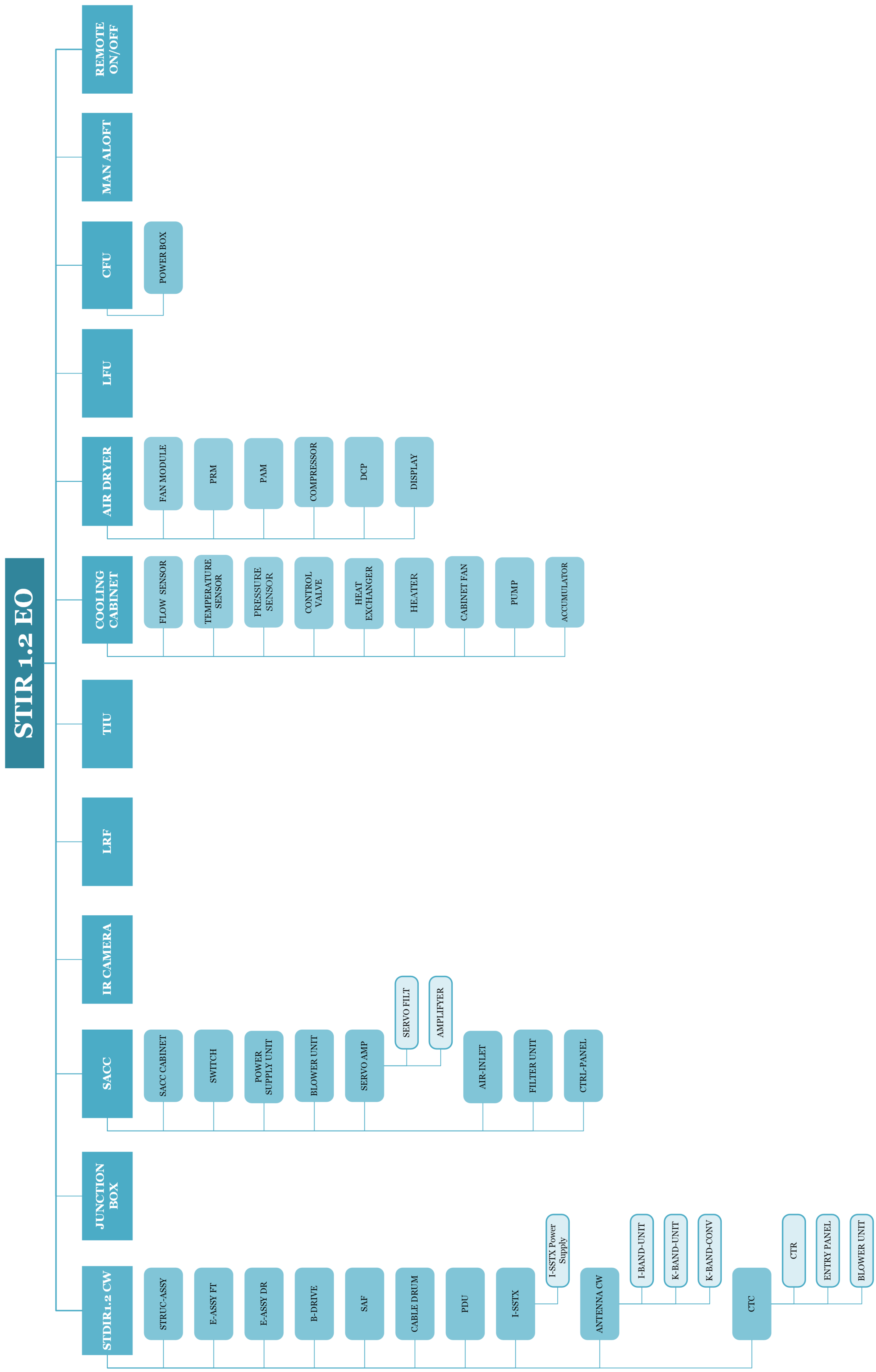


Figure 23: STIR component hierarchy used in this application case.

5.1.2 STIR System Capabilities

The STIR is a Fire Control Radar, which means that it is tasked with surveilling the surrounding airspace for incoming threats, and tracking threats with ultra-high precision to support gun fire control. Specifically, the STIR 1.2 EO discussed in this thesis, has both radar and EO surveillance capabilities. These radar and EO surveillance functions are the systems main operational capabilities. However, a greater distinction in individual capabilities can be made within both the radar surveillance and optical surveillance capabilities. Furthermore, there are also other capabilities that are realized in the system through certain components. Examples are components that fulfill maintenance support functions or components used for system operability test functions. These capabilities are also accounted for in the ecodesign approach. For the ecodesign case applied in this thesis, the capabilities are structured and categorized based on their role in the system. The capabilities of the STIR have been categorized as follows:

- Main Capability
- Subsidiary Capability
- Support Capability
- Stand-alone Capability

The full list of capabilities considered in this analysis, their structure, and to which category they belong is shown in Figure 24. The remainder of this section explains these capability categories and explain how they will be treated in the ecodesign approach, specifically relating to the calculation of capability carbon footprint. A detailed breakdown of the capabilities is out of the scope of this thesis due to confidentially agreements.

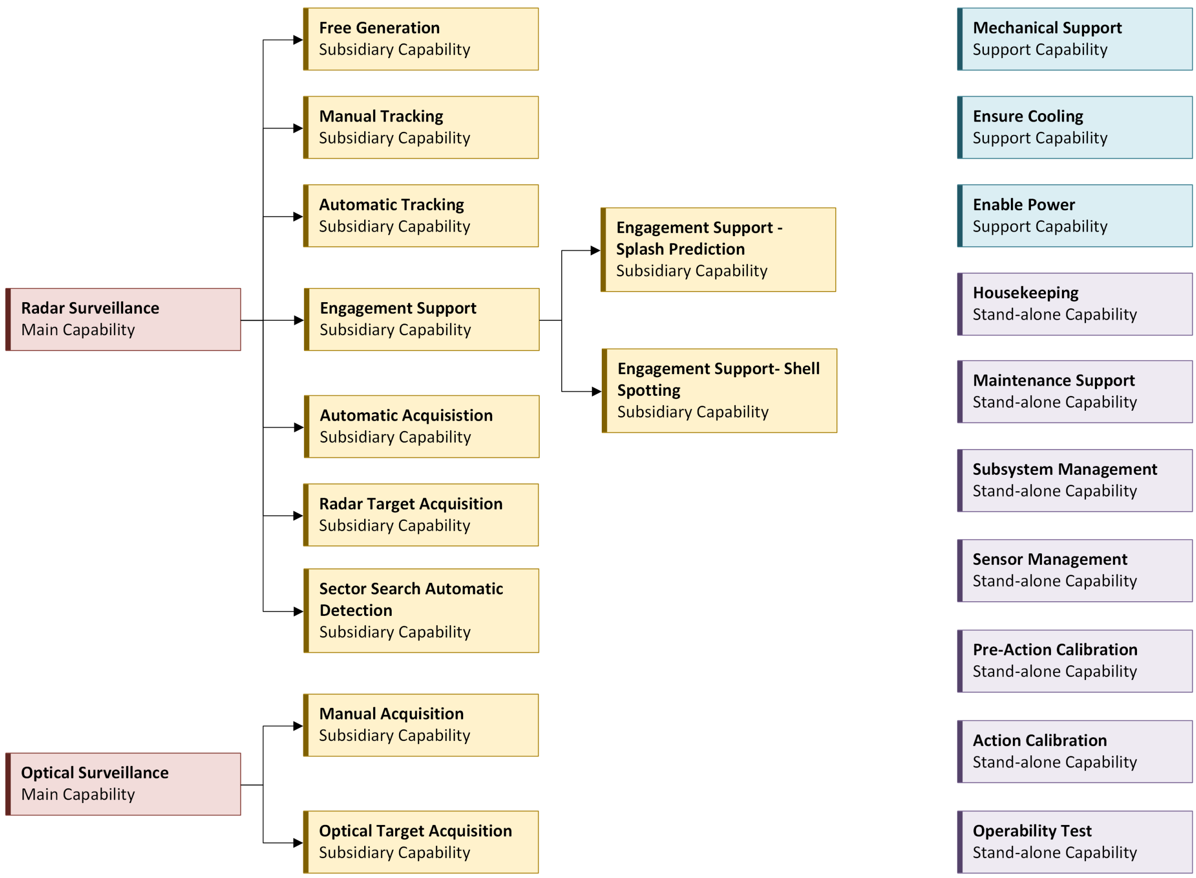


Figure 24: STIR list of capabilities and their structure.

The Main Capabilities in this thesis relate to the top-level operational capabilities performed by the STIR; (1) Radar surveillance, and (2) Optical surveillance. These capabilities are more layered, consisting of multiple focused capabilities. For example, radar surveillance includes a whole set of individual capabilities that are considered separately, such as the ability to detect targets, acquire target locks, track targets and provide gun control support.

These capabilities fall under the category of Subsidiary Capabilities. As shown in Figure 24, in one case there is an additional distinction in the capabilities, the Engagement Support capability. Within this capability, we can distinguish between Splash Prediction and Shell Spotting. In case a component is contributing to both these capabilities it will only be accounted for once when calculating the carbon footprint of the Engagement Support capability. The calculation of capability carbon footprint directly follows the method described in the ecodesign approach, detailed in Section 4.3.5, and those results will be presented later in this chapter.

Alongside the main operational capabilities, certain components in the system complete functions that are required for continued operation of the system, but are not involved in any Subsidiary Capability in specific. For this reason, the category of Support Capabilities is made in this ecodesign application case. Under this support category, three capabilities are present; (1) Mechanical Support, (2) Ensure Cooling, (3) Enable Power. An example are components used for system cooling only. The Ensure Cooling capability is required in order for the system to continue operation and carry out its main capabilities. Therefore, it supports all the other operational capabilities in the system, i.e. all other subsidiary capabilities.

The last category of capabilities are not directly operational capabilities of the system, and also do not provide a supportive aspect to the them in the same way that the support capabilities do. These capabilities are categorized as Stand-Alone Capabilities.

The last important factor to consider is how the components are allocated to their capabilities. In Capella this happens automatically based on the traceability between the model elements as explained in Section 4.2.1. When performing the ecodesign hotspot analysis, only the Subsidiary Capabilities, Support Capabilities and Stand-alone Capabilities are considered for comparison, as no single component is responsible for one the main operational capabilities of the STIR on its own. A single component can complete functions that are used for both Subsidiary Capabilities as well as Stand-alone Capabilities, meaning its shares functionality with multiple capabilities and even categories.

5.1.3 STIR Data Sources

This section explains the differences between the proposed ecodesign approach from Chapter 4, and the exact approach followed in this case of application. Due to data available in the Capella models of the STIR at the time of conducting this thesis, some information streams of ecodesign approach had to be changed slightly. The data required to calculate carbon footprint of components and subsequently conduct the ecodesign hotspot analysis, was not yet available in the models. This data relates to the technical specification of the components with which carbon footprint is calculated. It meant that the technical specifications had to be retrieved from a different source. Figure 25 shows how the information streams were realized in order to follow the developed ecodesign approach. Retrieving technical data specifically relates to step 3 in the ecodesign approach, as discussed in Section 4.3.3.

The STIR Capella models in the Physical Architecture included a complete description of the system's architecture and components. All of the required diagrams were made available, detailing the systems component, their hierarchy, their functions and overall system capabilities.

The links between the modeled elements were also modeled correctly between the different Capella diagrams.

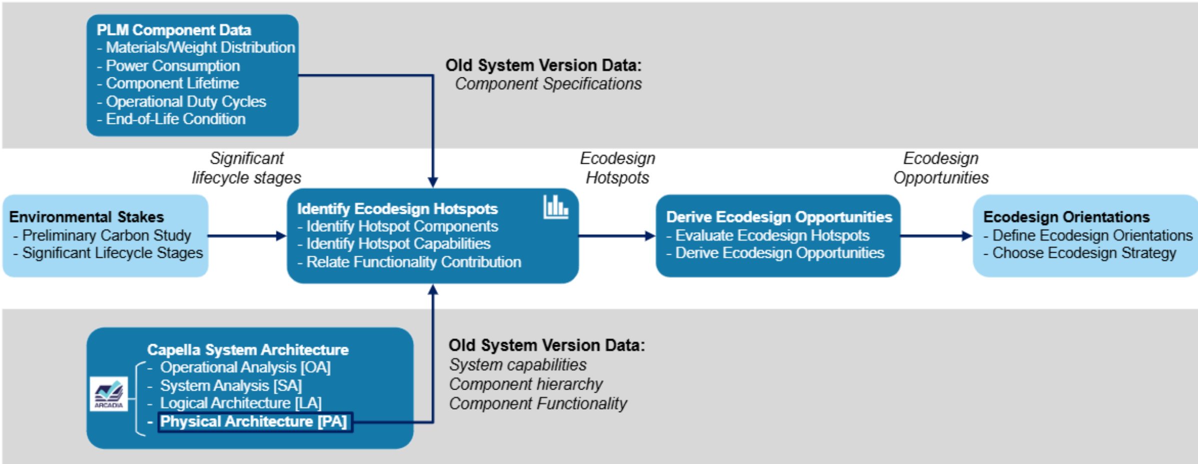


Figure 25: Information streams in used the application case of the ecodesign approach, adapted from Figure 15.

Since the models lacked the necessary technical specifications associated to each Physical component (P) in Capella, that data was retrieved from documents in the Product Lifecycle Management (PLM) system. Sources include CAD drawings, design specification documents and a maintenance analysis report of the STIR. The CAD drawings were used to source component mass and material distribution, and the design specifications were used to source component power consumption.

The maintenance report includes a full breakdown of the system into its components and reports on maintainability. This document provided key technical parameters, such as component duty cycles and Mean Time Between Failure (MTBF) values. The MTBF values of the components were used as an estimation of component lifetime. This reasoning is based on a policy for easy maintenance applicable to the STIR, namely repair by replacement.

This concludes the explanation how limitations in the STIR Capella models meant that the information sources for the ecodesign approach were slightly different than prescribed. The remainder of this chapter focuses on the results of the ecodesign study of the STIR, following the proposed ecodesign approach. The focus will be specifically on the two added ecodesign activities of the proposed ecodesign approach; (A.3) Identifying ecodesign hotspots, and (A.4) Deriving ecodesign opportunities. Every step of the ecodesign approach will be followed in order to conduct the ecodesign activities. The results of the ecodesign study on the STIR will act as a proof of concept for the developed ecodesign approach and help validate its effectiveness.

5.2 STIR Ecodesign Approach Application

This section presents the results of the ecodesign approach application. The application centers on the activities in the orient phase of product development, A.2 to A.5 in Figure 14. This means that first, the environmental stakes of the STIR will be determined. Thereafter, ecodesign hotspots are identified, and subsequent ecodesign improvement opportunities are derived for the hotspot components. The approach ends by defining specific ecodesign orientations for the STIR.

The entire analysis of identifying ecodesign hotspots is conducted in Excel, where all the required data was structured and assembled in one workbook. Excel was used as it is a common platform that can be accessed by everyone in Thales and is understood by every individual working there. Furthermore, Excel as a tool works well to provide a proof of concept.

The list of steps established in Section 4.3, is followed in order to complete the ecodesign development process in the orient phase of product development. The results of the steps are presented in individual subsections.

5.2.1 Step 1 & 2: Determine the Main Environmental Stakes

According to the first two steps of the ecodesign approach, detailed in Sections 4.3.1 and 4.3.2, the most impactful lifecycle stages of the STIR must be determined, making use of the internal PETER tool. As the use of PETER is outside the scope of this thesis, only the important results of this step in the approach are provided, such as the lifecycle carbon footprint breakdown of the STIR in Figure 26. Note how the End-of-Life phase is not shown in the figure, as no end-of-life strategy has been defined for the product.

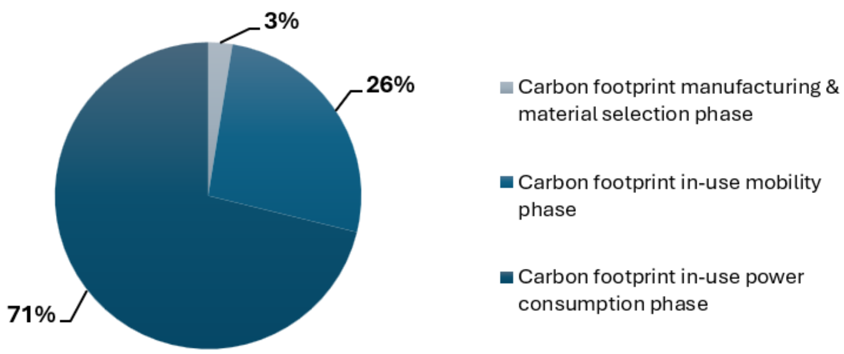


Figure 26: Lifecycle carbon footprint breakdown of the STIR

As this application case aims to provide a proof-of-concept, both the manufacturing and use phase lifecycle are taken into account. In summary, the following findings are carried over from the initial ecodesign activity, which detail the most important environmental stakes to consider:

- Total lifecycle carbon footprint of the STIR calculated by PETER is 1041 [t CO_2 eq.]
- The most significant lifecycle stages to consider for the remainder of the analysis include the Manufacturing and the Use Phase.

It is important to know exactly what technical parameters belong to the most significant, and subsequently included lifecycle stages for the remainder of the ecodesign approach. Table 5 details exactly which technical parameters need to be assembled for every component shown in Figure 23 to calculate component carbon footprint. It also highlights which technical parameters are required for each lifecycle stage. This knowledge is carried over as input for the next step.

Table 5: Technical parameters needed to calculate carbon footprint per lifecycle stage.

	$Mass$ [kg]	$M_{Materials}$	$Lifespan$ [h]	P_{mean} [W]	DC [%]	LS_{system} [h]
Manufacturing	✓	✓	✓	×	×	✓
Mobility	✓	×	×	×	×	✓
Power Consumption	×	×	×	✓	✓	✓

5.2.2 Step 3: Extracting and Assembling Component Data from Capella

Following step 3 of the ecodesign approach, detailed in Section 4.3.3, all of the required technical and functional data from the components in the STIR are extracted from the relevant sources and assembled into a single tool. In this case Excel is used as the central tool. Section 5.1.3 discussed how the approach in this case had to deviate from the proposed ecodesign approach given various data limitations. This meant that only the component hierarchy, functions and capabilities could be extracted from the MBSE source, Capella. The technical specifications of the components required for the ecodesign hotspot analysis came from the other specified sources.

Component Functionality & Capabilities of the STIR
The first part of this step is to extract the functional and architectural information from Capella. This includes the list of components, their hierarchy, the functions and contribution to system capabilities. From Capella, a simple extract of components, functions and related capabilities could be exported into Excel. Specifically, the following information was directly exported from Capella:

- Physical components (P)
- Physical Functions (PF)
- Capability Realizations (C_R)

Table 6 provides a selection from the complete list of components, showing the number of functions each component performs and a description of these functions. The number in the first column represents the level in the systems hierarchy. The selection of the components are all part of the STDIR 1.2 CW (level 1) equipment element in Figure 23, and are therefore level 2 components. Section 4.3.3 already explained how there is full traceability between these elements in Capella, and thus this information was also exported into an Excel sheet.

Table 6: Shortened list of components their related functions.

	Component	# PF	Function Description
2	STRUC-ASSY	1	Provide mechanical structure for director
2	E-ASSY FT	7	Activate and calibrate sensors Monitor splash point and adjust trajectory Lock onto the detected target Identify targets automatically Track selected targets automatically Monitor engagement process in real-time Assess damage post-engagement
2	E-ASSY DR	1	Enable turning of director in elevation
2	B-DRIVE	4	Enable turning of director Scan a wide area Track targets manually with operator assistance Track the projectile's flight path
2	SAF	1	Prevent director damage by shock by providing shock absorption
2	CABLE DRUM	2	Allow transport of signals, power, cooling liquid over rotating mechanical housing Transmit radar signals to a specific sector
2	PDU	1	Director power distribution

This traceability makes it possible to analyze how each component contributes to the overall system performance and identify components with significant functional contribution. For this ecodesign case, a total of 155 unique functions have been modeled in Capella, all of which are linked to the system capabilities included in the analysis. This level of detail provides the foundation for identifying ecodesign hotspots and derive selective opportunities for improvement. Table 7 presents this aspect, showing how components play a role in enabling the system's capabilities.

Table 7: Shortened list of components and their involvement in system capabilities.

	Component	# C_R	Capability
2	STRUC-ASSY	1	Mechanical support
2	E-ASSY FT	4	Automatic Tracking Mode Automatic acquisition Sensor Management Engagement Support
2	E-ASSY DR	1	Mechanical support
2	B-DRIVE	4	Radar Target Acquisition Manual Acquisition Automatic Acquisition Engagement Support - Splash Prediction
2	SAF	1	Mechanical support
2	CABLE DRUM	1	Sector Search Automatic Detection
2	PDU	1	Enable power

The component-to-function data already provides a comprehensive overview of each component's contribution to the STIR. However, an even clearer picture emerges when components are directly linked to their contributions to the system's capabilities. This component-to-capability information is particularly useful when analyzing the potential impact of ecodesign changes. Once a component is selected for ecodesign improvements, this data can be used to identify other components within the system that also contribute to the same capability. This highlights interdependencies within the STIR's components and helps indicate how changes to one component might affect overall system performance. This information provides the basis for identifying ecodesign hotspots in the system, however first the technical specifications on the components have to be assembled to calculate component carbon footprint.

Technical Component Specifications STIR

The technical specifications for the STIR have to align with the lifecycle stages included in the ecodesign hotspot analysis. The results from step 2 in subsection 5.2.1 highlighted that the most significant lifecycle stages where the Manufacturing and Use phase. This means that the technical parameters related to the Manufacturing, In-use Mobility and In-use Power Consumption lifecycle phases had to be assembled for every component of the STIR considered in this ecodesign analysis. This includes component mass, materials, lifespan, mean power consumption, and duty cycle as shown in Table 5.

Table 8 shows the assembled technical data of the components in the director of the STIR. The full table showing the technical specifications for every component in the analysis can be found in Appendix E.1. The component hierarchy shown in Figure 23 is adhered in the table, by assigning a hierarchy number to each component. Level 0, is the STIR 1.2 EO itself, level 1 will be all the Equipment Elements included in the analysis etc., meaning a higher number corresponds to a lower level component in the system hierarchy. The technical specifications also adhere to this hierarchy. Looking at the table it also becomes clear how the hierarchy is adhered in the technical specifications. For example, the power output of the CTC (level 2 component), is the sum of its underlying components; CTR, Entry Panel and Blower Unit (level 3 components). Only the most prominent material present in the component is presented in Table 8, for representation purposes.

Table 8: Technical specifications of the director and its underlying components.

	Component	DC [%]	Weight [kg]	Material	P_{mean} [W]	$LS_{component}$ [y]
0	STIR1.2EO	-	-	-	-	-
1	STDIR1.2CW	40%	890,9	Steel	1780	30
2	STRUC-ASSY	40%	351,4	Steel	0	30
2	E-ASSY FT	4%	6,90	Aluminium	0	30
2	E-ASSY DR	4%	54	Aluminium	77	30
2	B-DRIVE	4%	74,6	Steel	231	30
2	SAF	20%	171,8	Steel	0	30
2	CABLE DRUM	4%	70,5	Aluminium	0	30
2	PDU	20%	15,2	Aluminium	0	2,5
2	I-SSTX	4%	13,3	Aluminium	77	30
3	I-SSTX PS	4%	1,71	PCB	77	30
2	ANTENNA CW	4%	84,3	Aluminium	231	30
3	I-BAND-UNIT	4%	16,5	Steel	77	30
3	K-BAND-UNIT	4%	5	Steel	77	30
3	K-BAND-CONV	4%	9,95	Aluminium	77	22
2	CTC	20%	30,5	Aluminium	1164	30
3	CTR	20%	19,7	Steel	978,5	30
3	ENTRY PANEL	40%	5,8	Steel	89,5	30
3	BLOWER UNIT	20%	5	Aluminium	96	30

5.2.3 Step 4: Calculating Component Lifecycle Carbon Footprint

With all of the required technical specifications carefully assembled, the lifecycle carbon footprints of the components is calculated following the approach and equations described in Section 4.3.4. In Figure 27 a carbon footprint breakdown of the major equipment elements in the system is presented.

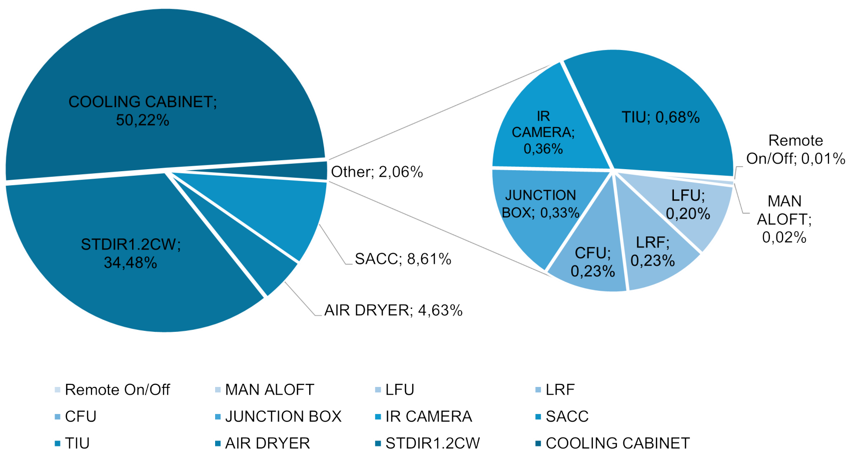


Figure 27: STIR Carbon footprint breakdown of major Equipment Elements.

This clearly shows that the Cooling Cabinet, Director, SACC and Air Dryer are the most emissive components in the system. This already gives a good indication where potential gains in the system can likely be made most effectively following an ecodesign approach. A breakdown of the director components into the carbon footprint of each lifecycle stage, including the total, is shown in Table 9. The entire list of carbon footprint breakdown is in Appendix E.2.

The component lifecycle carbon footprint provides a much more detailed insight into the STIR's carbon footprint than was previously achieved at Thales. The information can be used to see what aspects in the system are the largest contributors, i.e. what equipment elements are most emissive. Table 9 only shows the carbon footprint breakdown of the components in the director, but it highlights clearly how the carbon footprint is distributed over the various lifecycle stages included in the analysis. For nearly every component the Manufacturing phase of the lifecycle contributes only very little to the lifecycle carbon footprint of the components.

Table 9: Carbon footprint of director components across lifecycle stages.

	Component	Manufacturing [t CO2 eq.]	In-use mobility [t CO2 eq.]	In-use power consumption [t CO2 eq.]	Lifecycle Footprint [t CO2 eq.]
0	STIR1.2EO	22,43	254,49	689,52	966,45
1	STDIR1.2CW	13,39	151,45	168,40	333,24
2	STRUC-ASSY	3,58	59,74	0,00	63,32
2	E-ASSY FT	0,08	1,17	0,00	1,26
2	E-ASSY DR	0,35	9,18	0,73	10,26
2	B-DRIVE	0,41	12,68	2,19	15,28
2	SAF	0,52	29,21	0,00	29,72
2	CABLE DRUM	0,85	11,99	0,00	12,83
2	PDU	3,27	2,58	0,00	5,85
2	I-SSTX	0,57	2,26	0,73	3,56
3	I-SSTX Power Supply	0,43	0,29	0,73	1,45
2	ANTENNA CW	0,66	14,33	2,19	17,18
3	I-BAND-UNIT	0,05	2,81	0,73	3,58
3	K-BAND-UNIT	0,02	0,85	0,73	1,59
3	K-BAND-CONV	0,16	1,69	0,73	2,58
2	CTC	3,10	5,19	55,06	63,35
3	CTR	2,91	3,35	46,29	52,55
3	ENTRY PANEL	0,02	0,99	8,46	9,47
3	BLOWER UNIT	0,17	0,85	4,54	5,56

Additionally, this approach leverages MBSE tools for a deeper analysis, assessing the carbon footprint of capabilities and subsequently identify ecodesign hotspots. The next steps in the approach focus on these aspects.

5.2.4 Step 5: Tracing Component Carbon Footprint to Capabilities

Following the ecodesign approach, step 5 focuses on tracing component carbon footprint to the STIR's capabilities. The component carbon footprint data from step 4 is used to calculate the carbon footprint related to each system capability. As section 4.3.5 discusses how to trace the carbon footprint of components to capabilities in the system, only the carbon footprint of each capability is presented here.

Table 10 shows this list from the most inefficient capabilities from top to bottom. The capabilities at the top of this list are the capabilities in the STIR that have the highest carbon footprint per component contributing to it. It becomes apparent how the Stand-Alone capabilities sit at the top of the list according to this metric.

A possible explanation for this could be that the components used to complete these capabilities are truly separate entities and share little other functionality with other components in the system. The operational capabilities directly related to the STIR's surveillance and engagement support performance, possibly sharing more functionality among each other and therefore becoming more efficient as a result.

Table 10: Carbon footprint of capabilities, ranked by the carbon footprint per involved components.

Capability	Category	CFP [t CO2 eq.]	# P	[t CO2 eq.]/ # P
Maintenance Support	Stand-Alone	97,6	4	24,40
Subsystem Management	Stand-Alone	92,8	4	23,21
Housekeeping	Stand-Alone	92,8	5	18,57
Action Calibration	Stand-Alone	94,8	6	15,80
Pre-Action Calibration	Stand-Alone	94,8	6	15,80
Operability Test	Stand-Alone	24,6	4	6,14
Sensor Management	Stand-Alone	18,5	4	4,61
Engagement Support - Splash Prediction	Engagement Support	31,2	7	4,45
Sector Search Automatic Detection	Radar Surveillance	42,2	10	4,22
Automatic Acquisition	Radar Surveillance	39,9	10	3,99
Manual Acquisition	Optical Surveillance	43,3	11	3,94
Radar Target Acquisition	Radar Surveillance	50,4	14	3,60
Optical Target Acquisition	Optical Surveillance	46,4	13	3,57
Manual Tracking Mode	Radar Surveillance	35,7	10	3,57
Free Generation Mode	Radar Surveillance	23,6	8	2,95
Engagement Support	Radar Surveillance	20,4	7	2,92
Engagement Support - Shell Spotting	Engagement Support	16,4	6	2,74
Automatic Tracking Mode	Radar Surveillance	24,6	9	2,74

This list excludes the support capabilities, since they cannot be compared with this same metric as the other capabilities. The reason being that the support capabilities are required for the completion of every other capability. Even though the support capabilities cannot be directly compared to the other capabilities, it is still insightful to look at them independently. Table 11, shows the three support capabilities of the STIR, ranked from top to bottom for the most to least significant. It clearly shows how both the mechanical support and cooling capabilities could be targeted for ecodesign.

In conclusion, the specific capabilities that may require additional attention from an ecodesign perspective, are some of the Stand-Alone capabilities and some of the Support Capabilities. From the Stand-Alone capabilities, the Maintenance Support, Subsystem Management, Housekeeping, Action Calibration and Pre-Action Calibration are particularly of interest, given their

Table 11: Carbon footprint of support capabilities, ranked by the carbon footprint per involved components.

Capability	Category	CFP [t CO2 eq.]	# P	[t CO2 eq.] / # P
Mechanical Support	Support	128,4	4	32,10
Ensure Cooling	Support	577,4	20	28,87
Enable Power	Support	43,4	8	5,42

large total amount of carbon footprint as well as the highest score in carbon footprint per number of components. Similarly for the Support Capabilities, the Mechanical Support and Ensure Cooling capability are clear candidates for closer inspection. It will be interesting to see if this is also reflected by the hotspot components in the system, which are idenitfied in the next step.

5.2.5 Step 6: Identifying Ecodesign Hotspots

This section discusses step 6 of the ecodesign approach, discussed in Section 4.3.6. This section presents the results of the ecodesign hotspot analysis, highlighting the identified hotspot components in the architecture of the STIR. By analyzing the carbon footprint of each component in relation to its functions, clear hotspot components are identified.

The identification of hotspot components in this case relies on a straightforward metric: for each component, an index is calculated that relates its lifecycle carbon footprint to the number of Physical Functions (PF) it performs. This method of calculating a hotspot index is also reflected in Equation 7. This provides a normalized measure of environmental impact per function, helping to pinpoint components that are relatively inefficient. In collaboration with the STIR development team, it was determined that no Physical Functions (PF) has a higher priority than another in this ecodesign study. This means that the Function Factor (FF) is equal to the number of functions of a component, as reflected in Equation 8.

Using the above-mentioned metric and ranking all components in the architecture, regardless of hierarchy, from top to bottom, we get a list of the most significant components in the architecture in terms of carbon footprint contribution per function. Figure 28 shows the most inefficient components by this metric, where to components are not in order of hierarchy. The number of components in the figure is limited to components that have at least ten tonnes of CO_2 equivalent per function.

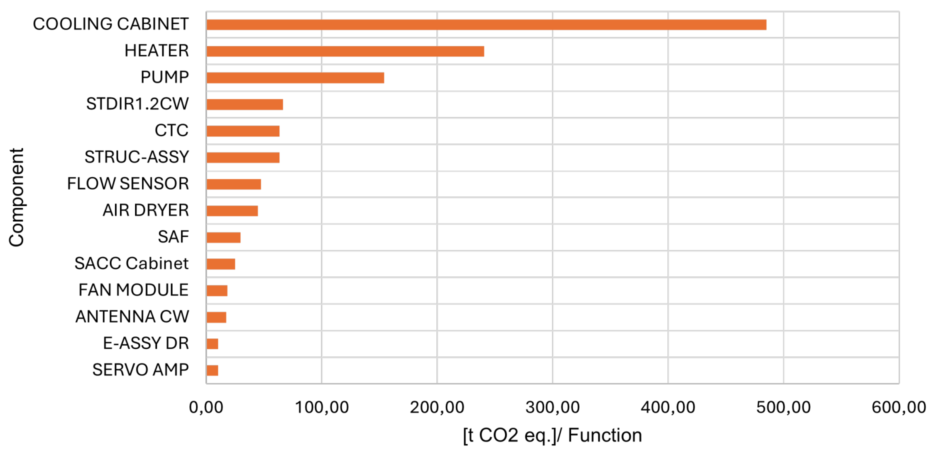


Figure 28: Representation of the components with the highest carbon footprint per function.

The components at the top of the figure are the most inefficient components the STIR from an ecodesign perspective. This figure can also be represented in tabular form, as shown in Table 12, where the last column shows the calculated Hotspot Index values. A full breakdown of all the hotspot values is presented in Appendix E.3. Looking at Table 12, some interesting characteristics can be identified. Notice for example, how the SACC Cabinet is involved in this table, however the SACC as a whole is not. This can be explained by the number of functions that the SACC as a major system fulfills, 18 to be exact. This distinction in functionality highlights how the SACC as a system is reasonably efficient, however the cabinet on its own is not. Secondly, it becomes apparent how inefficient the cooling cabinet is. Moreover, two of its underlying components, the heater and pump, also sit at the top of this list.

Table 12: List of the components with the highest carbon footprint per function, highlighting components with the largest relative contribution to the STIR carbon footprint.

	Component	Lifecycle CFP [t CO_2 eq.]	Footprint Fraction [%]	# PF	[t CO_2 eq.] / # PF
0	STIR1.2EO	966,45	100,00%	-	-
1	COOLING CABINET	485,34	50,22%	1	485,34
2	HEATER	240,87	24,92%	1	240,87
2	PUMP	154,03	15,94%	1	154,03
1	STDIR1.2CW	333,24	34,48%	5	66,65
2	CTC	63,35	6,55%	1	63,35
2	STRUC-ASSY	63,32	6,55%	1	63,32
2	FLOW SENSOR	47,40	4,91%	1	47,40
1	AIR DRYER	44,73	4,63%	1	44,73
2	SAF	29,72	3,08%	1	29,72
2	SACC CABINET	25,09	2,60%	1	25,09
2	FAN MODULE	18,38	1,90%	1	18,38
2	ANTENNA CW	17,18	1,78%	1	17,18
2	E-ASSY DR	10,26	1,06%	1	10,26
2	SERVO AMP	10,17	1,05%	1	10,17

Table 12 shows what the total contribution of a component is to the systems entire carbon footprint. For this study, it has been decided that the hotspot components must contribute to at least 5% of the systems total carbon footprint. Although the table is ranked by the value of carbon footprint per function, it still shows how only the top six components contribute to more than 5% of the total carbon footprint of the system. Not all six components will be selected for further analysis however, as both the Heater and Pump are part of the Cooling Cabinet, and both the CTC and STRUC-ASSY are part of the STDIR 1.2 CW. Only the lower level components are selected for further analysis, as it is likely that these components are the reason that the higher level assembly is also part of this list. Thus, the Heater, Pump, CTC and STRUC-ASSY are the identified ecodesign hotspots of the STIR.

This concludes step 6 and the activity for identifying ecodesign hotspot (A.3 in Figure 14) for the STIR. By linking lifecycle carbon footprint to functions, key components with a disproportionately high carbon footprint were identified. Additionally, the capability analysis step 5 also provided additional insight into the system, by highlighting inefficient capabilities. The identified hotspots serve as a starting point for deriving concrete ecodesign opportunities. In the next section, these hotspots will be examined more closely, giving more attention to the exact functions that hotspot components have and their relation to the hotspot capabilities.

5.2.6 Step 7: Evaluating Ecodesign Hotspots

Following step 7 of the ecodesign approach, detailed in Section 4.3.7, the identified hotspot components are evaluated in detail, considering their functionality and their impact on the overall system. By analyzing the relationships between components and their associated capabilities, the interdependencies within the system are explored. This evaluation provides insights into how each hotspot component impacts the broader system's capabilities, helping to justify the selection of specific hotspot components as targets for deriving ecodesign opportunities.

The hotspot components identified in step 6 are based on their relatively high carbon footprint for the number of functions they complete. Furthermore, the specific selection handled in this evaluation includes the lowest level components from a specific branch in the STIR's hierarchy (Figure 23) with a carbon footprint fraction of at least 5%. This means that the selected components account for at least 5% of the systems total lifecycle carbon footprint. That gave the following components:

1. Heater (part of the cooling cabinet)
2. Pump (part of the cooling cabinet)
3. CTC (part of the director)
4. Struc-Assy (part of the director)

These components only complete a single function, indicating equal importance between these components according to the metric applied in this case. However, we can also take a look at these components from a capability perspective. Including the capabilities into this evaluation, it shows how the Heater, Pump and Struc-Assy are all contributing to just one capability. The CTC actually contributes to 18 capabilities. Table 13, shows what functions the components actually fulfill and to what capabilities they contribute.

If these components would be ranked differently, by taking into account the number of capabilities in the same way as the number of functions are taken into account when identifying hotspots, the CTC rank much lower in the list of all the components, and certainly rank lowest between the components evaluated in this section. This indicates that the CTC actually should not be considered for ecodesign efforts compared to the other components. Although, from this table it is not directly apparent why the CTC contributes to 18 capabilities.

Table 13: Hotspot component functions and contributions to capabilities, highlighting carbon footprint per function and capability.

Component	# PF	Function	# C_R	Capability	[t CO2 eq.] / # PF / #C_R
HEATER	1	Heat coolant	1	Ensure Cooling	240,87
PUMP	1	Circulate coolant	1	Ensure Cooling	154,03
CTC	1	Collect sensor data	18	*Multiple*	3,53
STRUC-ASSY	1	Provide structure	1	Mechanical Support	63,32

The reason that the CTC contributes to 18 capabilities actually has to do with the fact that it is not the lowest level component in its hierarchy branch. In fact, the CTC consists of multiple components, one of which consists again of even more component elements. Figure 29 shows this hierarchy and also provides a diagram showing the carbon footprint breakdown into its components. If the components in the CTC were ranked independently in the hotspot analysis, they would not be considered hotspot component. For more information, look at Tables 23 and

24 in Appendix E.3. What is means for this evaluation, is that the CTC is not considered an opportunity for ecodesign and will not be evaluated further.

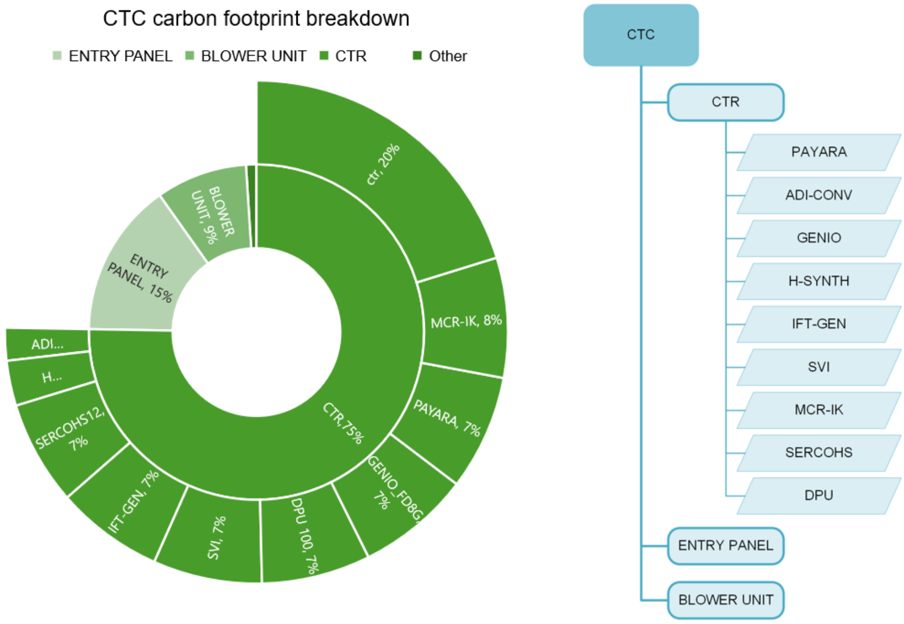


Figure 29: Carbon footprint breakdown of the CTC subsystem and the hierarchy of components in the CTC.

The remaining components, Heater, Pump and Struc-Assy, all have one function that is part of just one capability. The capabilities these components are part of are all support capabilities; (1) Ensure Cooling, and (2) Mechanical Support. Considering the components contribution to their capabilities, Table 14 shows how large the impact of these components is for their respective capabilities. It becomes trivial that the Heater and the Pump should be the targets for ecodesign. Their relative contribution to the capability has a much larger impact than that of the Struc-Assy. This is because the total carbon footprint contribution of the Heater and the Pump to the system is so much greater.

Table 14: Adapted list of support capabilities with and without the Heater, Pump and Struc-Assy components.

Capability	CFP [t CO2 eq.]	# PC	[t CO2 eq.]/ # PC	Difference [%]
Current state				
Mechanical support	128,4	4	32,10	-
Ensure cooling	577,4	20	28,87	-
Without Heater, Pump, Struc-Assy				
Mechanical support	65,05	3	21,68	-32,5 %
Ensure cooling	182,53	18	10,14	-64,9%

Moreover, the Heater and the Pump are not only part of the same capability, they are also part of the same subsystem, the cooling cabinet. Their proximity, both in the nature of their functionality in the system, and physically within the system, provides more opportunity for ecodesign improvements. Pair that with the larger potential for environmental improvement, because they hold largest fractions to the STIR's total lifecycle carbon footprint, then both the Heater and the Pump are the logical candidates for ecodesign opportunities. Specific ecodesign opportunities will be derived for both the Heater and the Pump in the next step.

5.2.7 Step 8: Deriving Ecodesign Opportunities

Building on the evaluation of the hotspot components in the previous subsection, this subsection focuses on deriving concrete ecodesign opportunities for both the Heater and the Pump. By considering relevant lifecycle stages, technical aspects and operational characteristics, specific areas for improvement are derived. This section relates directly to step 8 of the ecodesign approach, detailed in Section 4.3.8. These opportunities provide a clear direction for reducing the system's environmental impact while maintaining or enhancing its performance.

Looking at the carbon footprint breakdown into the lifecycle stages of both the Heater and the Pump in Figure 30, it is evident that the In-use Power Consumption stage is by far the most significant contributor for both components. To better understand this, it is crucial to consider the operational modes and duty cycles of these components. In the performed analysis, both the Heater and the Pump have high duty cycles, which substantially influence their environmental impact in the In-use power consumption stage. Taken a look at the operational characteristics of the components will reveal why that is the case.

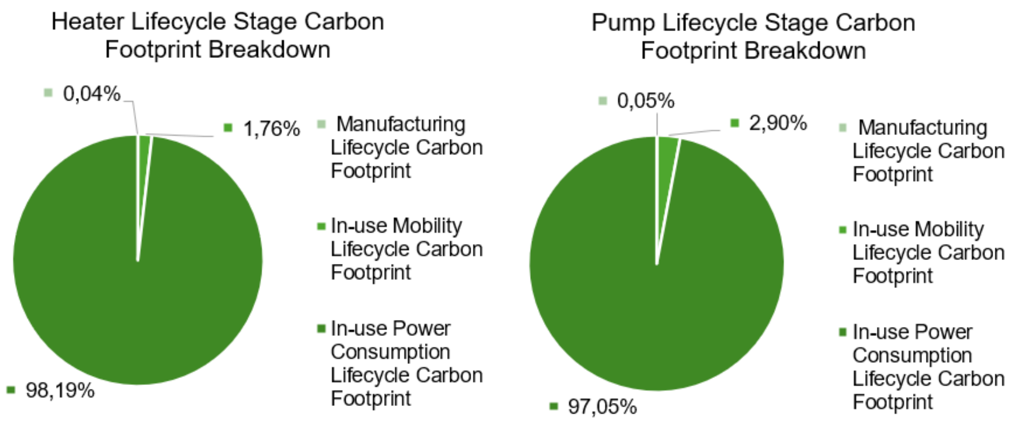


Figure 30: Heater and pump lifecycle carbon footprint breakdown in a pie-chart.

Heater

The high carbon footprint of the Heater is a combination of its high average power consumption and its high duty cycle. In reality, the duty cycle of the Heater depends heavily on the climate where the STIR system is deployed. For instance, in colder climates, the Heater is active for long periods, leading to significant power consumption. On the contrary, in warmer regions near the equator, the Heater may rarely be used, resulting in minimal power usage. In this case, the power consumption of the Heater represents a worst-case scenario where the system is always in a cold climate.

This variability means its is a challenge to derive a clear ecodesign opportunity that applies across all scenarios. While Thales cannot control where the system is deployed and thus influence its duty cycle, a clear-cut opportunities may still exist in improving the efficiency of the Heater. For example, more efficient insulation in the STIR could help reduce power consumption in cold climates, meaning the Heater has to operate less frequently and less intensely.

Pump

The Pump represents a more straightforward case for deriving ecodesign opportunities. Its high carbon footprint arises from several factors: the Pump is oversized for the radar's relatively modest cooling demands, it has a high duty cycle, and it operates with only two power modes; On or Off, with no in between. The reason that the Pump is oversized, is that it is a standardized component used in multiple radar systems, each with varying cooling demands. The STIR, is a relatively small radar in Thales's portfolio, and therefore requires less cooling power than other systems for which the pump is also designed.

Given these factors, the clear opportunity lies in optimizing the Pump's power consumption profile. Potential ecodesign orientations could include adapting the size of the Pump to better suit the STIR's maximum cooling demands or introduce variable operating modes to adapt to varying cooling demands, reducing energy consumption during periods of low demand. These changes could significantly reduce the Pump's in-use power consumption while maintaining its functional performance. Definitive orientations will be defined in the next steps, through CLOE.

In conclusion, the following opportunities have been derived for the Heater and the Pump:

- The Heater should optimize its power consumption profile according to the operational case of use.
- The Pump should optimize its power consumption profile to the demands of the STIR.

The opportunities identified for the Heater and the Pump highlight how the hotspot evaluations can lead to targeted ecodesign opportunities that address specific lifecycle stages and operational characteristics. This concludes the activity of deriving ecodesign opportunities (A.4 in Figure 14). These findings form the input for the next steps in the ecodesign approach, the use of CLOE to define ecodesign orientations for reducing lifecycle carbon footprint based on Thales ecodesign strategies.

5.2.8 Step 9 & 10: Defining STIR Ecodesign Orientations

In the last steps of ecodesign approach, specific ecodesign orientations are defined for the STIR, following steps 9 and 10 discussed in Section 4.3.9. The specific ecodesign recommendations for the STIR based on the identified opportunities from step 8. The ecodesign opportunities identified in the previous step are; (1) improving the power consumption efficiency of the Heater, and (2) optimizing the power consumption profile of the Pump. Specific recommendations for the Heater and Pump, in the form of ecodesign orientations, are defined in this final activity.

Following the ecodesign approach steps, the CLOE tool will be used to define and select specific ecodesign strategies. The details of this process is not detailed further in this report, as the use of CLOE is outside the scope of this project since it is an internal tool. However, using CLOE to define and select ecodesign orientations for both the Heater and the Pump, the following orientations are selected as definitive ecodesign recommendations for the STIR:

1. **Strategy #1: Fight against over-engineering** (Pump)
   Reduce size of the Pump to fit the actual cooling demands of the STIR.

2. **Strategy #2: Downsize the whole or its part** (Pump, Heater)
   Reduce size of the Pump to fit the actual cooling demands of the STIR.
   Reduce size of the Heater to fit the actual cooling demands of the STIR.

3. **Strategy #3: Maximize shared workload** (Heater)
   As the Heater has over-capacity in many operating scenarios, it could share the heating function to heat multiple on-board systems.

4. **Strategy #4: Adapt up and down** (Pump)
   Add a variable power mode to the Pump to adapt to fluctuating cooling demands.

This concludes the entire ecodesign process taking place in the orient phase of product development, which is the main focus of this case of application. These recommendations aim to address the key environmental hotspots and suggest targeted improvements that align with the STIR's functional and operational requirements.

With the completion of this stage in the product development process on account of ecodesign, the redesign project will transition to the Design phase (Figure 14). During this phase the first ecodesign activity will be to perform impact assessments on each of the recommended ecodesign improvement strategies. Costs, maintainability, ease of integration and other factors will be considered here, leading to the formalization of the exact solution, its requirements and its integration into the STIR.

5.3 Ecodesign Approach Validation

This chapter concludes with a reflection on the results and effectiveness of the proposed ecodesign approach. By focusing the analysis at the component level rather than the system level, as was previously the case at Thales, the approach significantly streamlines the ecodesign process. Applying the proposed ecodesign on the STIR showed how the approach allows for a selective and efficient ecodesign assessment, ensuring that the most impactful components are identified early in the development process. By investing more effort at this stage, the approach intends to reduce time and effort required later in the product development cycle.

If we start to broaden the scope again of how the ecodesign approach fits into the overall development process, it becomes visible how the activities contribute to the development of the MBSE architecture models through the different development phases. Figure 31 shows how the outcomes of the activities in the ecodesign approach will lead to developing the architecture models in Capella further, following the ARCADIA methodology. This provides more context for the integration of MBSE and ecodesign in the product development process, which has not been visualized before.

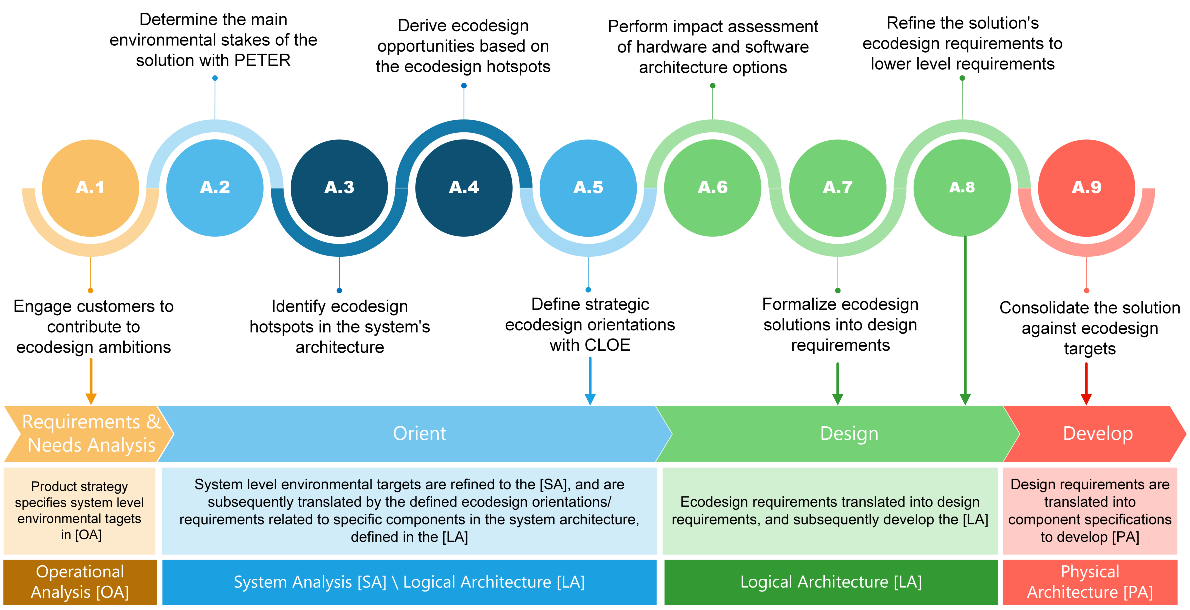


Figure 31: Ecodesign approach inputs for the ARCADIA layers and model development throughout the development process.

Whereas the application case of the STIR stopped at the orient phase of product development, the next steps would be to formulate design requirements which in turn shape the development of the system in the Logical Architecture [LA]. These in turn will shape the physical design of the components and their technical specifications, which will be modeled in the Physical Architecture [PA] diagrams. This closes the development loop that was initiated by the ecodesign activities.

It is worthy to mention that the pump was also identified as a key component for improvement in Thales's own ecodesign pilot on the STIR. However, while the radar team's pilot study highlighted the significance of the pump, the ecodesign approach developed in this thesis provides additional value by making the process more efficient and structured. The approach offers a more robust approach for identifying and justifying ecodesign improvement opportunities, by leveraging a data-driven approach and integrating functional aspects enabled by MBSE. Unlike the pilot analysis, which was more exploratory, this approach streamlines the process and provides clear, actionable recommendations. This comparison underscores the strength and reliability of the proposed ecodesign approach, demonstrating its potential to build on and enhance the existing ecodesign approach.

In conclusion, the results validate that the proposed ecodesign approach achieves its intended purpose of providing a structured and stepwise approach that targets specific components with significant potential for environmental improvement, while leveraging MBSE. This validation comes from the internal stakeholders in this project. The targeted focus of the approach ensures that improvement strategies are grounded in sound reasoning and data, offering clear and actionable recommendations. The success of the STIR case demonstrates the potential of this approach to streamline the ecodesign process, delivering early-stage insights that guide environmentally conscious design decisions, which is of great value to the stakeholders.

6 Discussion & Recommendations

The discussion is centered on evaluating the extent to which the proposed ecodesign approach addresses the challenges identified at the outset of the project. I will discuss the value of the proposed ecodesign approach and developed engineering steps for conducting the ecodesign at Thales against the stakeholder requirements and feedback. This perspective is gained by reflecting on the existing ecodesign challenges at Thales and reviewing how the proposed solution addresses ecodesign and aligns with current practices. The satisfaction of the stakeholders with the developed ecodesign approach, and the extent to which the key points are addressed will highlight the impact of this thesis on the ecodesign at Thales.

This discussion therefore focuses on how well the approach addressed the key points. First, the focus will be on the extend to which the lessons learned from the Thales's ecodesign pilot, discussed in Section 2.3.3, are taken into consideration by the approach. The key findings from literature, summarized in Section 3.3, and their implementation into the ecodesign approach will be discussed. Furthermore, the list of stakeholder needs from Section 2.4 naturally form a key aspect of this discussion. As a final step, I will provide specific recommendations to improve on the approach and develop ecodesign further within Thales, which will be based on the feedback from the involved stakeholders on the proposed ecodesign approach, as well as personal insights.

6.1 Integration of Ecodesign Lessons From Thales

The lessons learned from the pilot ecodesign case, Section 2.3.3, have shaped the development of the proposed ecodesign approach significantly. The challenges identified and insights gained during the pilot are revisited here, to evaluate how effectively they have been addressed by the developed ecodesign approach. The ecodesign pilot case at Thales revealed that ecodesign practices and tools must be introduced early in the development process of redesigned products. As a result, the major focus of this thesis has been on the implementation of ecodesign practices in the orient phase of Thales development.

The first three key lessons from the ecodesign pilot case indicated the importance of being able to identify specific areas for improvement early in the development process, based on the largest environmental improvement potential, while using existing carbon footprint data. Using the existing carbon footprint data on the product, especially the latest iteration of that product, will result in the most accurate ecodesign study on the product, without having any technical design parameters of the new version of the product known beforehand.

The proposed ecodesign approach embodies these first three lessons, by specifying that ecodesign opportunities must be derived early in the product development. The approach highlights how existing data on the system should be used to assess carbon footprint, and proposes to gather that information from Capella. In the application case of the STIR, the most up-to-date component data could not be directly sourced from Capella given data availability constraints. It means from that perspective there is still room for improvement before the approach can be directly integrated into the engineering processes, but the approach does indicate how to solve this issue by getting the data from the latest iteration of component and system specifications from the PLM tool.

Lesson four indicates the importance of quantifying the expected carbon footprint and costs of alternative solutions. Furthermore, these alternative solutions should be analyzed by a standardized metric. The focus of the developed approach was not on developing technical solutions and thus determining their costs. Upon analyzing the existing ecodesign maturity and reviewing the literature, it became clear that the focus should first be on analyzing the system for carbon footprint improvement opportunities, and not directly on solution orienting. Although this additional insight and a focus on solution orienting would still be valuable, the approach lacks in addressing this aspect. Future work on ecodesign could try to incorporate this aspect and integrate it with MBSE.

Similarly, lesson five indicates that technical solutions must not have a negative impact on the system. As the approach did not focus on finding technical solutions, this was not directly tackled. However, this lesson did partially shape the idea to integrate a functionality based metric for identifying hotspots for ecodesign. This aspect of the approach does provide key insight in assessing the system before technical solutions are developed.

Lastly, the sixth lesson state that it would be helpful for the ecodesign activities to have a much better description of what must be done. This clarity is clearly reflected by the approach and the 10 engineering steps during the orient phase of product development. So, of the six key lessons that Thales learned from its ecodesign pilot, five of them are clearly represented by the ecodesign approach proposed in this thesis. This strategy of learning from previous projects is key to enhancing ecodesign at Thales, and is subsequently very important to keep doing it.

6.2 Implementation of Literature Practices

This section reflects on the implementation of the key literature findings in Section 3.3 in the ecodesign approach. As the literature on the implementation of ecodesign integrated with MBSE is still very limited, the literature study in this thesis also centered on analyzing multiple different ecodesign approaches by different authors. A well-established set of ecodesign principles has emerged from the literature, emphasizing key factors such as focused lifecycle assessment, key decision-making factors, integration of MBSE, and integration with engineering workflows. Comparing key findings from literature with the developed approach provides insights into its strengths and areas for improvement.

To start, literature findings showed that ecodesign efforts should focus on system elements and lifecycle stages that have the most impact. Unnecessary complexity can be avoided by limiting the scope of the ecodesign project. Adding to this, was the conclusion of integration of decision-making factors that expand on carbon footprint, such as functionality or costs. The ecodesign approach achieves this by linking functionality to environmental impact of components, and comparing these based on standardized indicators, during the early phases of product development. However the approach could further standardize how functional importance is weighted and how to evaluate trade-offs to select the best option quantitatively.

No quantitative trade-off analysis was developed for the ecodesign approach, but an assessment of the ecodesign hotspots was included in the approach in steps 7 and 8 to account for this aspect. This helped determine the best candidates for ecodesign based on various aspects, such as carbon footprint, a components functionality and its relation to other components sharing the same capability or subsystem, but more on a qualitative measure. This did lead to clear ecodesign strategies focused on reducing carbon footprint for both the Heater and the Pump, but could be improved in the future.

lastly, a key aspect of the approach was the integration of MBSE. Literature showed that MBSE should be used to retrieve information from the architecture, which allows to evaluate how much carbon footprint is tied to a particular component or function. The ecodesign approach has done exactly that, which shows how this aspect of the literature review directly shaped the development of the ecodesign approach. Secondly, both research articles relating to MBSE and ecodesign directly, highlighted the potential difficulty for companies to integrate ecodesign processes in an MBSE environment. The required link to data and various tools or systems in place was identified as a potential hazard, which was a key reason for not developing an ecodesign approach that modeled carbon footprint in Capella at this stage. Nevertheless, this thesis still had its challenges with data, but from a data availability and MBSE readiness perspective in the case of the STIR, not from the integration of MBSE. The full integration of the ecodesign hotspot analysis into Capella could be the next step for Thales to advance and streamline ecodesign.

6.3 Satisfying the Stakeholder Needs

Probably the most important aspects of this discussion, is the extent to which stakeholder expectations were met, which were discussed in Section 2.4.2. The internal stakeholders of this project had been involved with this thesis very early on in the project, which meant they were able to steer the project from its early beginnings. Their involvement and interest in this project was established by regular contact with the three key stakeholder groups and their representatives. Regular presentations and meetings ensured that the thesis was going into a direction that satisfied all involved parties.

Furthermore, their feedback both on the developed approach and my approach to the problem was actively taken into account. Feedback was not just coming from the stakeholder to me, but also from me to the stakeholders. This thesis highlighted key gaps in knowledge and processes for all parties involved, which meant that the stakeholders were interested in results of the thesis as a result. Each of the important stakeholder groups for this thesis are discussed below, based on addressing their needs, from Table 1, and satisfaction with the developed ecodesign approach.

Environmental
The most important requirement from the environmental stakeholder group was to mitigate the gap between high-level ecodesign incentives to engineering activities during product development. The proposed ecodesign approach achieves this by making use of current engineering tools, fitting seamlessly into the current ecodesign engineering practices during product development, and making the whole process of ecodesign more streamlined as selective. The approach is holistic by detailing specific engineering steps that are aimed to support the objectives of the overall ecodesign activities in the approach. What's more, the application of the ecodesign approach to a Thales product highlighted the practicality of the approach and showed clearly how the overall approach translates to actionable engineering practices.

The stakeholders also expressed the need to calculate carbon footprint similarly to Thales's current carbon footprint assessment methods, and to consider architectural aspects of the system under consideration for ecodesign. Both of these aspects are adhered to by the developed approach. That first need again highlights the practicality of the approach since no new carbon footprint method is introduced, that for example may use alternative software that Thales does not have. In regards to including architectural aspects of the system relating to technical parameters, the ecodesign hotspot analysis does adhere to it. However, it falls short in relating it to technical solutions, which the new activities in ecodesign approach do not develop. This is a clear direction for future work.

Product Development Teams
The product development team's involvement was not only key in determining what expectations they have on an ecodesign approach, but also in the use case. I relied on them to get a lot of information of the STIR. This communication was key to establish an application case for the ecodesign approach that reflects on a real world system.

Moreover, the results of the ecodesign application case were to the satisfaction of this stakeholder group, as the ecodesign approach not only provided actionable engineering activities, a structured process for conducting ecodesign was developed in this thesis that lead to selective ecodesign opportunities. The approach implements a functionality parameter to identify ecodesign hotspots in a quantifiable way, which enables to derive improvement opportunities for environmental improvement in the system. The analysis is conducted in a common tool, not introducing new software to Thales, and makes use of the latest product specifications.

All things considered, the needs from this stakeholder group have been addressed or are incorporated by the ecodesign approach that was developed in this thesis. Integrating MBSE into the engineering activities and using Capella not just as a description of the system, but as a source of information to conduct ecodesign activities, is also in line with their expectations. However, they also see how in the case of the STIR, where product information was not readily available yet, should not be the way forward. The ecodesign approach could build on this aspect in the future. Overall, this stakeholder group has expressed their contentedness with the work done in this thesis to support ecodesign processes during product development.

Systems Engineering
The connection with the systems engineering stakeholder group that are involved with ecodesign and with this thesis was slightly different from the other stakeholders. Their involvement in this project was a lot about controlling and providing the amount of information currently made possible through MBSE, as it is still a growing discipline within Thales.As a result, they also controlled the level of detail for the analysis with regards to product hierarchy and technical information that is realistic in the models.

As it turned out, the level of detail that is ideally present in the models to follow the ecodesign approach of this thesis was not great enough for the STIR. This highlighted a key gap in the state of MBSE at Thales currently, which was not ready yet for the full implementation of the ecodesign approach for all products. For this thesis, all of the technical component specifications were sourced from the PLM server and technical documents. The ecodesign approach should use Capella models as its only source of information. With the maturity of MBSE growing, there was overall consensus that this could be made possible in the near future, hence the reason for developing the ecodesign approach with MBSE in mind for the technical specifications.

The MBSE group in particular did also experience another benefit of this thesis as a secondary result of this thesis. As MBSE is still growing within Thales, their involvement with this project opened up a new door for using MBSE within Thales and supports the development of MBSE within Thales as a whole. One aspect of this thesis, is how MBSE enabled to consider non-functional requirements, such as ecodesign requirements, into the initial development of the approach.

6.4 Recommendations

The developed ecodesign approach is seen as a success by Thales's stakeholders, but there are still plenty of opportunities to improve ecodesign within Thales in regard of the proposed approach. I will provide recommendations for Thales that are centered on several different aspects of the approach. The recommendations will be of a practical nature, and center on what Thales could do to improve on the ecodesign approach of this thesis. This opens the door for future development of the approach and ecodesign as a whole in Thales.

Integrating ecodesign hotspot analysis into capella:
Considering the advancements MBSE is making in Thales, I see a logical opportunity to incorporate the ecodesign hotspot analysis directly into Capella as an extension. Since the system and component data should be captured within the Physical Architecture [PA] layer elements, it is possible to develop a model that links this information to carbon footprint calculations. This would make the process much more efficient and eliminate the need for external tools. It also allows for real-time monitoring of carbon footprints throughout product development. Although this wasn't feasible within the scope of this thesis due to time constraints and the complexity of integrating environmental aspects into MBSE, I believe this is a promising direction for advancing the integration of ecodesign within MBSE.

Closing the development loop with MBSE:
A critical next step is to ensure the insights gained from the activities in the orient phase of product development are translated into design requirements. These requirements serve as the foundation for further MBSE models beyond the orient phase of product development, reinforcing the connection between environmental objectives and systems engineering practices. The results of the case hint at this step, but does not actually achieve it, and hence the exact requirements for this steps need to be further defined. By closing the development loop, the integration of MBSE into ecodesign not only strengthens the alignment with systems engineering workflows but also ensures a continuous and iterative process that contributes to Thales's sustainability objectives.

Including cost analysis for a broader perspective:
Another area worth exploring for further development is to include cost information in the analysis. Understanding the costs of each individual components would provide a more complete picture, combining environmental and economic considerations. This will help Thales make more informed decisions and create a better balance between sustainability goals and overall costs.

Incorporating software aspects of the system:
One aspect that I could not address is the role and function of software in the system's environmental impact. Specifically, understanding the power requirements of software and its energy consumption could provide a more detailed view of the system's footprint. Software is a major element in the solutions that Thales produces. I think future work should consider incorporating software aspects into the ecodesign approach to ensure that this important element is not overlooked.

Re-evaluating the treatment of capabilities:
I think the way system capabilities are treated in the current approach could also be revisited. There are be other ways to analyze capabilities in terms of their environmental impact. Specifically, I recommend that there should be an alternative way of calculating and allocating a carbon footprint to each capability, by introducing a usage profile for each component. This usage profile will show how much of the time a component is actively contributing to each capability, which can be used to determine how much of the component carbon footprint should be allocated to each capability. This information is currently not available, so it would have to be investigated if this can be made available and if it is worth doing. However, the expected benefit is that this kind of approach increases the fidelity of the carbon footprint calculations of capabilities.

Reassessing the metric for rating functionality:
Finally, I recommend exploring alternative ways to rate functionality in the ecodesign process. In this thesis, I used the number of functions as a metric to identify ecodesign hotspots, but this might not always be the most accurate approach. Functions can vary widely in complexity and importance, so it might be worthwhile to develop a standardized rating system that works across all radar systems in Thales. This would help ensure that the hotspot analysis is targeting the most impactful areas for improvement in an even more repeatable and standardized way throughout the organization.

7 Conclusion

This thesis has explored how MBSE can be effectively integrated into the early phases of product re-development to support ecodesign activities at Thales. Thales faced the problem of trying to effectively bridge the gap from its high-level environmental incentives to tangible engineering activities through MBSE. As a result, the main research question of this thesis was: *How to mitigate the gap from Thales's high-level incentives on ecodesign to practical engineering activities by leveraging MBSE-enabled capabilities?*

The main objective of this thesis was therefore to develop an ecodesign approach consisting of actionable engineering activities that are enabled by MBSE and integrated into the early phases of the standard product development process. To support this main objective, a set of six sub-objectives were establish in Section 1.2. Each sub-objectives supports the main objective by tackling a specific aspect.

Sub-objective 1 aimed to develop an understanding of the role and maturity of MBSE in product development at Thales. This understanding was gained by analyzing the existing product development process and the early product development phases. Specifically relating to MBSE, the analysis revealed how MBSE is currently used to support the standard development phases following the ARCADIA methodology. This highlighted how the ARCADIA methodology aligns with the product development process to develop the system architecture. The key tools Thales uses to conduct MBSE development activities, as well as key modeling elements describing the system were identified. This understanding laid the foundation for developing an ecodesign approach that leverages the information available in the Capella models.

To address sub-objective 2, the existing ecodesign initiatives were also analyzed to understand the current challenges of conducting ecodesign activities during product development. This analysis provided insights into how ecodesign is currently approached within Thales and highlighted obstacles such as a lack of clear methodologies for ecodesign implementation. A key outcome of this investigation was a set of lessons learned from the one ecodesign pilot project, offering valuable reflections on both the strengths and shortcomings of the existing approach. These lessons provided a foundation for identifying opportunities to improve ecodesign practices.

Sub-objective 3 aimed to identify the stakeholder needs for improving ecodesign within Thales. The stakeholder needs emanate from the current ecodesign challenges and the desire to integrate MBSE into ecodesign. The analysis revealed a need for a more structured approach that aligns with existing engineering processes, leveraging existing product data from MBSE, and integrating a quantified assessment metric including multiple technical aspects of the system to support early-stage ecodesign decision-making. These needs played a crucial role in shaping the development of an improved ecodesign approach supported by MBSE, and highlighted key gaps that needed to be addressed.

In line with sub-objective 4, a literature review was conducted to identify suitable practices and concepts for integrating MBSE into the ecodesign process, and establish how Thales's ecodesign needs and knowledge gaps can be addressed. The literature review revealed the importance of expanding on existing assessment methods by introducing additional technical parameters such as functionality, to support ecodesign decision-making, and indicated how MBSE can contribute to these efforts by providing the necessary architectural information. Additionally, it highlighted how the ecodesign approach can be structured by focusing on specific targets for ecodesign improvements, early in the product development process.

Addressing sub-objective 5, an MBSE enabled ecodesign approach was developed, by bringing together the key stakeholder needs and the lessons learned from the literature review. This provided the rationale for the ecodesign approach that aligns with existing practices and integrates MBSE to support the key activities. Two new key activities were integrated into the ecodesign approach. First, to identify ecodesign hotspots through the assessment of the system's components, and second, to derive clear improvement opportunities by evaluating these hotspots. The integration of MBSE into the approach was achieved by providing the technical information necessary to link environmental impact with component functionality, thus supporting ecodesign decision-making. Additionally, the activities were materialized by providing a comprehensive list of engineering steps, making the approach tangible and actionable for product development teams.

Lastly, sub-objective 6 aimed to validate the developed ecodesign approach through an application study. The approach was tested on an existing Thales radar product, which provided an opportunity to demonstrate its practical applicability. The study confirmed the effectiveness of the approach in identifying and evaluating ecodesign hotspots, which allowed for a more structured and streamlined approach to ecodesign. Thales recognizes the usefulness of the approach, particularly the integration of MBSE, by utilizing its capabilities to structure ecodesign activities and integrate them into the development process. This in turn provides the validation of the approach by the stakeholders, as the approach is made more practical and accessible to engineering development teams and addressed the key needs. This validation not only reinforced the relevance of the approach but also highlighted its potential to enhance future product development by embedding environmental considerations early in the development process.

In conclusion, this thesis developed an MBSE ecodesign approach that effectively mitigates the gap between Thales's high-level environmental incentives and engineering approach by developing practical ecodesign activities enabled by MBSE in the early development process, therefore addressing the main objective. The approach demonstrated how MBSE can support ecodesign activities by identifying key improvement opportunities in the system architecture early in the development phases of product. The MBSE enabled ability to consider the entire system architecture and component functionality in ecodesign decision-making provides Thales with a straightforward and standardized approach to conduct ecodesign studies early in the product development. The application of the developed ecodesign approach on an existing radar product, highlight the effectiveness and practicality of the ecodesign approach for Thales, which is recognized by the involved stakeholders. Considering the bigger picture, this thesis contributes to developing Thales's engineering processes such that it can meet its long-term environmental objectives. The realized collaboration between the ecodesign and systems engineering disciplines not only drives immediate progress in ecodesign efforts by the development of the ecodesign approach in this thesis, but also establishes a foundation for future innovation on ecodesign.

Limitations

While this thesis provides valuable insights for integrating MBSE into ecodesign practices, certain limitations must be acknowledged to contextualize the results and effectiveness of the approach. One key limitation is that the proposed approach was demonstrated using only a single case study involving an existing radar system. While this allowed for a focused and detailed exploration of the approach's feasibility, the results would benefit from validation across multiple systems to assess how generic the approach is for Thales products.

To give an example, the application of the approach on the STIR showed that there were fairly large and easy environmental gains available. Although the approach successfully identifies the environmental hotspots and potential opportunities, deriving the specific ecodesign opportunities, relating to steps 7 and 8, was not necessarily based on specific and quantifiable metrics. The stakeholders were satisfied with the current approach, but that may not always be the case. If the hotspot components are ranked more closely to each other and a larger selection of hotspots is available, it may be the case that a more standardized and quantitative analysis is valuable during the part of the ecodesign approach that evaluates the hotspots for actual opportunities.

Secondly, the limited selection of existing literature on the integration of MBSE and ecodesign made it harder to challenge the developed approach in a broader engineering context, as there are less opposing views and constraints related to this specific aspect. This is also true for the involved stakeholders. Both the shared lack of understanding on the combination of the two topics, and the complete lack of an existing ecodesign approach that uses MBSE, likely made it harder for the stakeholders to challenge the proposed ecodesign approach. This could have resulted in the stakeholders being less critical of the developed ecodesign approach. As this understanding in both literature and within Thales grows, new insights may provide additional constraints and needs for the ecodesign approach.

Lastly, the results of the thesis could be strengthened by closing the engineering loops that are opened by the ecodesign approach. The approach does well in deriving ecodesign opportunities and specifying ecodesign orientations, but is not comprehensive enough to allow for developing new requirements with MBSE yet. Requirements engineering is a key aspect within systems engineering and subsequently drives MBSE modeling within Thales in general. This more extended application could have provided additional insights into the practical challenges of implementing the approach at different stages of product development.

Future research

A possible future assignment centered around ecodesign at Thales could explore the integration of ecodesign principles across the entire product development process. It could investigate how MBSE can support later development stages stages, such as design, development or even production phase. The discussion already recommended how modeling environmental aspects directly in Capella could benefit the established approach. Further research that centers on the design phase of product development could help close the engineering loop by supporting design exploration and formalizing requirements. As mentioned in the limitations section, formalizing ecodesign requirements supports the development of new models in Capella, driving system development to the next level.

Another potential area for future research could focus on investigating the feasibility of building a comprehensive portfolio of environmental impacts for products, building blocks, and individual components across Thales's product portfolio. By leveraging MBSE, this portfolio could support product development by illustrating how design changes to a specific component in one system may affect the environmental impact and functionality of other systems, emphasizing the interconnectivity of standardized components within the broader product ecosystem. Through this approach, MBSE can help assess whether designing new, more sustainable versions of components is beneficial, and how improvements to individual components might optimize environmental performance across multiple systems. Investigating the potential for creating and integrating this dataset on a company-wide scale would not only evaluate its feasibility but also explore the challenges and benefits of using MBSE to drive sustainability efforts, ultimately supporting more informed, environmentally conscious product development decisions.

At last, the thesis also opens doors for further enhancement of both ecodesign and MBSE in general. Academic research could investigate the role of digital twins in supporting MBSE-driven ecodesign activities, particularly for real-time assessment of environmental impacts. This would enable dynamic updates to design strategies as systems evolve during the development phase. Given that this thesis primarily focused on a static approach to ecodesign, future research could explore how MBSE-enabled ecodesign frameworks can be iteratively refined based on feedback and changing environmental regulations or customer demands. This could involve developing a feedback loop that allows for the continuous improvement of both the ecodesign process and the underlying MBSE models used to support it.

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Appendix A ARCADIA

The ARCADIA (Architecture Analysis and Design Integrated Approach) methodology is a model-based systems engineering approach. It provides a structured framework for designing, analyzing, and validating complex systems. ARCADIA is highly focused on fostering collaboration among various stakeholders while ensuring a robust engineering process. Thales uses Capella as its modeling tool, and employs the ARCADIA methodology for the developments of its products. The framework that ARCADIA provides follows a structured approach, that starts with understanding the needs of the products user and ends with a complete definition of the product and the physical components that its made of. The ARCADIA framework is shown in Figure 32.

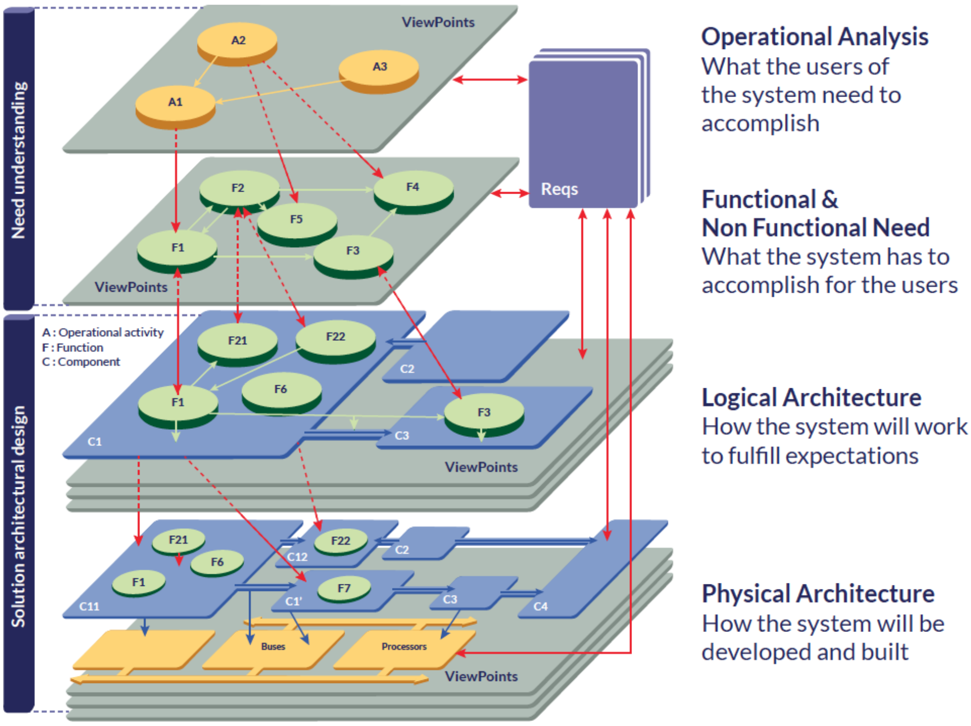

Figure 32: ARCADIA framework [36].

The ARCADIA framework consists of four layers, that each describe the system from a different view, providing more complexity and information on the system. The most basic description of the system can be found in the Operational Analysis, which details what the users of the product must accomplish. This will provide input for the System Analysis, which describes what the system must accomplish for the users. From the System Analysis, the Logical Architecture will be derived, after which the Physical Architecture is developed. The key modeling elements and activities in the architecture layers are shown in Figure 33.

In order to capture the information of the system, different views of the system are created in Capella diagrams. As each ARCADIA layer provides different information on the system, they consist of different diagrams to be modeled in Capella. However, the key modeling elements will be transferred from one layer to the next. A full breakdown of the main diagrams that are used to capture the activities and modeling elements of the ARCADIA methodology is shown in Figure 34.

Arcadia layer	Requirements	Capability	Capability description	Functional	Structure
Operational Analysis	R-OA Capture Stakeholder requirements	OA1 Define Operational Capabilities	OA2 Define processes and scenarios	OA3 Define Operational Activities and interactions	OA4 Capture Operational Entities and Actors. Allocate Operational Activities to Operational Actors, Entities
System Analysis	R-SA Derive Stakeholder requirements and capture System requirements	SA1 Define System Missions and System Capabilities	SA2 Define Functional Chains and Scenarios	SA3 Define System Functions. Define Functional Exchanges and components	SA4 Allocate System Functions to System and Actors
Logical Architecture	R-LA Derive system requirements and Capture components requirements	LA1 Transition Capabilities Realization from system layer	LA2 Define Functional Chains and scenarios	LA3 Derive System Functions and define Logical Functions. Define Functional Exchanges and components.	LA4 Allocate Logical Functions to Logical Components
Physical Architecture	R-PA Derive logical requirements and capture physical requirements	PA1 Transition Capabilities Realization from logical layer	PA2 Define Functional Chains, Scenarios, and Physical Path	PA3 Derive Logical Functions and define Physical Functions. Define Functional Exchanges and components.	PA4 Define Physical Nodes and refine Behavioural Physical Components. Allocate Behavioural Components.

Figure 33: ARCADIA architecture layers, activities and modeling elements [10].

Arcadia layer	Capability	Capability description	Functional	Structural
Operational Analysis	OA1 [OCB] Operational Capabilities	OA2 [OAS] Operational Activity Scenario [OPD] Operational Process Scenario [OES] Operational Entity Scenario	OA3 [OABD] Operational Activity Breakdown Diagram [OAIB] Operational Activity Interaction Blank	OA4 [OEBD] Operational Entities Blank Diagram [ORB] Operational Roles Blank [OAB] Operational Architecture Blank
System Analysis	SA1 [MCB] Mission and Capabilities Blank [CC] Contextual Capability	SA2 [FS] System Functional Scenario [ES] System Entity Scenario [SFCD] System Functional Chain Description	SA3 [SFBD] System Functional Breakdown Diagram [SDFB] System Data Flow Blank	SA4 [CSA] Contextual System Actor [SAB] System Architecture Blank
Logical Architecture	LA1 [CRB] Capabilities Realization Blank [CRI] Contextual Capability Realization Involvement	LA2 [FS] Logical Functional Scenario [ES] Logical Entity Scenario [LFCD] Logical Functional Chain Description	LA3 [LFBD] Logical Functional Breakdown Diagram [LDFB] Logical Data Flow Blank	LA4 [LCBD] Logical Component Breakdown Diagram [LAB] Logical Architecture Blank
Physical Architecture	PA1 [CRB] Capabilities Realization Blank [CRI] Contextual Capability Realization Involvement	PA2 [FS] Physical Functional Scenario [ES] Physical Entity Scenario [PFCD] Physical Functional Chain Description	PA3 [PFBD] Physical Functional Breakdown Diagram [PDFB] Physical Data Flow Blank	PA4 [PCBD] Physical Component Breakdown Diagram [PAB] Physical Architecture Blank

Figure 34: Arcadia diagrams matrix adapted from [10].

Appendix B Thales Ecodesign Strategies

Thales has developed their own set of ecodesign strategies that are tailored to the specific products Thales generally develops. The list of ecodesign strategies is presented here.

1. **Fight against over-engineering:** (frugality)
   A product should meet only the actual needs of the user and can reasonably be expected to be made with the engineering resources available. Adding additional features or product variability should be controlled.

2. **Downsize the whole or its parts:** (Frugality)
   It is important to consider a product from an architectural perspective and conduct multidisciplinary design optimization to analyze alternative design solutions, in order to consume fewer resources. Practices like SWAP (reducing Size, Weight and Power) are good practices.

3. **Maximize shared workload:** (frugality)
   Specific to electronic and digital solutions, sharing applications via virtualization on a single server can reduce the overall workload and energy consumption. More generally, sharing functionality by extending it to multiple subsystems can reduce overall workload and energy consumption.

4. **Adapt up and down:** (frugality)
   A solution should be sized according to the needs and operational conditions of use. Elastic architectures should be implemented to anticipate increasing but also decreasing needs.

5. **Be smart rather than big:** (frugality)
   Bigger problems are not directly solved by bigger solutions that require more resources.

6. **Redistribute:** (frugality)
   Related to electronic and digital solutions, it makes sense to reconsider the architecture in order to provide possibilities in terms of localizing data processing nearer to the source.

7. **Build to evolve and last:** (circularity/frugality)
   Although new needs cannot always be foreseen, the capacity for change can in must be planned in. Creating a longer life for a solution is a lever for avoiding unnecessary consumption of resources.

8. **Stick to the actual end-of-life conditions:** (circularity/innocuity)
   When designing a product, it is important to take into account the reality of what will happen when a product reaches the end of its life. Product that won't or can't be recycled, should not take recyclability into account during design.

9. **Reuse assets to close the loops:** (Circularity)
   Closed-loop systems can help reduce reliance on external resources, as well as provide financial benefits. Integrating recycled contend or reconditioned parts reduced environmental impact.

10. **Minimize harmful or controversial solutions:** (innocuity/frugality)
    It is important to minimize the use of harmful substances or solutions, especially if most competitors do so, in order to not be left out or gain a bad reputation.

11. **Inspire from nature:** (innocuity)
    Innovative solutions to save resources and energy can be inspired by nature. Often, effective solutions for a complex problem are found by looking at things from a different perspective.

Appendix C Stakeholders

The stakeholder register in Table 15, details stakeholders both from Thales and the university. Especially Thales stakeholders had an active involvement in setting boundaries, providing information and steering the project in general.

Table 15: Stakeholder register

Stakeholder Register Graduation project Thales Ecodesign				
People	**Category**	**Status**	**Job Role**	**Project Concerns**
Name	*Thales / University / External*	*Key Player / Keep Informed / Meet needs*	*Stakeholder role*	*Primary interest in the project*
T.G.	University	Key Player	Graduation student	Directly responsible for the success and progression of the project Primary contributor to develop new ecodesign process at Thales
V.S.	Thales	Key Player	Thales Supervisor Systems Engineer MBSE Expert	Primary supporter of graduate within Thales Enables communication with Thales partners
M.P.P.	University	Key Player	University Supervisor	Primary supporter of graduate from university Enables guidance and support for the Thesis
J.T.	Thales	Key Player / Keep Informed	Ecodesign Specialist	Needs to be informed of the status of the project and confirm the value added Can support with ecodesign directives and spread ideas within Thales Is able to provide data on carbon footprint reporting methodology within Thales
N.L.	Thales	Keep Informed	Product Line Manager Fire Control Radar	Needs to be informed of the status of the project and confirm the value added Acts as ecodesign communication within Thales for future projects
D.B.	Thales	Key Player / Keep Informed	Radar Architect	Provides the scope to the level of detail ecodesign can go from an architectural perspective Relates to radar components specifications availability
M.T.	University	Keep Informed	LCA specialist	Helps with Ecodesign environmental analysis Support ecodesign calculation methods
C.R.	Thales	Keep Informed	Systems Engineer MBSE expert	Helps with enabling MBSE as part of the analysis and identify opportunities with the MBSE tools

Appendix D PETER Environmental Analysis

This section of the appendix provides additional information on the PETER tool, internally developed by Thales. PETER works by converting technical aspects of the system into a carbon footprint. Thales has assembled their own database that considers environmental aspects relevant to their solutions. This environmental database relies on publicly accessible and recognized emission factors that are regularly updated. These emission factors are coefficients used to convert a source activity into GHG emissions, in this case converted into kilogram CO_2 equivalent. It is the average rate of emission of the source activity relative to its units.

In order to calculate the carbon footprint of individual components and enable the task of identifying ecodesign hotspots, these same emmission factors are used. The emissions factors used in this thesis come from, ADEME Base Carbone, the International Energy Agency (IEA) or, internal factors developed by Thales. From each of these lifecycle stages included in PETER, the associated emission factors are shown in Table 16.

Table 16: Carbon equivalent emission factors for each lifecycle stage used by PETER.

Lifecycle Stage	Category	Specifics	Factor	Unit
Manufacturing	Category	Material class	$EF_{material}$	
	Mechanical	Steel and its alloys	3	[kg CO2/kg equip.]
		Copper and its alloys	4	[kg CO2/kg equip.]
		Aluminium and its alloys	12	[kg CO2/kg equip.]
		Titanium or magnesium and its alloys	45	[kg CO2/kg equip.]
		Thermoplastic polymers	5	[kg CO2/kg equip.]
		Thermosetting polymers	8	[kg CO2/kg equip.]
	Electronic	Displays	30	[kg CO2/kg equip.]
		PCB	250	[kg CO2/kg equip.]
		Batteries	9	[kg CO2/kg equip.]
In-use Mobility	Sector	Platform	$EF_{mobility}$	
	Naval	Vessel	170	[kg CO2/kg equip./ ship lifespan]
In-use Power Consumption	Power Source	Source	EF_{power}	
	Grid	Grid	0.416	[kg CO2/kWh]
	Generator	Generator	0.9	[kg CO2/kWh]
	Renewable	Renewables	0.01	[kg CO2/kWh]
End-of-Life	Strategy	Equipment type	EF_{EoL}	
	Recycling	Electronic	1	[kg CO2/kg equip.]
		Cooling	1.2	[kg CO2/kg equip.]
	None	-	0	-

Note that the use-phase is split up in two different categories, In-use Mobility and In-use Power Consumption. In-use mobility considers the impact of component movement during its lifetime. These are the emissions emitted by the transporting vehicle on which the system is embedded, but can be related to the mass of the component. In-use power consumption considers the total power consumption of the component during its operational lifetime and depends on the power source. For embedded naval equipment, the source will be a generator on the vessel.

The manufacturing stage represents emissions related to the material composition of the component during component manufacturing. There is also an additional category here, specifying if the type of equipment is mechanical or electronic. This distinction is specifically important for the electronic equipment. For example, batteries have there own category here, and even though the casings may be made of steel or aluminium, the total battery mass will be multiplied by the emission factor belonging to this component to find its carbon footprint. The factors are averages of all types of typical manufacturing processes that are often used for these materials.

Lastly, the emission factors for recycling include, collection, waste treatment, materials sorting and recycling itself, compiled into an average value. Generally, End-of-Life is not significant factor for typical Thales products, however it can be considered if more information is required specifically on this topic. If no recycling is considered, then the emission factor will be zero, as no information is specified given on this aspect of the systems lifecycle. This means that this lifecycle stage will not be considered in the analysis.