EPFL Space Center

Semester Project

Sustainability in Space Systems Engineering

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Spring 2025

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Abbreviations

- **DSM:** Dependency Structure Matrix
- **WSO:** Weighted Stakeholder Occurence
- **SVN:** Stakeholder Value Network
- **CDF:** Concurrent Design Facility
- **ENG-411:** Concurrent Engineering Course
- **EE-587:** Space Sustainability Course
- **ESA:** European Space Agency
- **EUCASS:** European Conference for Aero-Space Sciences
- **ESL:** MIT Engineering Systems Laboratory
- **CEO:** Chief Executive Officer
- **CTO:** Chief Technology Officer
- **OPM:** Object Process Methodology
- **UN:** United Nations
- **SDG:** Sustainable Development Goals
- **LCA:** Life Cycle Assessment
- **ISO:** International Organization for Standardization
- **EOL:** End-Of-Life
- **MDO:** Multidisciplinary Design Optimisation
- **IADC:** Inter-Agency Space Debris Coordination Committee
- **OOI:** Outcome of Interest
- **DMM:** Domain Mapping Matrix
- **MDM:** Multi-Domain Matrix
- **LEO:** Low Earth Orbit
- **CONOPS:** Concept of Operations
- **SE:** Systems Engineer
- **SMI:** Singular value Modularity Index
- **NZF:** Non-Zero Fraction
- **EPS:** Electrical Power System
- **ST:** Structure
- **PR:** Propulsion
- **ULA:** United Launch Alliance
- **LV:** Launch Vehicle
- **ROA:** Real-Options Analysis
- **GEO:** Geostationary Orbit
- **VaR:** Value-at-Risk
- **EPFL:** Ecole Polytechnique Fédérale de Lausanne
- **MIT:** Massachussetts Institute of Technology
- **CO_2:** Carbon Dioxide
- **kg.CO_2.eq:** Carbon Footprint
- **kWh:** Energy consumption (kilo Watt hour)
- **AI:** Artificial Intelligence

Acknowledgment

During this project, I have learned much more than initially expected. There is not a single section of this report that I have not enjoyed writing, not a single topic that I have not found interesting. Space sustainability is a topic where everything needs to be discovered and challenge is not missing. I was especially surprised by the breadth of subjects related to space sustainability, and how interconnected it is with other properties of engineering systems. It was very complementary with my previous experience, and strongly consolidated my knowledge of space systems, or even engineering systems in general.

I want to thank Pr. Dr. Volker Gass for letting me explore a wide variety of topics and providing valuable guidance for each of them. This freedom allowed me to follow tracks that were not initially intended and only made this project more valuable as a learning opportunity. It is this same freedom that has enabled me to steer my education at EPFL in a very specific direction, which very few have the chance to pursue that early in their studies or career.

I want to thank Mathieu Udriot for his trust all along the ENG-411 course, which allowed me to pursue different directions and experiment with multiple ideas. Allowing to connect the course with this project and giving the opportunity of contributing to a research paper gave a strong and clear purpose to this project, with its own dose of challenge, which only made it more interesting.

Finally, I want to thank Pr. Olivier De Weck for having the kindness of sharing his work and letting me access to data analysis that was performed for his book *"Engineering Systems: Meeting Human Needs in a Complex Technological World"* (2011). It greatly helped on the topic of ilities, to which the main subject of this project belongs.

Use of Generative Artificial Intelligence

Generative Artificial Intelligence (OpenAI ChatGPT) was used at multiple occasions during this project, for the following purposes:

- General research of information, similar to the intended purpose of a search engine.
- Coding support for the design of figures on Python or MATLAB.
- Knowledge gap support for the section on high-level LCA (explained in subsection 6.1).

1 Introduction

1.1 Purpose

This project aims at designing and testing a system to integrate a sustainability role in the concurrent engineering process, specifically applied to the design of space missions. Moreover, a survey of industry engineers and managers is conducted to assess the current state-of-the-art and receive feedback for the designed system. Ultimately, the goal of the project is to contribute to a EUCASS paper on the subject of sustainability in space systems engineering (See appendix A, p.95, and appendix G, p.113).

The main objective of integrating sustainability aspects in high-level design processes of space missions is to provide methods to the space industry to align with the Sustainable Development Goals that were defined by the United Nations [13] for 2030 (See figure 1).

Figure 1: Sustainable Development Goals of the United Nations [13] for 2030.

1.2 Methodology

The system is designed following the philosophy that is prescribed by the traditional V-Model of systems engineering (See figure 2). This methodology aims at setting the stakeholders of the project as the core driver of design choices, and effectively managing complexity.

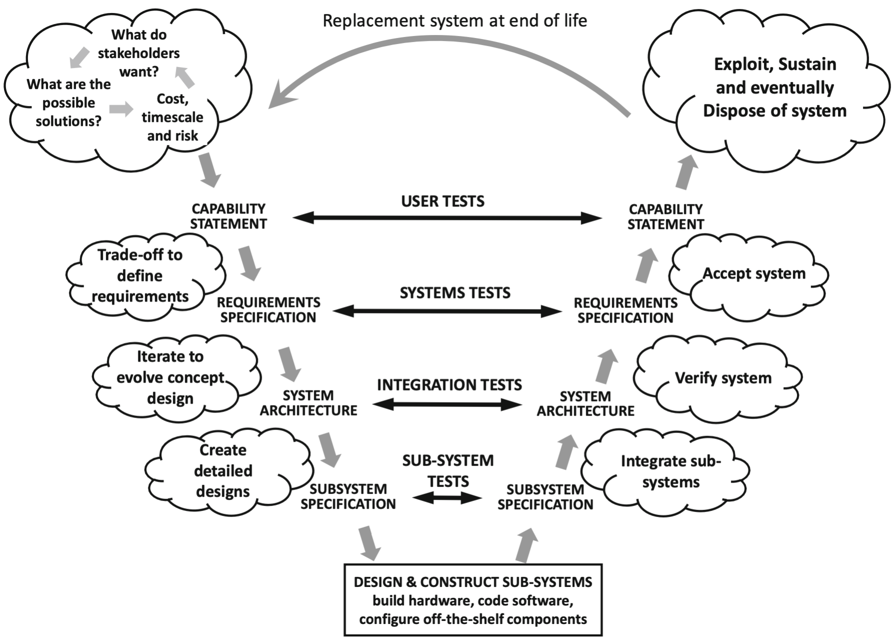

Figure 2: Traditional V-Model of Systems Engineering. Figure from Maier et al. [11].

The system is also tested in the course ENG-411 and iterated upon between design sessions. These tests allow to verify whether the system was compliant with expectations and use the conclusions to contribute to the EUCASS paper.

1.3 Report Structure

Following the methodology of the V-Model (See figure 2, p.7), this report is composed of 6 sections:

- **Stakeholder Analysis:**
  - This section identifies the relevant stakeholders of the project, how they interact with one another, and their relative importance to the project itself. It also analyses a broader spectrum of connections to define an optimal strategy for the industry survey, by identifying stakeholders that have the highest potential for maximising the value back to the project and providing their relative importance.
- **State-of-the-Art:**
  - A full state-of-the-art analysis is performed to identify all the key components to integrate in the system and the research gaps that can be filled to design a system that is innovative. By analysing different topics like ilities in engineering systems, concurrent engineering or sustainability, it enables to create bridges and design a comprehensive system.
- **System Requirements:**
  - Directly derived from the results of the stakeholder analysis and the state-of-the-art analysis, system requirements are defined. They intend to ensure the integration of desired properties into the system, the right balance between diverging objectives, and the highest compliance with stakeholder expectations.
- **System Architecture:**
  - Architecting a system is a step that is often overlooked, and its benefits are underestimated. It is however a critical process that allows to effectively manage complexity, and integrate relevant ilities into the system. Conceptual modeling is performed and followed by quantitative assessment of modularity to identify critical interfaces. Low level requirements are produced to enable the specification of subsystems and facilitate future integration.
- **Subsystems Specification:**
  - Each subsystem that was defined in the architecture is independently designed, and compliance with low level requirements is verified to qualify for system integration. Each of them is conceptually modeled, specified, and an example or case study is shown to demonstrate the functionality.
- **System Verification:**
  - This section constitutes the down-top part of the V-Model, where we get back to the system requirements and verify that the system is compliant with them. This step qualifies the system for operation and demonstrates compliance with stakeholder expectations.

2 Stakeholder Analysis

This stakeholder analysis aims at providing comprehensive and clear insight on the most appropriate stakeholder strategy to adopt in the context of this semester project.

First, we are going to analyse the initial network, composed of the stakeholders that are close and already implicated in the project, and in a second part we will define a strategy to enhance this network and return more value to the project. This network enhancement intends to define an optimal strategy for an industry survey.

2.1 Initial Stakeholder Network

2.1.1 Stakeholders List

The identification of stakeholders is not a well-defined process and many uncertainties are associated with it. These uncertainties mainly come from the lack of a clear definition of a "stakeholder".

Here, we have a more systematic approach using the definition of the MIT System Architecture Group, and the following categories are used to identify the different stakeholders.

MIT System Architecture Group's Definition of a Stakeholder (Feng [8])

Those who: *(1) have a direct or indirect affect on the focal organisation's activities, or (2) receive direct or indirect benefits from the focal organisation's activities, or (3) possess a significant, legitimate interest in the focal organisation's activities.*

"Stake" Holders

The *"Stake" Holders* are defined by those who have a direct stake in the project. The following are identified:

- **Martin Lemaire**
  - Justification: Main contributor of the project.
- **Mathieu Udriot**
  - Justification: Corresponding author of the paper that includes this project as content.
- **Marnix Verkammen**
  - Justification: Co-author of the paper that includes this project as content.
- **Emmanuelle David**
  - Justification: Co-author of the paper that includes this project as content.

Beneficiaries

The *Beneficiaries* are defined as those who derive benefits from the project. The following are identified:

- **eSpace**
  - Justification: eSpace is the entity that hosts the publication and draws benefit from it.
- **EUCASS**
  - Justification: It is the conference at which the paper is presented and published.

Users

The *Users* are defined as the ultimate consumers or users of the project's output. The following are identified:

- **EE-587 Space Sustainability Students**
  - Justification: The research of the project and its output will help improve the course.
- **ENG-411 CDF Students**
  - Justification: The research of the project and its output will help improve the course.

Agents

The *Agents* are defined as those who act on behalf of other stakeholders in the model. The following are identified:

- **Pr. Volker Gass**
  - Justification: Professor supervising the semester project. Agent of EPFL in this sense.

Institutions

The *Institutions* are defined as the official bodies or organisations that directly impact the project. The following are identified:

- **EPFL**
  - Justification: Academic institution that hosts eSpace and provides an academic structure for the semester project.

Interests

The Interests are defined as those with a significant, legitimate interest in the project's output, who may not be considered a direct stakeholder in the traditional sense. No relevant stakeholders are identified in this category.

Project

Relatively, the focal project itself is also a stakeholder in the eyes of other stakeholders. We therefore have:

- **Semester Project**

2.1.2 Quantitative Stakeholder Network Model

The ultimate deliverable of the stakeholder analysis is the SVN. To produce it, we want to identify the different communities and the relative importance of stakeholders. To derive these we need a quantitative model of the network, allowing us to apply graph theory and perform network analysis.

The model that we are going to use is the Dependency Structure Matrix (DSM), and we are also going to apply weights to the edges of the graph to represent the value flows. To this end, we will use a qualitative scoring process taking into account the source importance and the intensity of the need.

Quote from Feng [8]

Specifically, the Intensity of a need characterises a value flow from the demand side of the recipient stakeholder; Source importance in fulfilling a need characterises a value from the supply side of the recipient stakeholder.

They are both evaluated on a five criteria basis with the following rationale:

Source Importance (Reproduced from Feng [8])

If this need were to be fulfilled, how important would this specific source be in fulfilling the need?

1. Not important - I do not need this source to fulfill this need (*Numeric Score: **0.11***)
2. Somewhat important - It is acceptable that this source fulfills this need (*Numeric Score: **0.33***)
3. Important - It is preferable that this source fulfills this need (*Numeric Score: **0.55***)
4. Very Important - It is strongly desirable that this source fulfills this need (*Numeric Score: **0.78***)
5. Extremely Important - It is indispensable that this source fulfills this need (*Numeric Score: **0.98***)

Need Intensity (Reproduced from Feng [8])

How would you characterise the presence/absence of fulfillment of this need?

A. I would be satisfied by its presence, but I would not regret its absence (*Numeric Score: **0.11***)
B. I would be satisfied by itspresence, and I would somewhat regret its absence (*Numeric Score: **0.19***)
C. I would be satisfied by its presence, and I would regret its absence (*Numeric Score: **0.33***)
D. Its presence is necessary, and I would regret it absence (*Numeric Score: **0.57***)
E. Its presence is absolutely essential, and I would regret its absence (*Numeric Score: **0.98***)

From this the value of the flow can be determined, using the following matrix:

Source Importance Score						
	5 = 0.98	0.11	0.19	0.32	0.56	0.96
	4 = 0.78	0.09	0.15	0.26	0.44	0.76
	3 = 0.55	0.06	0.10	0.18	0.31	0.54
	2 = 0.33	0.04	0.06	0.11	0.19	0.32
	1 = 0.11	0.01	0.02	0.04	0.06	0.11
		A = 0.11	***B = 0.19***	***C = 0.33***	***D = 0.57***	***E = 0.98***
		Need Intensity Score				

Figure 3: Matrix for the evaluation of the value flow score. Figure from Feng [8].

We are now able to assign values to each connection in the DSM (See figure 4).

	Semester Project	Emmanuelle David	EE-587 Space Sustainability Students	Volker Gass	EPFL	Martin Lemaire	Mathieu Udriot	Marnix Verkammen	EUCASS	ENG-411 CDF Students	eSpace
Semester Project	0	0.1	0.11	0.31	0	0.96	0.44	0.18	0.1	0.44	0.18
Emmanuelle David	0.11	0	0.96	0.44	0.96	0.25	0.96	0.96	0	0	0.96
EE-587 Space Sustainability Students	0.1	0.96	0	0	0.76	0.96	0.96	0.44	0	0	0.96
Volker Gass	0.26	0.44	0	0	0.76	0.25	0.18	0	0	0	0.44
EPFL	0	0.96	0.55	0.55	0	0.32	0.55	0.55	0	0.55	0.96
Martin Lemaire	0.96	0.31	0.96	0.31	0.53	0	0.76	0.44	0	0.96	0.76
Mathieu Udriot	0.44	0.96	0.96	0.18	0.76	0.55	0	0.96	0	0.96	0.96
Marnix Verkammen	0.18	0.96	0.44	0	0.76	0.44	0.96	0	0	0.96	0.96
EUCASS	0.11	0	0	0	0	0	0	0	0	0	0.55
ENG-411 CDF Students	0.44	0	0	0	0.76	0.96	0.96	0.96	0	0	0.96
eSpace	0.18	0.96	0.96	0.44	0.96	0.55	0.96	0.96	0.76	0.96	0

Figure 4: Weighted Dependency Structure Matrix of the initial stakeholder network. The communities that are identified in the subsubsection 2.1.3 are represented in orange. Own figure.

2.1.3 Identification of Communities

As previously shown (See figure 4), we identified communities in the stakeholder network. The identification of these communities serves the purpose of managing the complexity of the network through the creation of a less complicated SVN. Indeed, if we represented all the edges of the model on the SVN, it would get very intricate and we would not be able to communicate effectively the results of the analysis. It is much easier to intepret a simplified SVN at the high level with clusters represented, and then if more details is wished, we can simply zoom-in in a given cluster. To identify the different communities, we use a spectral clustering technique from Newman [15], and we find the following clusters:

- **Cluster 1**
  - Emmanuelle David
  - EE-587 Sustainability Students
  - Volker Gass
  - EPFL
- **Cluster 2**
  - Martin Lemaire
  - Mathieu Udriot
  - Marnix Verkammen
  - EUCASS
  - ENG-411 CDF Students
  - eSpace

2.1.4 Relative Importance of Stakeholders

We have identified the communities of the network, which will allow us to create a simplified SVN while capturing the most important information. We now want to give some insight on the importance of each stakeholder with regard to the focal project. To this end, we will conduct a Focal Organisation Analysis (Feng [8]), performed by computing the Weighted Stakeholder Occurence (WSO) using the following equation:

$$WSO = \frac{\text{Score sum of the value cycles of the focal organisation containing a specific stakeholder}}{\text{Score sum of all the value cycles of the focal organisation}} \tag{1}$$

Value cycle computation (Feng [8])

The value cycle for the focal organisation are obtained by multiplying the quantified DSM by itself n times and looking at the diagonal item of the DSM of the focal organisation, where n represents the cycle length. The maximum value of n is the value of the dimension of the DSM. Moreover, to avoid loops, all diagonal elements of the DSM must be zero.

Here, we will limit ourselves to a maximum cycle length of 6, for computational efficiency purposes, with the algorithm already taking a few minutes to run. Given the evolution of the run time for the algorithm with regard to n, a value above 7 would take multiple hours to be computed. This is due to the fact that matrix multiplication is fast, but the identification of the different nodes within the score sum of the value cycles is extremely intensive and long, even for a computer. We therefore get the following result,

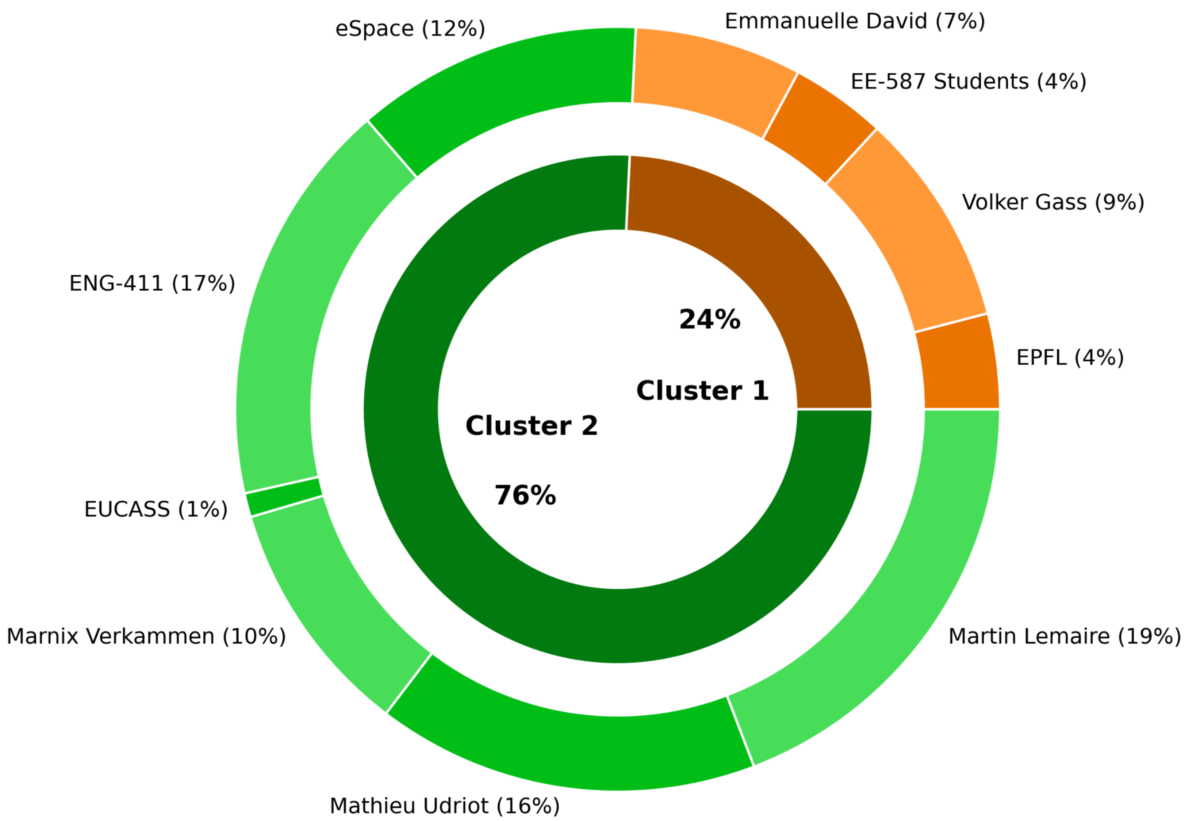

Figure 5: Weighted Stakeholder Occurence, normalised to obtain weights that sum to unity (i.e. 1). The weights of the clusters are derived by summing the weights of their associated stakeholders.

2.1.5 Stakeholder Value Network

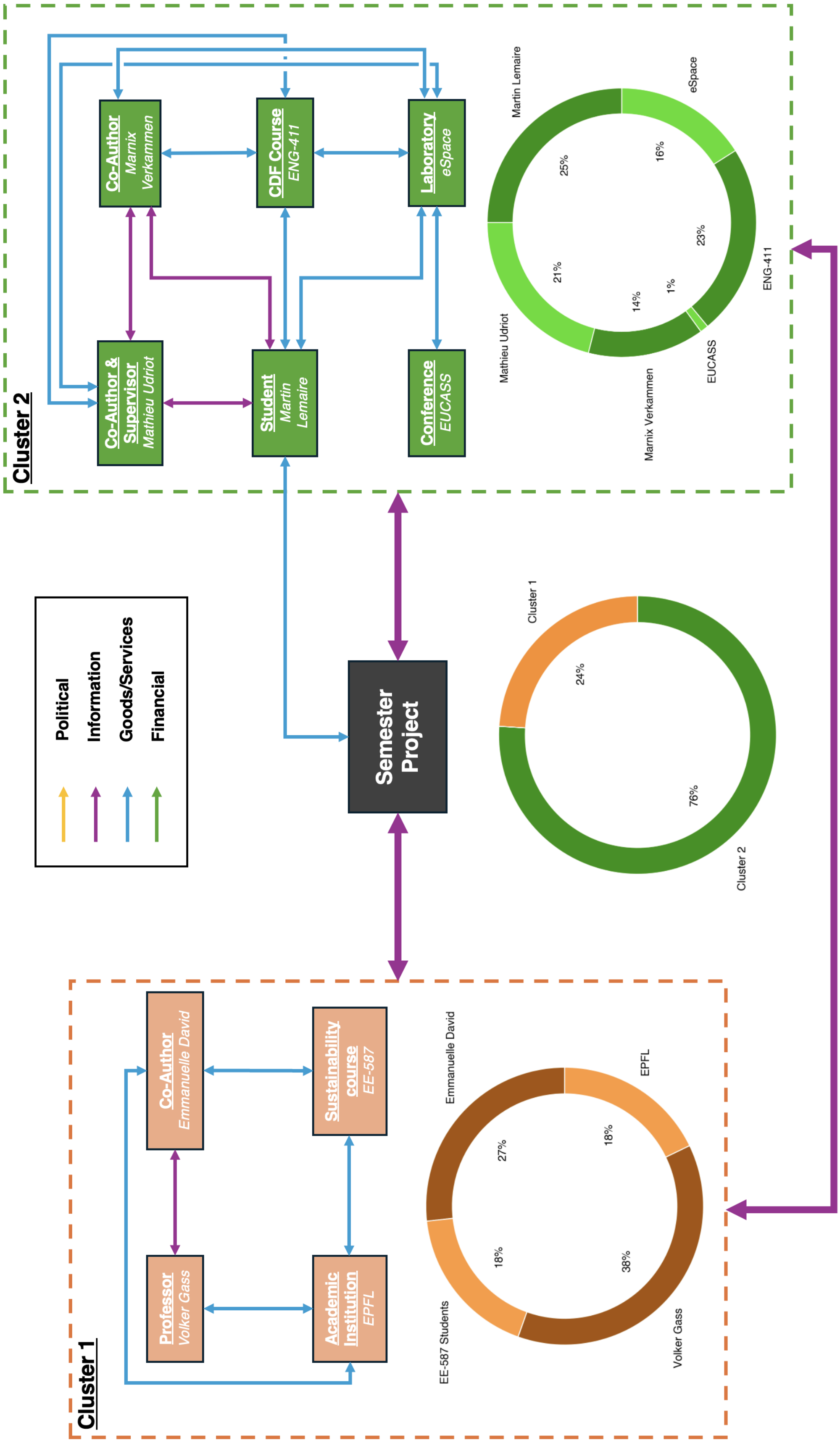

Figure 6: Stakeholder Value Network of the initial stakeholder network. Own figure.

2.2 Expanded Stakeholder Network Strategy

We have performed the analysis of the initial stakeholder network. Now, it is stated in the abstract of the paper (See appendix A, p.95) that interviews with engineers and managers from the industry shall be performed. In the previous network, none of such appear, and therefore a strategy needs to be defined to reach a more desirable state, and to have the right value flows towards the project.

2.2.1 Definition of Target Stakeholders and Gap Fillers

We want to identify two new types of stakeholders, the targets and the gap fillers. The target are the ones from which we desire to receive value, and the gap fillers are the one with which we have an existing value flow, and which themselves have an existing value flow with a target stakeholder (See figure 7). The goal of this identification is to evaluate which gap fillers are the most important in facilitating the creation of a value flow from a target stakeholder to the project, i.e. to "close the loop" (See figure 8).

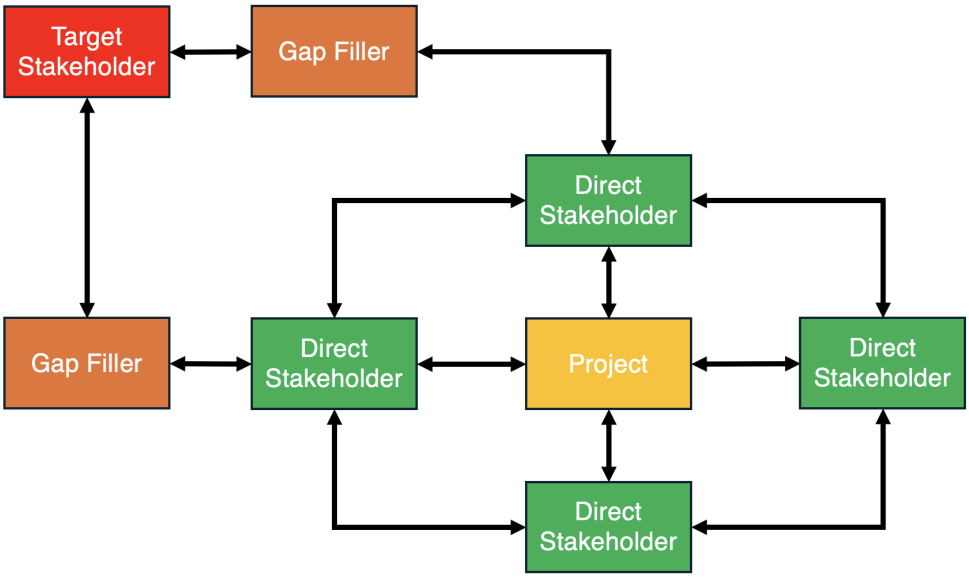

Figure 7: Illustration of a Stakeholder Value Network with the representation of the target stakeholders and the gap fillers. Own figure.

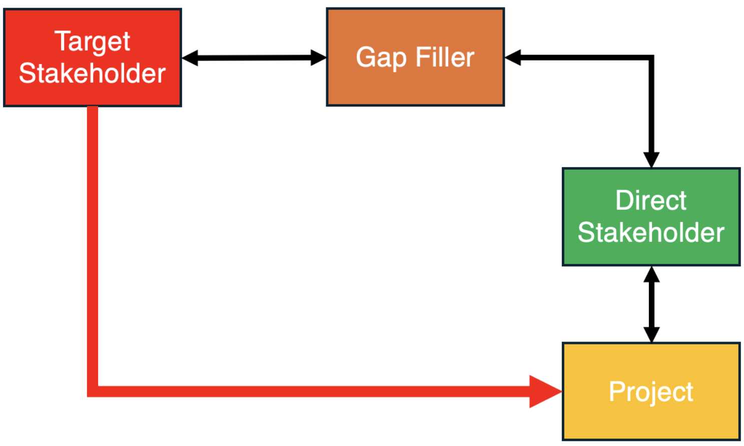

Figure 8: Illustration of the desired state, that the strategy aims to reach, where the loop to the target stakeholder is closed. Own figure.

For this project, we can define the following target stakeholders:

- **Airbus:** Largest european aerospace company.
- **ArianeGroup:** Leading launch vehicle manufacturer in Europe.
- **MIT ESL:** Research focused on the *ilities*, to which *sustainability* belongs.
- **ESA:** Hosts the majority of space activities in Europe.
- **Beyond Gravity:** Space systems designer and manufacturer in Switzerland.
- **RUAG MRO:** Aerospace and defense systems integrator in Switzerland.
- **EPFL Rocket Team:** Largest space-related (and technical) student association of EPFL.

Now, we can identify potential gap fillers that connect the close stakeholders of the current network to the target stakeholders, as such:

- **Yann Donon - Director of Telecommunications at RUAG MRO**
  - Target Stakeholders Connection: RUAG MRO
  - Other Stakeholders Connection: Martin Lemaire, Pr. Volker Gass
- **Mathias Burkhalter - Director of Strategic Projects at Beyond Gravity**
  - Target Stakeholders Connection: Beyond Gravity
  - Other Stakeholders Connection: Martin Lemaire, Pr. Volker Gass
- **Pr. Olivier De Weck - Professor of Astronautics at MIT ESL and former Vice-President for Technology Roadmapping at Airbus**
  - Target Stakeholders Connection: Airbus and MIT ESL
  - Other Stakeholders Connection: Pr. Volker Gass, Elwyn Sirieys, Mathieu Chaize
- **Elwyn Sirieys - Executive Assistant to the CEO at ArianeGroup**
  - Target Stakeholders Connection: ArianeGroup, Airbus and MIT ESL
  - Other Stakeholders Connection: Martin Lemaire, Mathieu Udriot, Emmanuelle David, Pr. Olivier De Weck, Mathieu Chaize, Cédric Renault
- **Cédric Renault - In charge of Technology Roadmapping at ArianeGroup**
  - Target Stakeholders Connection: ArianeGroup
  - Other Stakeholder Connection: Elwyn Sirieys
- **Mathieu Chaize - CTO at Alatyr and former Ariane 6 Systems Engineer**
  - Target Stakeholders Connection: ArianeGroup and MIT ESL
  - Other Stakeholders Connection: Mathieu Udriot, Emmanuelle David, Elwyn Sirieys, Pr. Olivier de Weck

2.2.2 Quantitative Stakeholder Network Model

Given the previous list of stakeholders, we can expand the former stakeholder model to append the additional ones. We want to determine the importance of the gap fillers to reach the desired state, therefore we add the "closing loop" connections in the model (in red on figure 9), though they currently do not exist. These connections are set as fixed source importance and need intensity values, except for the Rocket Team and ESA which are already close to eSpace, allowing a higher expected value.

	Semester Project	Emmanuelle David	EE-587 Space Sustainability Students	Volker Gass	EPFL	Martin Lemaire	Mathieu Udriot	Marnix Verkammen	EUCASS	ENG-411 CDF Students	eSpace	Yann Donon	Mathias Burkhalter	Beyond Gravity	RUAG	EPFL Rocket Team	European Space Agency	MIT ESL	Olivier De Weck	Airbus	ArianeGroup	Elwyn Sirleys	Cedric Renault	Mathieu Chaize
Semester Project	0	0.1	0.11	0.31	0	0.96	0.44	0.18	0.1	0.44	0.18	0	0	0.18	0.18	0.31	0.31	0.18	0	0.18	0.18	0	0	0
Emmanuelle David	0.11	0	0.96	0.44	0.96	0.25	0.96	0.96	0	0	0.96	0	0	0	0	0.55	0	0	0	0	0	0.18	0	0
EE-587 Space Sustainability Students	0.1	0.96	0	0	0.76	0.96	0.96	0.44	0	0	0.96	0	0	0	0	0.31	0	0	0	0	0	0	0	0
Volker Gass	0.26	0.44	0	0	0.76	0.25	0.18	0	0	0	0.44	0.44	0.18	0	0	0	0	0	0.18	0	0	0	0	0
EPFL	0	0.96	0.55	0.55	0	0.32	0.55	0.55	0	0.55	0.96	0.1	0	0	0	0.55	0.44	0	0	0	0	0	0	0
Martin Lemaire	0.96	0.31	0.96	0.31	0.53	0	0.76	0.44	0	0.96	0.76	0.31	0.06	0	0.31	0.18	0	0	0	0	0	0.53	0	0
Mathieu Udriot	0.44	0.96	0.96	0.18	0.76	0.55	0	0.96	0	0.96	0.96	0	0	0	0	0.44	0	0	0	0	0	0.18	0	0
Marnix Verkammen	0.18	0.96	0.44	0	0.76	0.44	0.96	0	0	0.96	0.96	0	0	0	0	0	0	0	0	0	0	0	0	0
EUCASS	0.11	0	0	0	0	0	0	0	0	0	0.55	0	0	0	0	0	0.76	0	0	0	0	0	0	0
ENG-411 CDF Students	0.44	0	0	0	0.76	0.96	0.96	0.96	0	0	0.96	0	0	0	0	0.53	0	0	0	0	0	0	0	0
eSpace	0.18	0.96	0.96	0.44	0.96	0.55	0.96	0.96	0.76	0.96	0	0	0	0	0	0.55	0.76	0	0	0	0	0	0	0
Yann Donon	0	0	0	0.44	0.1	0.25	0	0	0	0	0	0	0	0	0.96	0	0	0	0	0	0	0	0	0
Mathias Burkhalter	0	0	0	0.18	0	0.06	0	0	0	0	0	0	0	0.96	0.18	0	0.18	0	0	0	0	0	0	0
Beyond Gravity	0.14	0	0	0	0	0	0	0	0	0	0	0	0.96	0	0.76	0	0.53	0	0	0	0.76	0	0	0
RUAG	0.14	0	0	0	0	0.25	0	0	0	0	0	0.96	0.18	0.55	0	0	0	0	0	0.31	0	0	0	0
EPFL Rocket Team	0.25	0.76	0.25	0	0.76	0.18	0.44	0	0	0.32	0.76	0	0	0	0	0	0	0	0	0	0	0	0	0
European Space Agency	0.25	0	0	0	0.44	0	0	0	0.55	0	0.55	0	0.14	0.32	0	0	0	0.44	0	0.44	0.96	0.44	0.44	0
MIT ESL	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.44	0	0.96	0.44	0.06	0.44	0	0.18
Olivier De Weck	0	0	0	0.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0.96	0	0.44	0	0.44	0	0.44
Airbus	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.44	0.44	0.44	0	0.55	0.25	0	0
ArianeGroup	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0.55	0	0	0.96	0.06	0	0.76	0	0.96	0.55	0.18
Elwyn Sirleys	0	0.18	0	0	0	0.32	0.18	0	0	0	0	0	0	0	0	0	0.44	0.44	0.44	0.31	0.96	0	0.44	0.76
Cedric Renault	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.44	0	0	0	0.76	0.44	0	0
Mathieu Chaize	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.18	0.44	0	0.18	0.55	0	0

Figure 9: Weighted Dependency Structure Matrix of the expanded stakeholder network. The communities that are identified in the subsubsection 2.2.3 are represented in orange. The theoretical connection that we desire are represented in red. Own figure.

2.2.3 Identification of Communities

Using the same spectral clustering technique [15] as the previous one on the extension of the stakeholder network, we can identify the following clusters:

- **Cluster 3**
  - Yann Donon
  - Mathias Burkhalter
  - Beyond Gravity
  - RUAG MRO
- **Cluster 4** - EPFL Rocket Team
- **Cluster 5**
  - ESA
  - Olivier De Weck
  - ArianeGroup
  - Cedric Renault
  - MIT ESL
  - Airbus
  - Elwyn Sirieys
  - Mathieu Chaize

2.2.4 Relative Importance of Gap Filling Stakeholders

We now want to determine the relative importance of the gap filling stakeholders, to effectively reach the target state. To this end, we will perform a similar Focal Organisation Analysis (Feng [8]) as previous, but a few parameters are defined for it:

- The focal organisation here is defined as the merged nodes of the semester project and the close stakeholders that have a connection with gap filling stakeholders (i.e. Martin Lemaire, Mathieu Udriot, Pr. Volker Gass, and Emmanuelle David). This is done to capture the entirety of the connections to the gap filling stakeholders.
- We take the whole network and only keep the resulting WSO for the gap filling stakeholders. The WSO of the target stakeholders are much less useful here, because we don't have a direct impact on them and we want to know where to invest our time/resources to yield the highest return.

From this we get the following weights for the gap filling stakeholders,

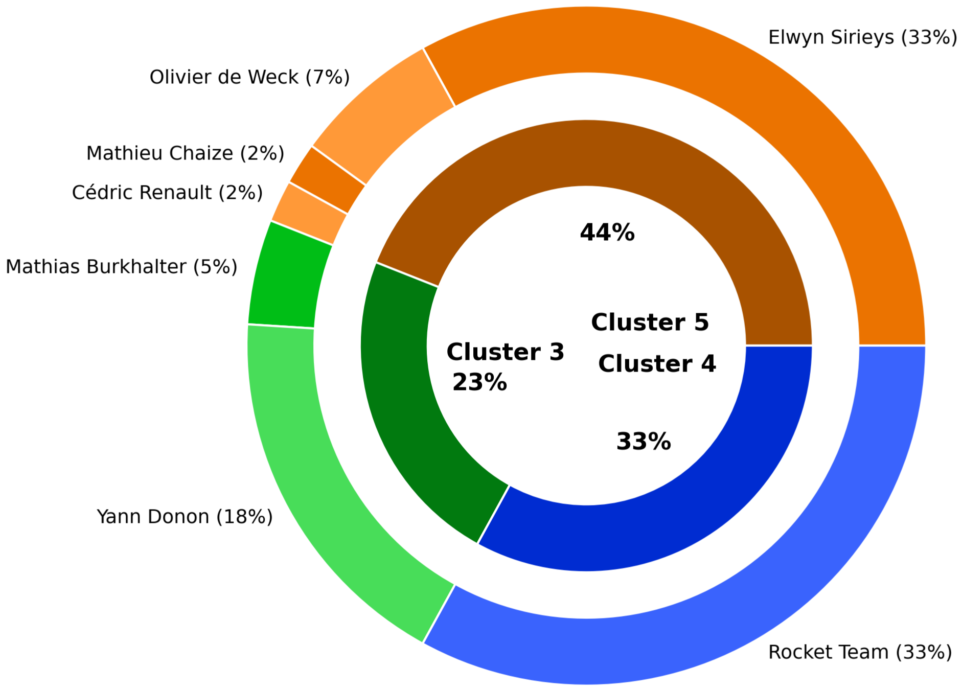

Figure 10: Weighted Stakeholder Occurence, normalised to obtain weights that sum to unity (i.e. 1). The weights of the clusters are derived by summing the weights of their associated stakeholders. Own figure.

2.2.5 Expanded Stakeholder Value Network

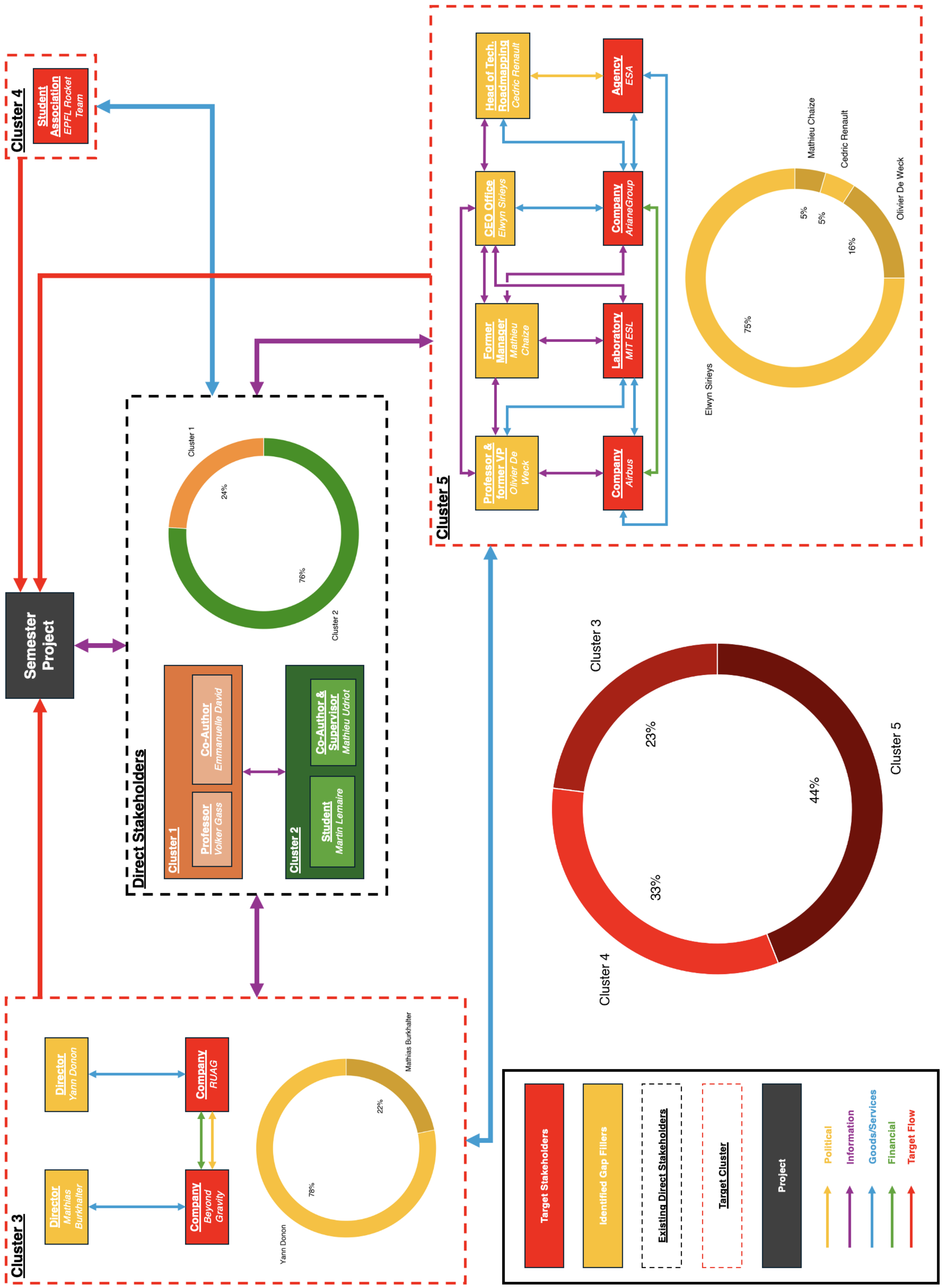

Figure 11: Stakeholder Value Network for the expanded stakeholder network. Own figure.

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3 State of the Art

We have performed a comprehensive stakeholder analysis, which will enable us to define requirements that are relevant with stakeholder expectations and target the right people to interview. A second element is needed to define these requirements - background knowledge on existing methods and processes - which is the purpose of this State-of-the-Art section. We will start by analysing the lifecycle properties (ilities) to which sustainability belongs, and it will allow us to identify the most relevant ones to gain guidance for further research.

3.1 Lifecycle Properties - Ilities

Typical engineering processes are centered around functionality and do not take into account other factors, or at least not explicitely. Although it may be acceptable at a very low system level where feedback is rapidly obtained and changes easily propagated, it is a different matter for complex engineering systems with thousands of components. Indeed, long design and life durations, as well as the very large amount of components and interfaces make the initial phases of the design "freeze" many choices early on. Once made, these decisions - such as the architecture - are nearly impossible to modify.

From this, the topic of lifecycle properties - also known as *ilities* - has been a growing research topic in engineering systems, and especially on methods to implement them in early design phases, such as system architecture. Accounting for ilities enables better awareness regarding the merit of different concepts and paves the way for trade-offs between architecture alternatives.

3.1.1 Role in Engineering Systems

As stated earlier, functionality cannot be the only accounted factor when selecting a system architecture, because many challenges arise which are not directly correlated with the function of the system. According to Rhodes et al. [11], ilities can be seen as a response to these challenges, which are identified as: *life cycle, complexity, human behavior, uncertainty, and dynamics*. The figure 12 shows the principal ilities identified as a relevant responses for each challenge.

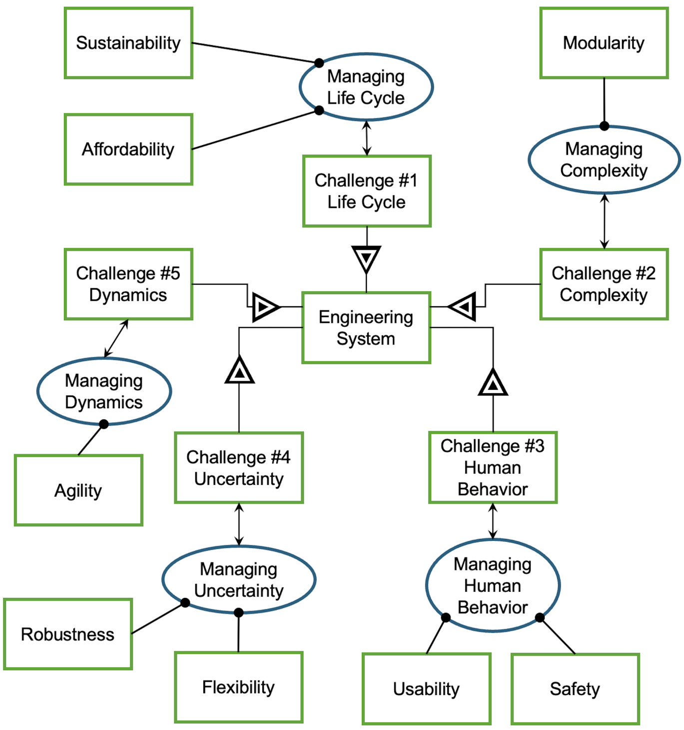

Figure 12: Object-Process Model (OPM) of the response that ilities provide to the challenges of engineering systems, the model is not complete but provides the most used ilities for each challenge. Inspired from Rhodes et al. [11]. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

3.1.2 Societal Analysis

The topic of ilities rises with the emergence of complex systems and is therefore a quite recent subject. This part aims at analysing the evolution and infusion of these properties into society, and especially the underlying dynamics. These results are important for the case of sustainability, because it is a fairly new topic that raises many concerns, and that seems very challenging to integrate in concrete applications. Hence, analysing for other ilities will allow to see how they evolved in the past, draw informed conclusions on the state of sustainability and define better suited strategies to improve the situation. To this end, data was collected on the ilities in three different areas - publications, patents, and policies (See figures 13, 14, and 15, respectively).

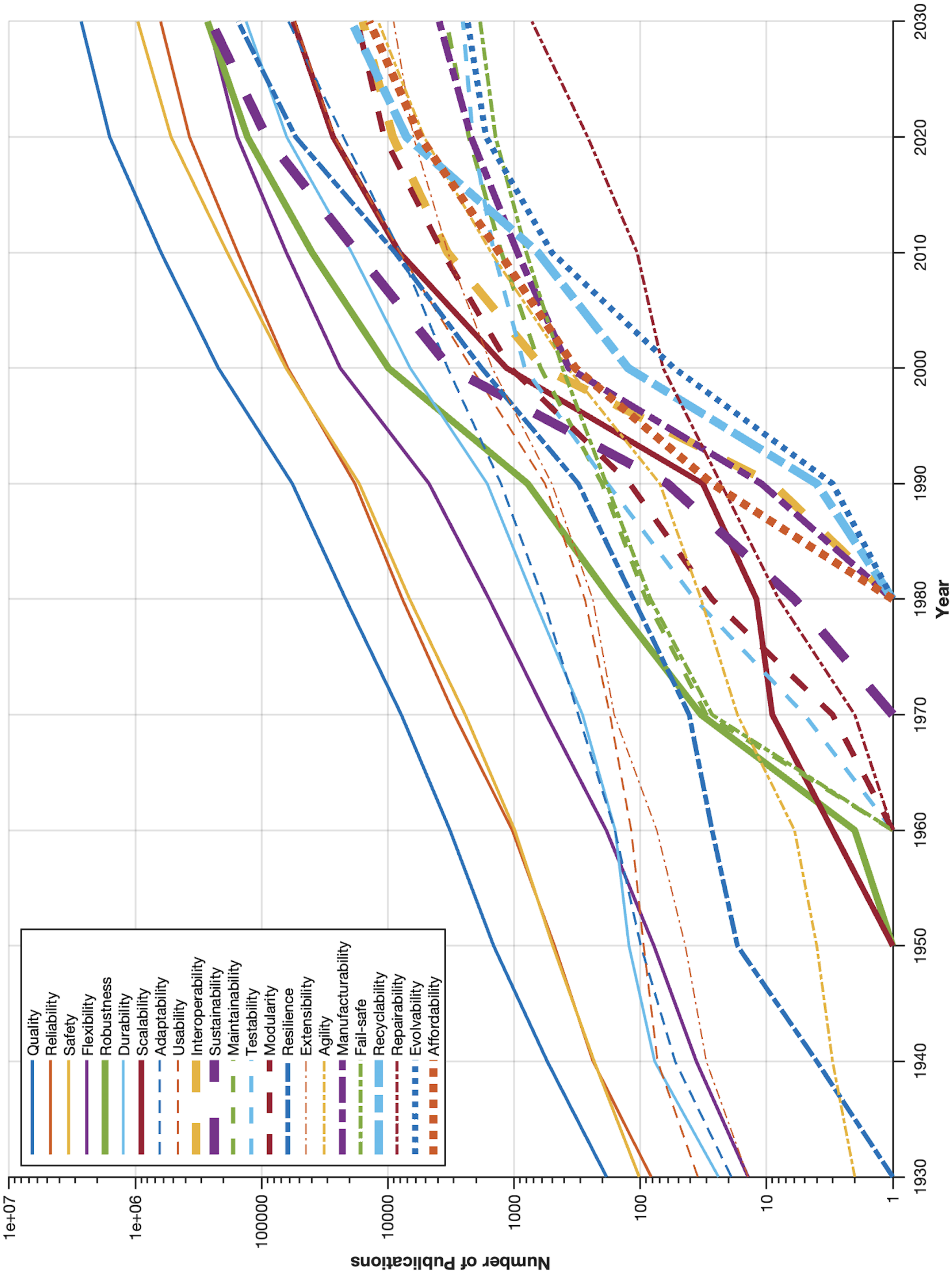

Figure 13: Cumulative number of publications related to ilities from 1930 to 2030. Data from Web of Science. The thickness of lines is proportional to the average growth, where the thickest is the ility that grows the fastest. The data for the current decade is linearly extrapolated up to 2030. Updated figure from De Weck [19].

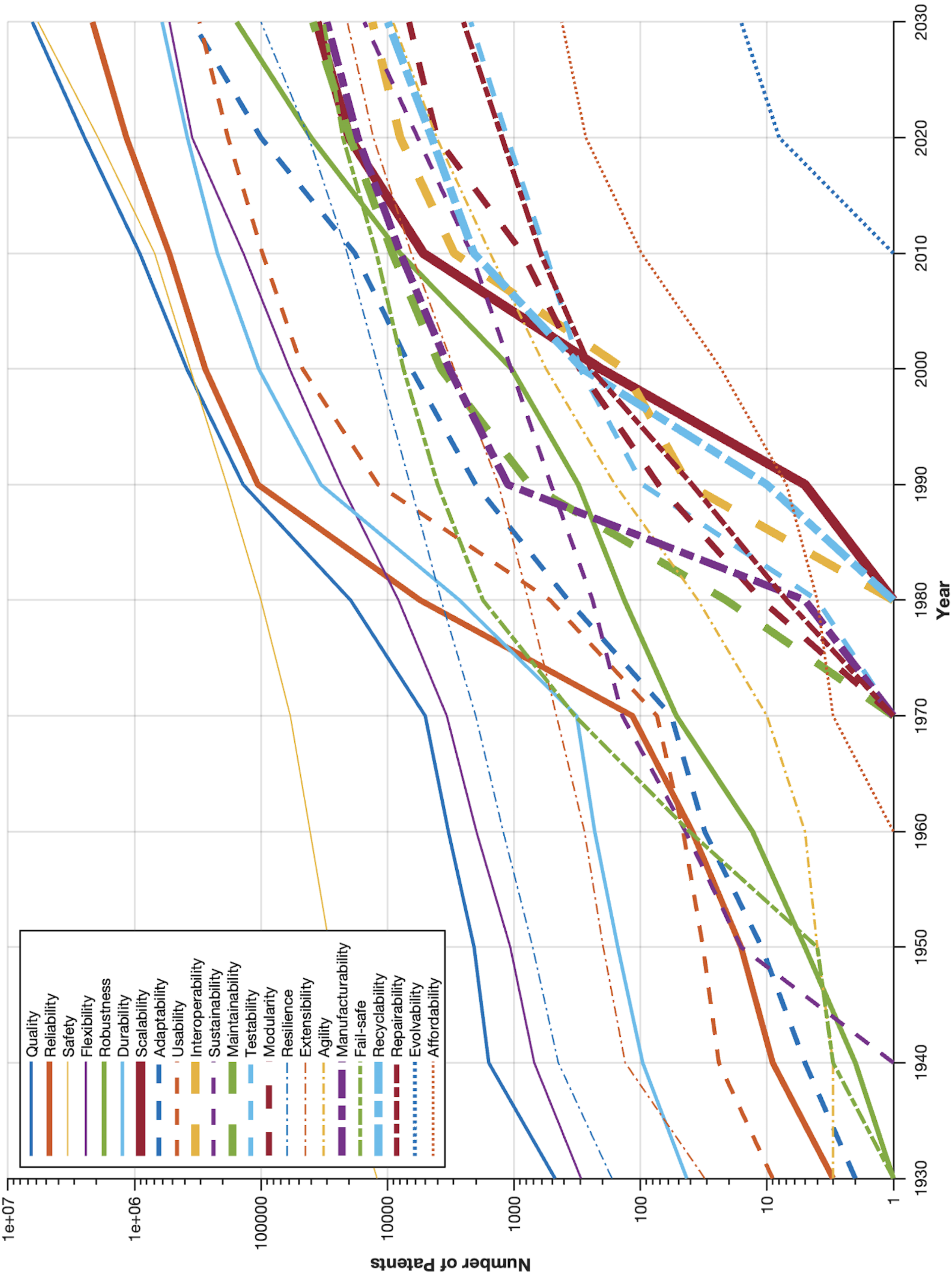

Figure 14: Cumulative number of patents related to ilities from 1930 to 2030. Data from Google Patents. The thickness of lines is proportional to the average growth, where the thickest is the ility that grows the fastest. The data for the current decade is linearly extrapolated up to 2030. Own figure.

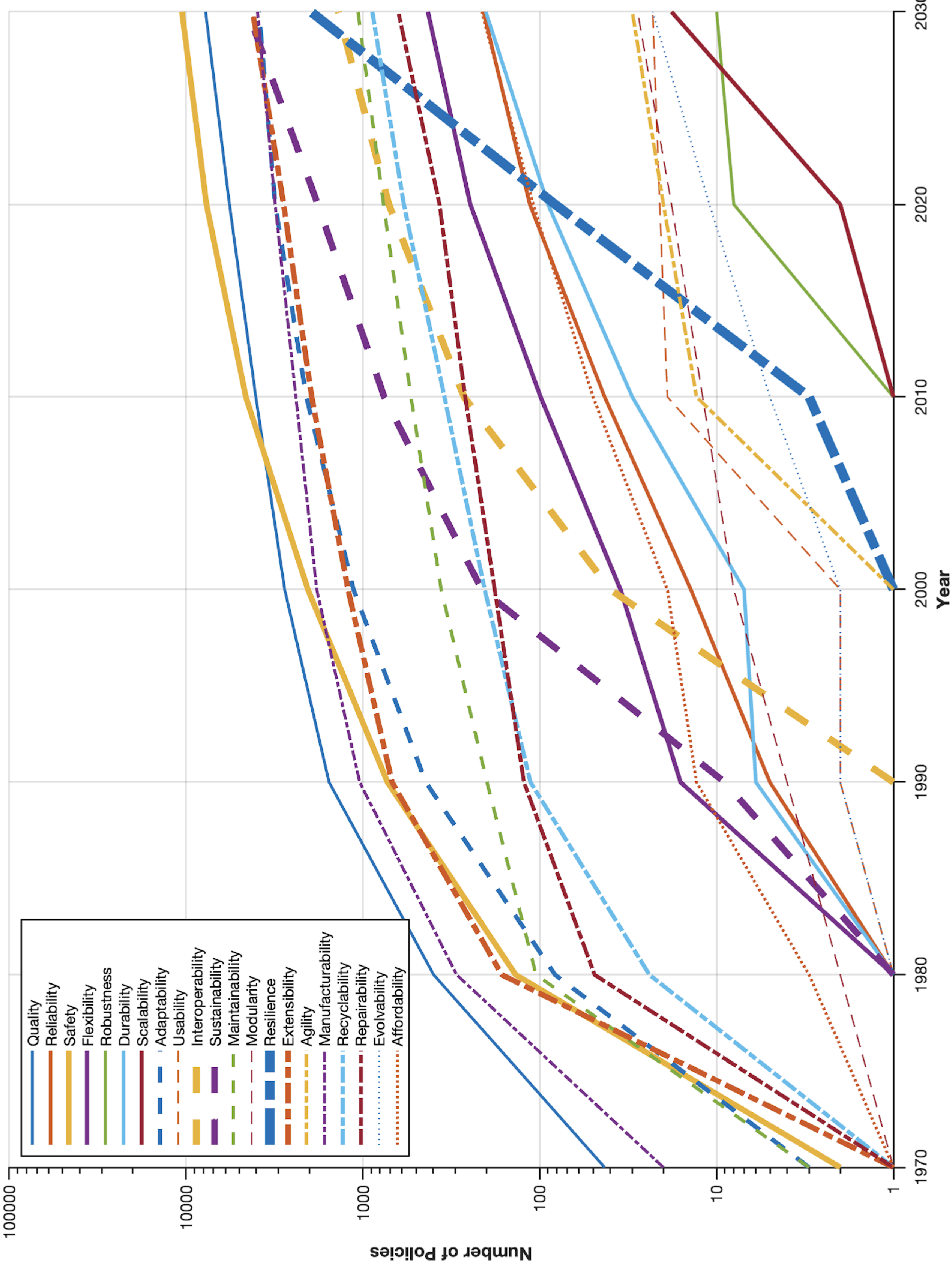

Figure 15: Cumulative number of european policies related to ilities from 1970 to 2030. Data from EUR-Lex. The thickness of lines is proportional to the average growth, where the thickest is the ility that grows the fastest. The data for the current decade is linearly extrapolated up to 2030. Own figure.

From this data, we want to compare the evolution of the three categories for each ility (See appendix C, p.99). The purpose is to identify patterns and similarities that enable a classification of the properties. To this end, we qualitatively assess the cumulative number for each ility, but also the variation in orders of magnitude (See figure 16).

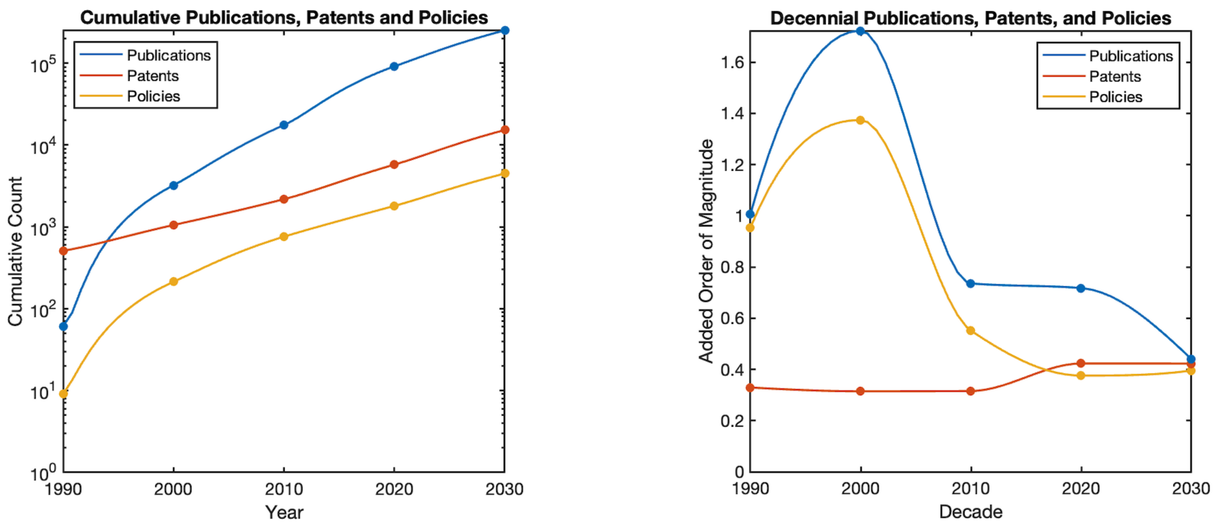

Figure 16: Example of comparative analysis for Sustainability. Own figure.

In this example of analysis, we can see that publications and policies regarding sustainability rise strongly in the 1990s, while a very slight acceleration can be observed for patents around the late 2010s. Due to a stronger and longer acceleration of publications, we can conclude that this ility is mostly driven by research, with a very small delay to be translated into policies. However, on the side of patents, the infusion seems much slower and delayed. It is important to note that patents regarding sustainability existed before the others and that the order of magnitude was not negligible, hence we could conclude that the peak was earlier and therefore market driven. However, when looking into the patents at that period, the definition of sustainability was different - much closer to durability - and deemed less relevant to environmental issues.

Performing a similar analysis for all the ilities, we can classify them into three categories (See table 1) - market driven, policy driven, and research driven. These classes of ilities reflect the most impactful "entry-point" for the growth of a given ility, but also the bottlenecks and areas of improvement for more efficient infusion.

Market Driven	Policy Driven	Research Driven
Reliability	Quality	Robustness
Durability	Flexibility	**Sustainability**
Adaptability	Interoperability	**Resilience**
Usability	Scalability	Evolvability
Maintainability	Modularity	Affordability
Manufacturability	Extensibility	
Fail-Safe	Agility	
Safety	**Recyclability**	
Repairability		

Table 1: Classification of ilities into three categories based on comparative analysis of publications, patents, and policies. In bold, ilities qualitatively assessed as being closely correlated to sustainability.

With the previous classification and the analysed behaviors for each ility, we are able to identify the dynamics of the evolution of ilities over time (See figure 17), with three distinct entry points driving the growth.

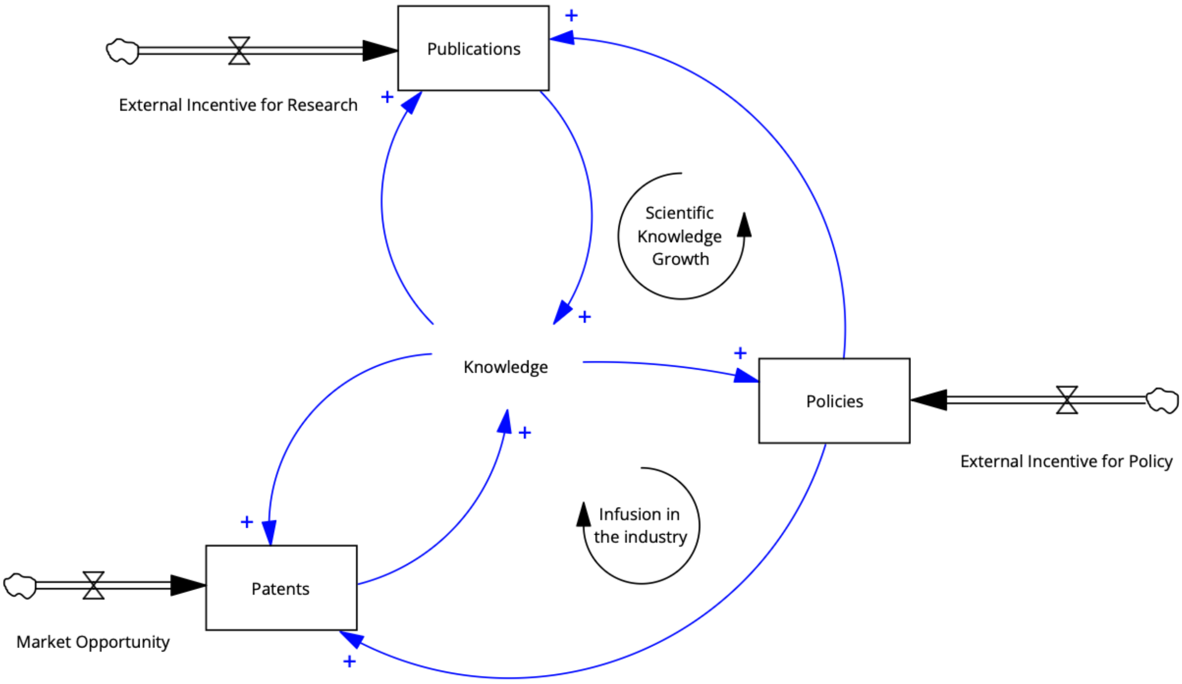

Figure 17: System dynamics model for the evolution of ilities over time. Three incentives for the different classes of ilities. Own figure.

From this societal analysis, we can conclude for sustainability that the most impactful driver is scientific research. Moreover, the infusion from research to policies is efficient, but much less for patents. This shows a clear gap between the research and what is concretely applicable in the industry. This generates a bottleneck and the creation of more applicable methods and processes should be explored, supposedly yielding a higher growth of patents than continuing research and regulations in a direction that is seemingly divergent from market needs.

3.1.3 Correlation Between Ilities

It was stated that ilities constitute properties of systems that are separated from the function itself, and that they offer a response to different challenges. However the definition and purpose of these properties can all be summarised as the answer to one question: *"What characterises a **quality** system?"*. Quality is the central ility that links them together and by integrating the right ilities for a given system, we can obtain a quality system by correlation.

Just like quality is correlated with other ilities, lifecycle properties are also correlated to some extent between one another (See figure 18, p.27). Hence, here again, integrating a specific ility does not necessarily mean a single method or objective but rather a set of characteristics that together yield a property.

In our case, in addition to the integration of methods solely made for sustainability, we can also add considerations for ilities that are correlated with it. Indeed, we can observe on the figure 18 that sustainability is especially correlated with safety and resilience. Considering other - correlated - ilities offers three main advantages:

- Safety is market driven (See table 1, p.25), hence integrating it can improve the infusion efficiency.
- Together with resilience, they have an extensive knowledge basis, therefore the processes are proven.
- If a direct integration of sustainability fails, emphasising safety and resilience would still enable to create a partly sustainable system through correlation.

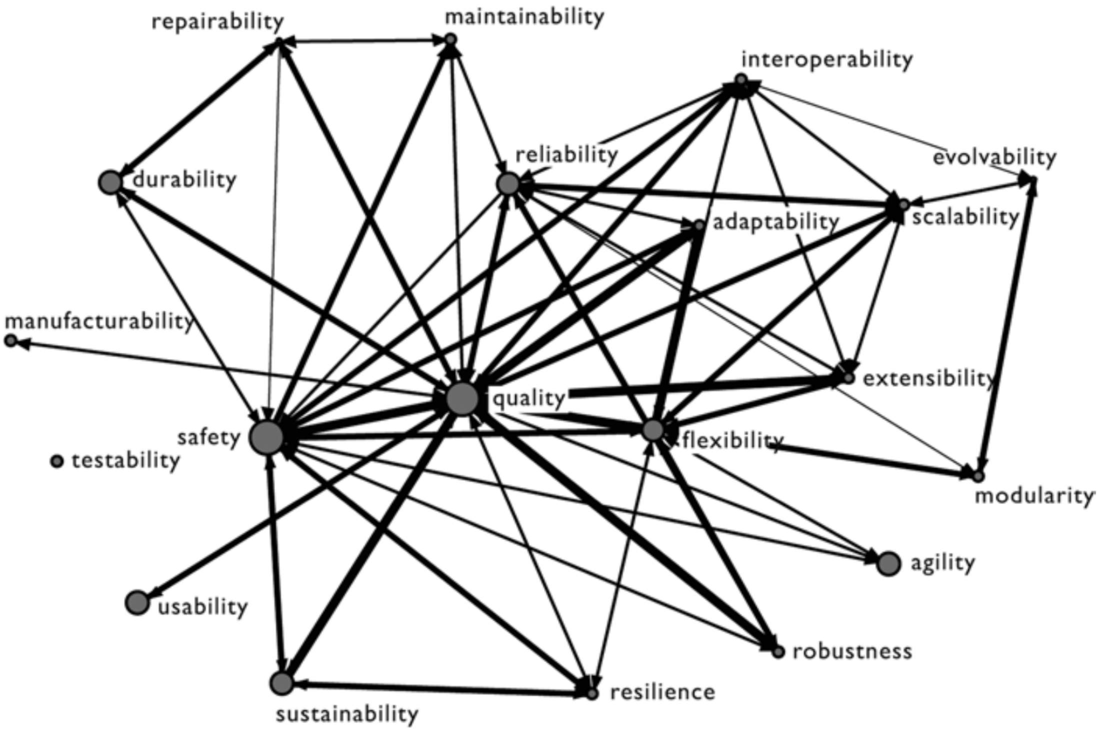

Figure 18: Correlation network of ilities. Graph from De Weck [19].

3.2 Sustainability

Sustainability is the main subject of this project, hence it is an important ility. A definition of this ility in the sense of systems is shown below, where we can observe concepts of time and cost. On the side of time, the definition shows that a system that is considered as sustainable is one that lasts in time. On the other hand, the concept of cost is not limited to financial resources but cost of any kind among environment, society and economy (See figure 19).

Definition of sustainability in the sense of systems (Maier et al. [11])

*Sustainable systems are those that can maintain performance at **cost** over a long period of time.*

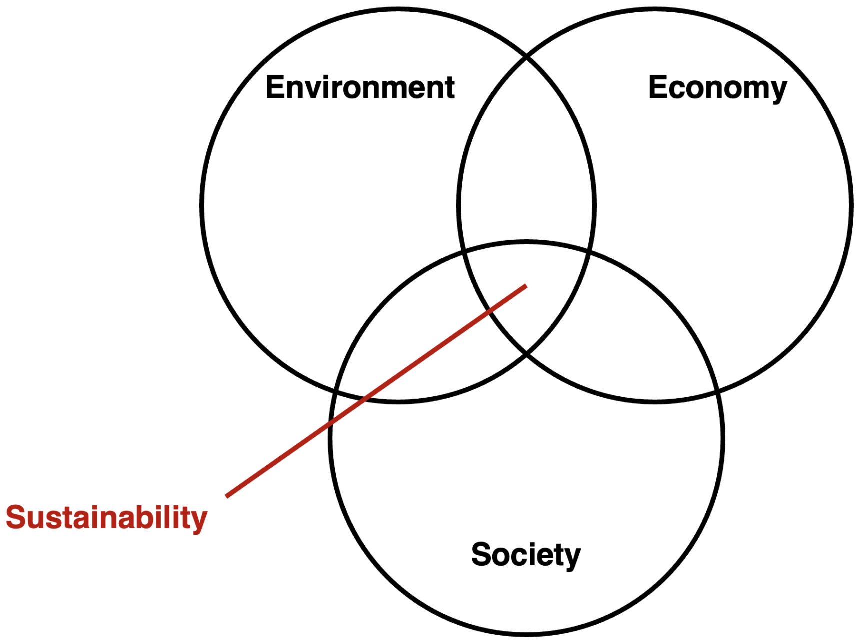

Figure 19: Three dimensions of sustainability. Reproduced from Maier et al. [11].

In 2015, the United Nations (UN) defined the Sustainable Development Goals (SDG) [13]. These goals provide an explicit foundation regarding the objectives that are targeted. They can be used to define a basis for a quantitative measure for sustainability. For example, in the work of Maier et al. [11], a metric of **eco-efficiency** (See equation 9) is produced with the SDGs (See figure 20, p.29), with some goals defined as *"Levers for transformation"*. We can hence observe that science and technology play an important role in improving the situation, with clear incentives on affordability, clean energies (Low environmental impact), innovation, and circular economy.

$$\text{Eco-efficiency} = \frac{\text{Human wellbeing}}{\text{Environmental impact}} \tag{2}$$

We can create a link between the space sector, Equation 9 and figure 12 (page 21), by correlating the *"Human wellbeing"* with usability and safety. And in the sense of space systems, usability can be translated into operability to be better suited, where it can immediately be linked with the well-known problem of debris. We can also add the factor of resilience, which is compliant with the concept of lasting systems that we evoked earlier, and correlated with sustainability according to figure 18 (page 27).

Hence we can define an adapted version of equation 9, tailored for space systems (See equation 3).

$$\text{Space Systems Sustainability} = \frac{\text{Operability} \cdot \text{Safety} \cdot \text{Resilience}}{\text{Environmental impact}} \tag{3}$$

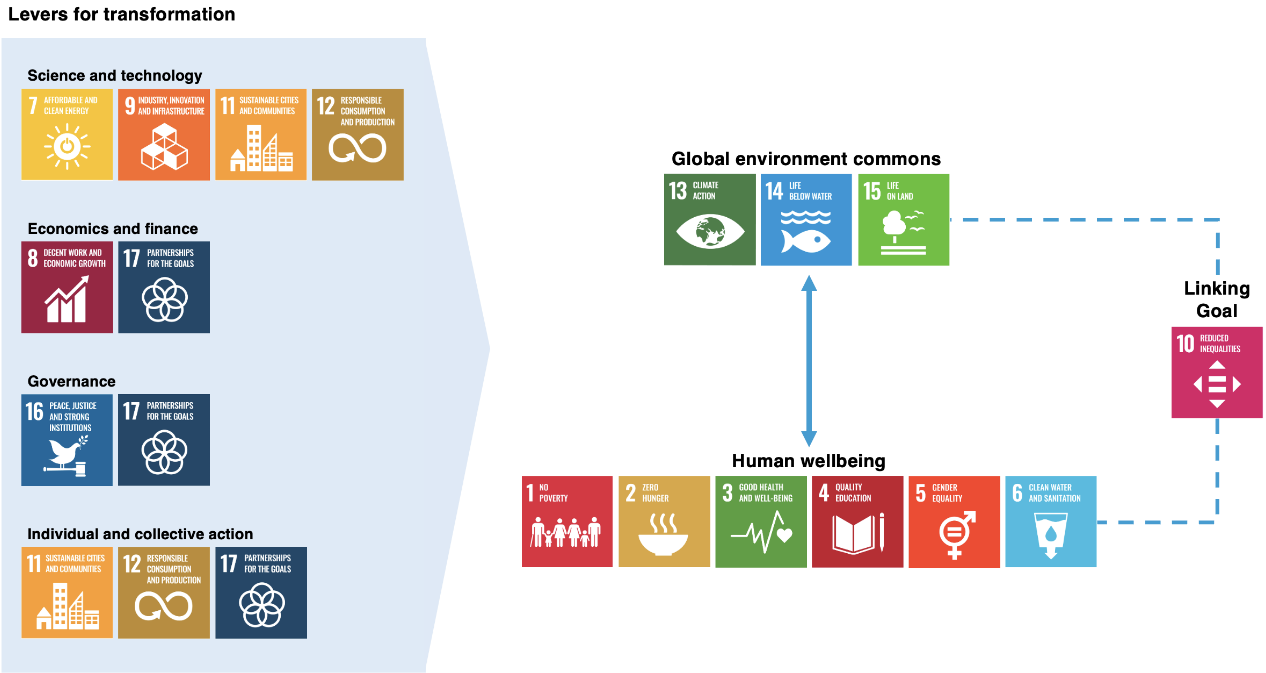

Figure 20: Illustration of the Sustainable Development Goals as means of transformation; a trade-off between human well being and the environment; and the link between them. Reproduced from Maier et al. [11], purpose of illustration and not readability of the SDGs.

Operability is already well defined and space debris are clearly the focal subject. Safety and resilience will be presented in following subsubsections. We can therefore focus on the aspect of environmental impact. The boundary of this subject is planetary, because the debris are already included in long-term operability, hence it is the impact on the Earth system or any other astre like the moon's surface. Life Cycle Assessment (LCA, see figure 21, p.30) provides a strong quantitative basis for the measurement of this environmental impact, although certain phenomena like the atmospheric impact of space launches are still very unknown. The figure 21 shows the different elements of the life cycle of a space system that impact the different components of the Earth system.

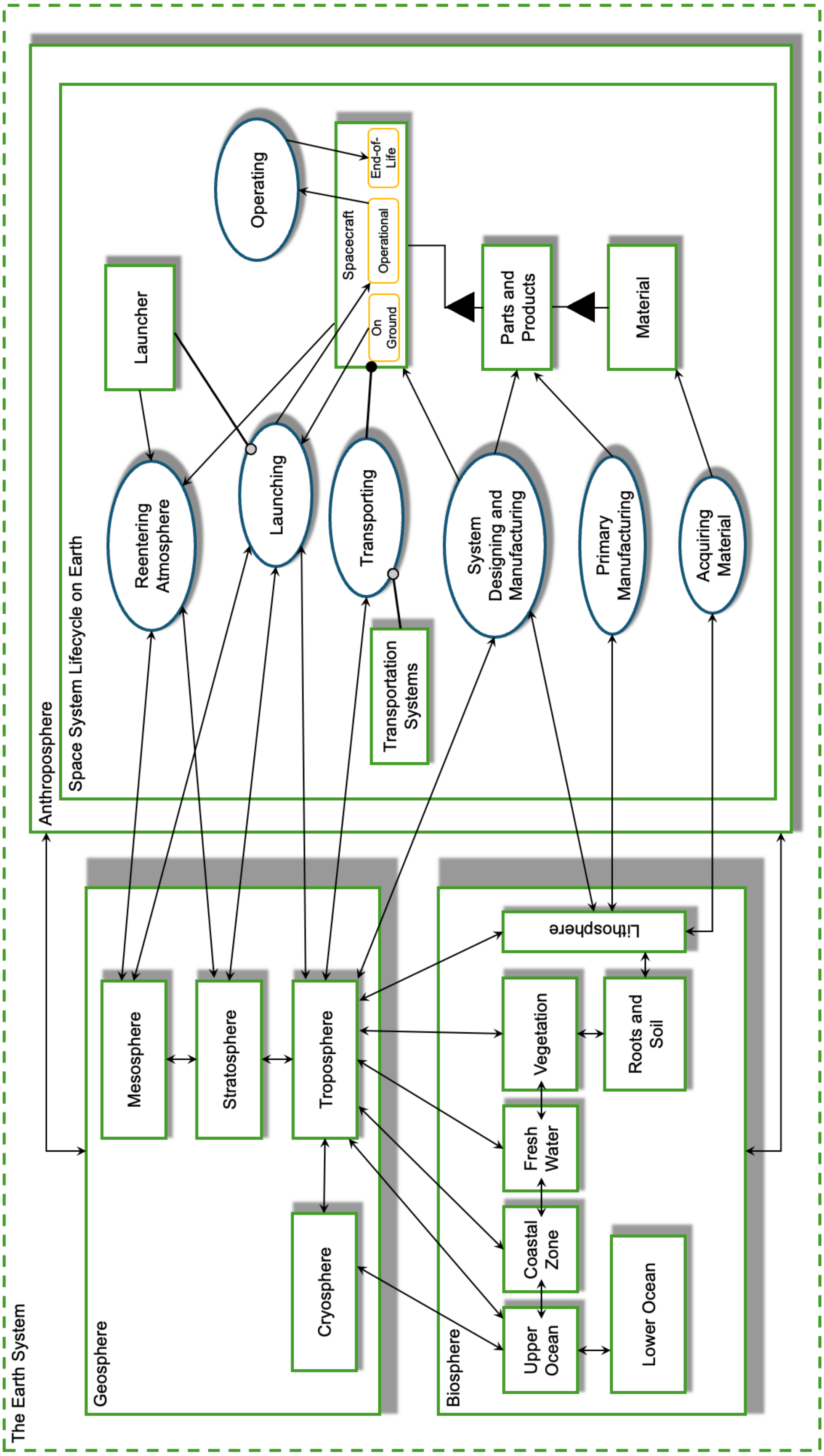

Figure 21: OPM conceptual model of the environmental impact of a typical space system's lifecycle on Earth. Inspired from Maier et al. [11]. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

3.3 Safety

Safety is an ility that is often related to sustainability (See figure 18, p.27), directly by ESA for example [7]. From a first impression, it can seem very similar to resilience that will be presented later, because they both relate heavily to risk management. However, safety differs because it is oriented towards the reduction of hazards that are identifiable and inherent to the system, while resilience is the capacity of a system to adapt to or absorb unexpected conditions. Hence a safe system is designed with a series of measures against these identified hazards and risks (See figure 22).

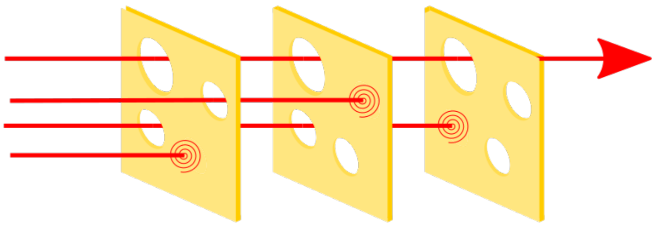

Figure 22: Swiss cheese model for safety measures against hazards.

This ility has been researched for a long time and is one of the ilities that accumulates the most publications (See figure 13, p.22). Three methods mainly exist for identifying hazards in a system (Maier et al. [11]), i.e. emergent phenomena that could lead to failure:

- Identification of interactions that are not intended by design.
- Identification of loops in the system's behavior (See figure 23).
- Identification of sequences that are not functionally related but that can - in their order - be consequential.

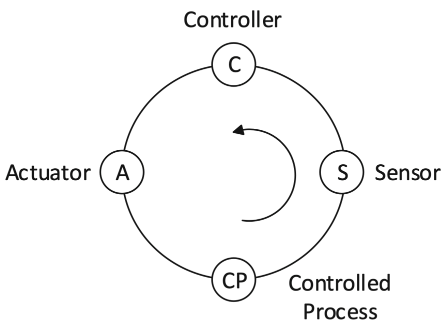

Figure 23: A simple control loop as an example of behavioral loop in a system. Figure from Maier et al. [11].

Once the hazards are identified and undesirable scenarios are defined, we are able to assess the level of risk and propose a set of solution that would reduce the risk. Then depending on the level of risk that was derived, the solution with the lowest "cost" and that brings the final level of risk under an acceptable threshold can be selected. The acceptable threshold creates new constraints for the system and therefore new requirements.

From a high-level perspective, any system's architecture can be represented as a network of processes and objects. The analysis of the safety of a system hence consists in assessing the propagation of failure or unintended behavior when a component or process fails. By identifying the behavioral loops in the system architecture - which can be mathematically be identified through the conversion of the system model (e.g. OPM) into a DSM and deriving the visualisation matrix (See equation 4) - we can deterministically make systems safe.

$$V = \sum_{n}^{N-1} DSM^n \tag{4}$$

3.4 Resilience

Resilience is an ility that has been researched for quite a long time (See figure 13, p.22) and is research driven (See table 1, p.25). Indeed, resilience is more oriented towards systems operating in extreme environments or possibly exposed to extreme conditions, and is therefore less critical in traditional systems on public markets. Examples of systems where resilience is very important and usually mentionned are the electric grid or the air traffic (The resilience of US air traffic after the occurence of 9/11 is a typical example).

Multiple definitions of resilience exist, a few being (Wied [20]):

- *"A spectrum ranging from avoidance of breakdown to a state where transformational change is possible."*
- *"An ability not just to recover from hits but to avoid problems altogether."*
- *"The intrisic ability of a system to adjust its functioning prior to, during, or following changes and disturbances."*
- *"First a reactive capacity to resist an external event; second, a more active capacity to anticipate events and thus open new development pathways."*

The figure 24 depicts the variety of elements that arise in the literature about resilience, which mainly revolve around:

- The resilience **of what**
- The resilience **to what**
- **How** the resilience

All of these means of creating resilience can be measured in different ways, like the time of recovery or the ratio between the disruption's amplitude and the measured variation of the system's performance. Overall, a first step to design a resilient system is to identify what may disrupt the system or in what way, then decide whether it is desirable to "absorb" or "adapt" - the two main philosophies that arise in the literature, and finally design a solution to integrate it.

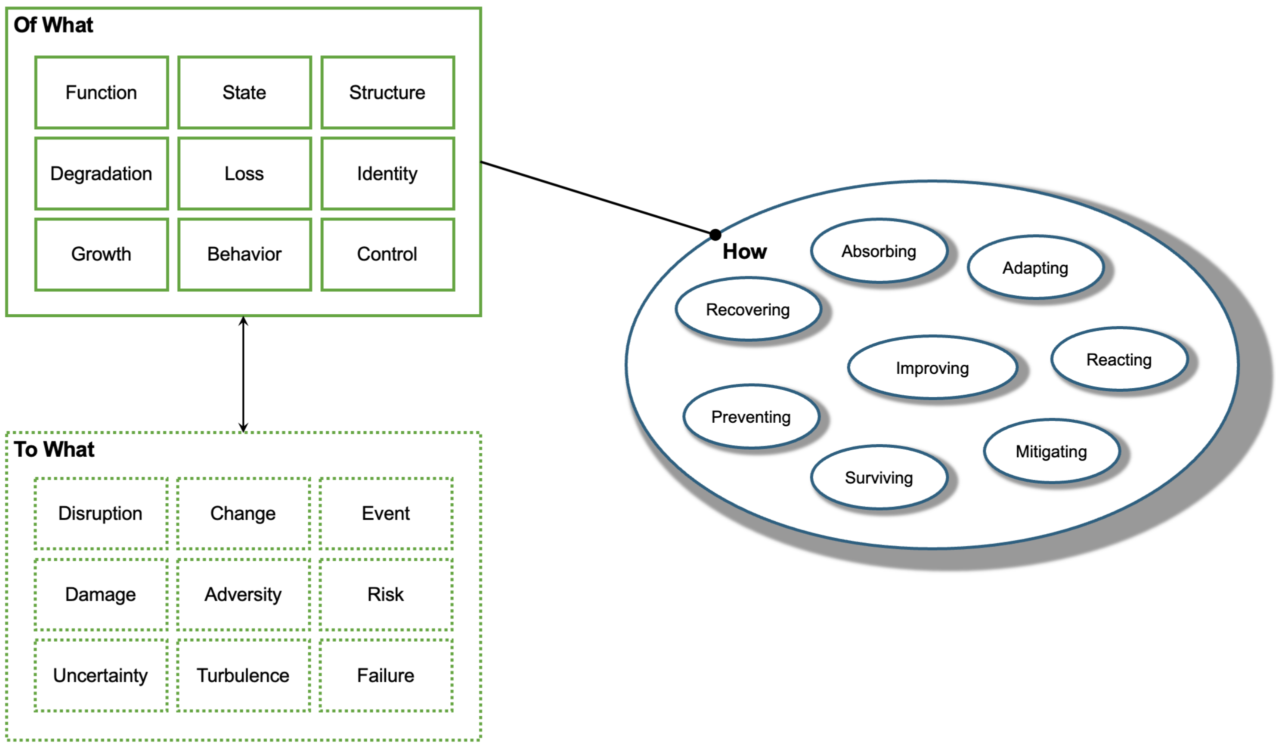

Figure 24: OPM conceptual model of a resilient system, with resilience *"of what"*, *"to what"*, and *"how"*. Inspired from Wied [20]. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

3.5 Concurrent Engineering

Another subject of this project is concurrent engineering, which will constitute the case study for the system that will be designed. It consists in grouping experts from different relevant domains in one "room" to concurrently design a mission or system. The experts assumably carry the knowledge of the State-of-the-Art in their relevant fields and directly face constraints from other parties to reach a compromise that is the most suited for the goals of the mission.

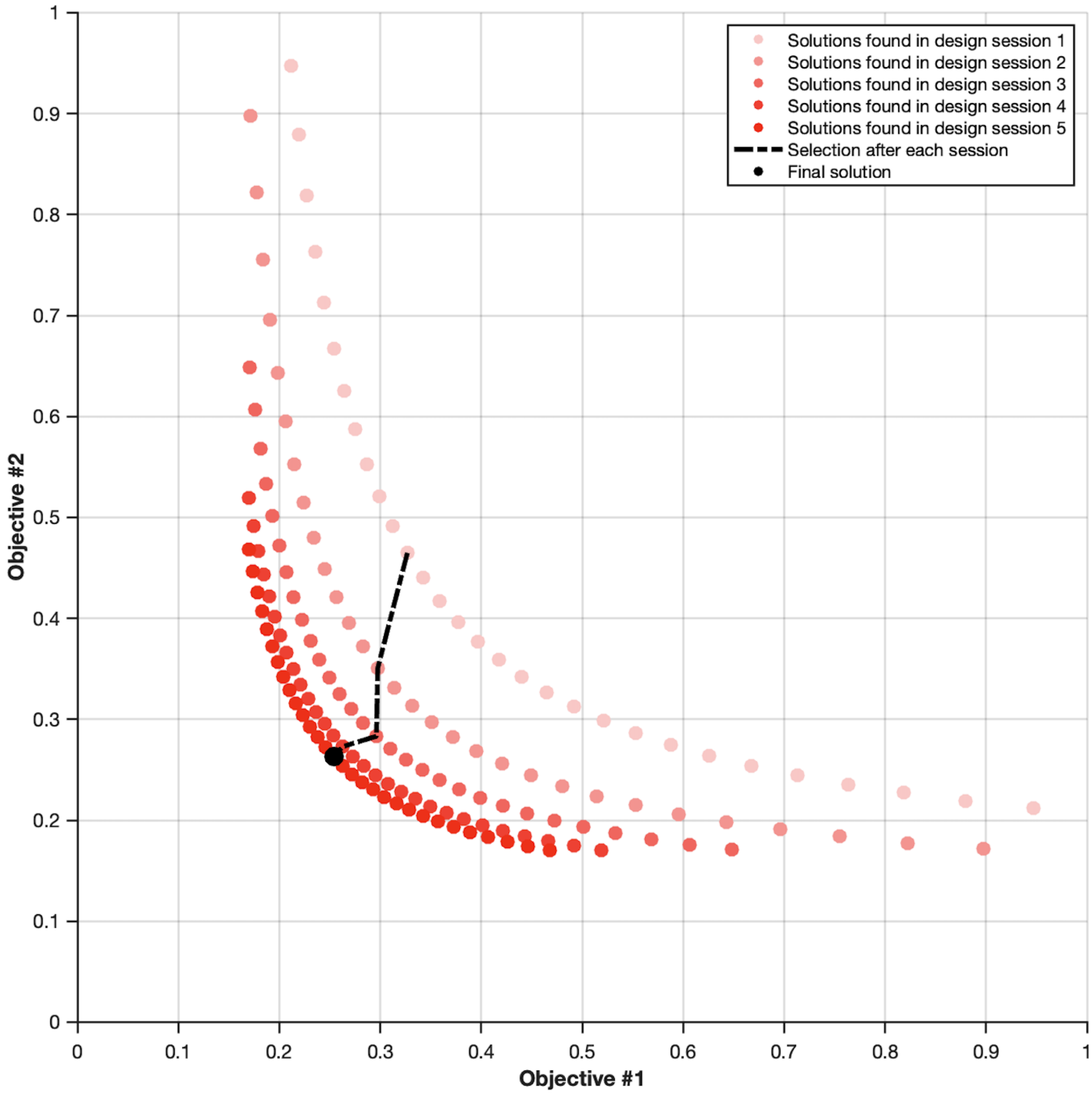

Figure 25: Illustration of the effect of concurrent engineering on the resulting system. At each session a set of solution is found and solutions converge towards the true pareto front through the sessions. Example where both objectives are cases of "the lower the better", i.e. utopia being the origin.

It is a practice that is getting more and more traction over the years, especially in very large technology firms for technology roadmapping (See figure 26, p.34) or mission planning, as it enables to produce feasible targets that are Pareto optimal. It also enables to perform optimisation in a way that is analogous to genetic algorithms but using humans directly as the "optimisation algorithm", also managing the communications between teams. It offers a similar result to fully automated Multidisciplinary Design Optimisation (MDO, see figure 25), but with reduced cost, reduced time, and reduced complicatedness, especially for very complex systems or even systems of systems. This is where ilities are integrated at the architecture level, and alternatives are assessed.

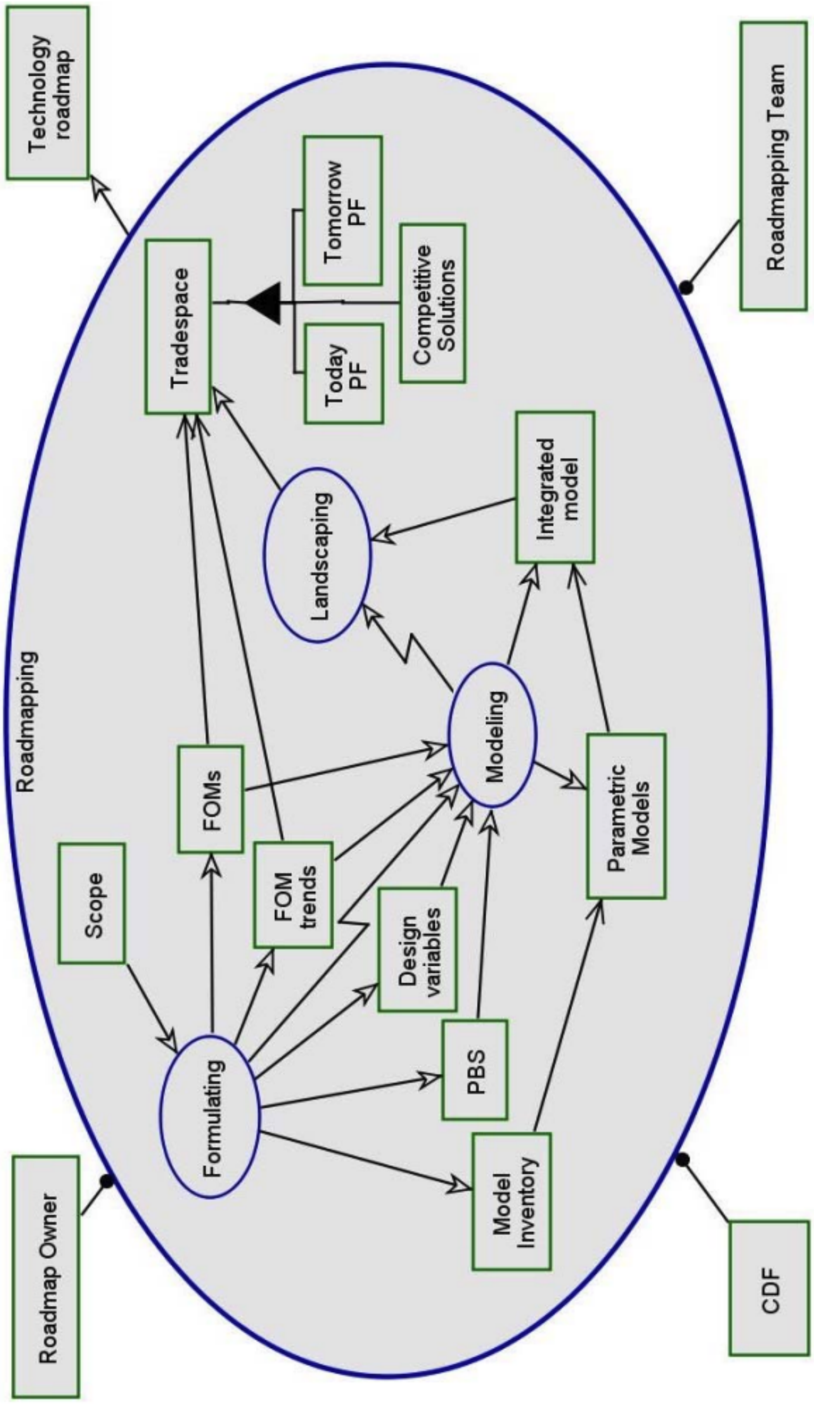

Figure 26: OPM model of the concurrent engineering process, adapted specifically to technology roadmapping. Figure from Knoll et al. [10].

3.6 Summary of a Sustainable Space System

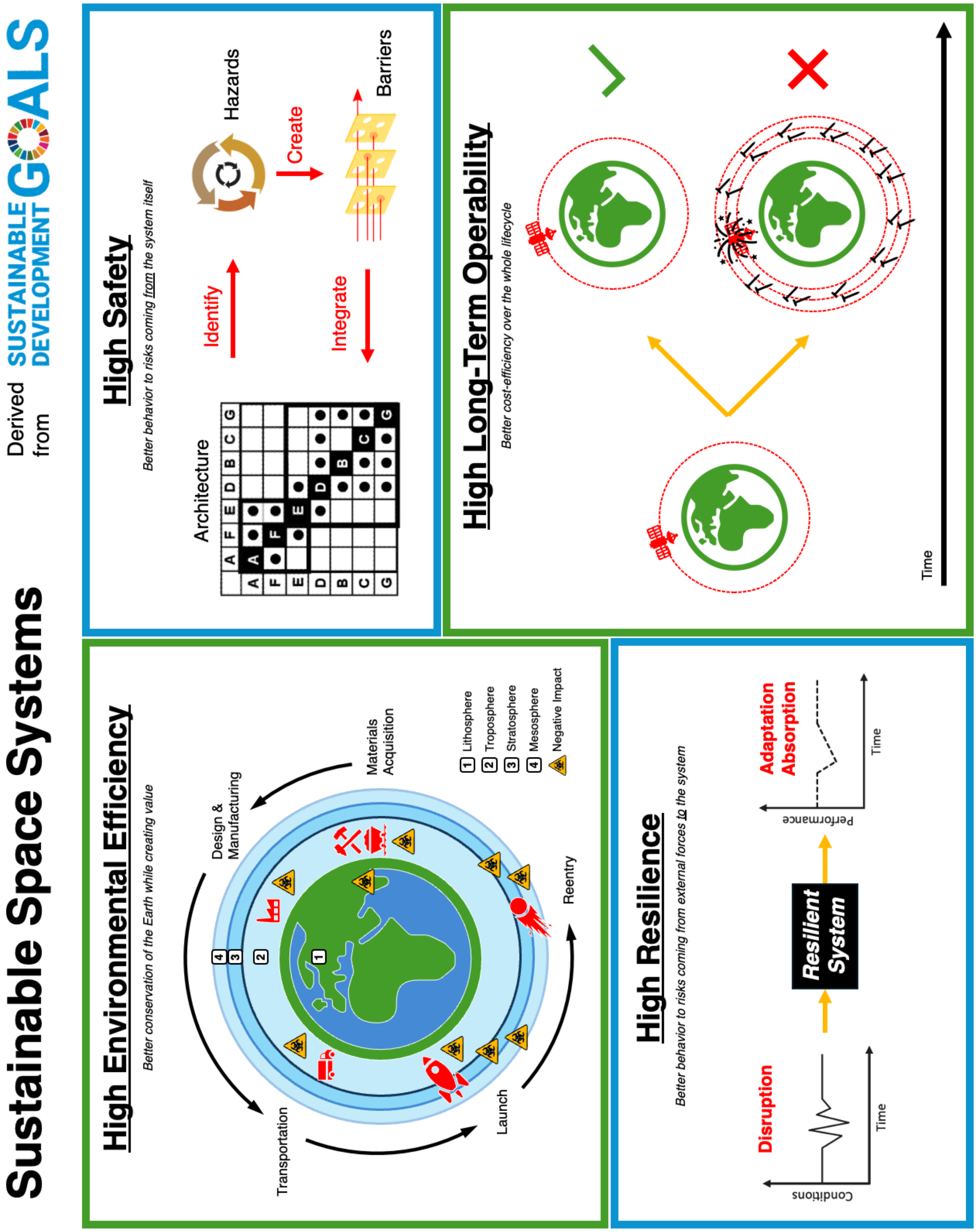

Figure 27: Summary of the state-of-the-art analysis of sustainable space systems. Own figure.

3.7 The Importance of Integrating Sustainability for Mission Concept Selection

At the very start of any space mission design, the concept is defined. Usually, this concept sets the high-level specifications of the mission, with the number of spacecrafts, their orbits, and the number of launches. There is no other parameter available at this point, but this decision already has an impact on the sustainability of the mission, if not the largest.

Indeed, high scale missions (e.g. mega constellations) represent a high risk of nocivity to the space environment and to Earth. In a context of *Old Space*, affordability was low and access to space mostly limited to a few spacecrafts and launches. However, as affordability increased drastically over the past few years, a transition into the *New Space Economy* is observed, enabling much larger scale missions and representing a possibility for less sustainable missions (See figure 28).

For that reason, it becomes critical to integrate criterias for sustainability directly at the mission concept selection and create tools for performing an effective trade-off with affordability (See figure 29, p.37), which was the only accounted objective to this date.

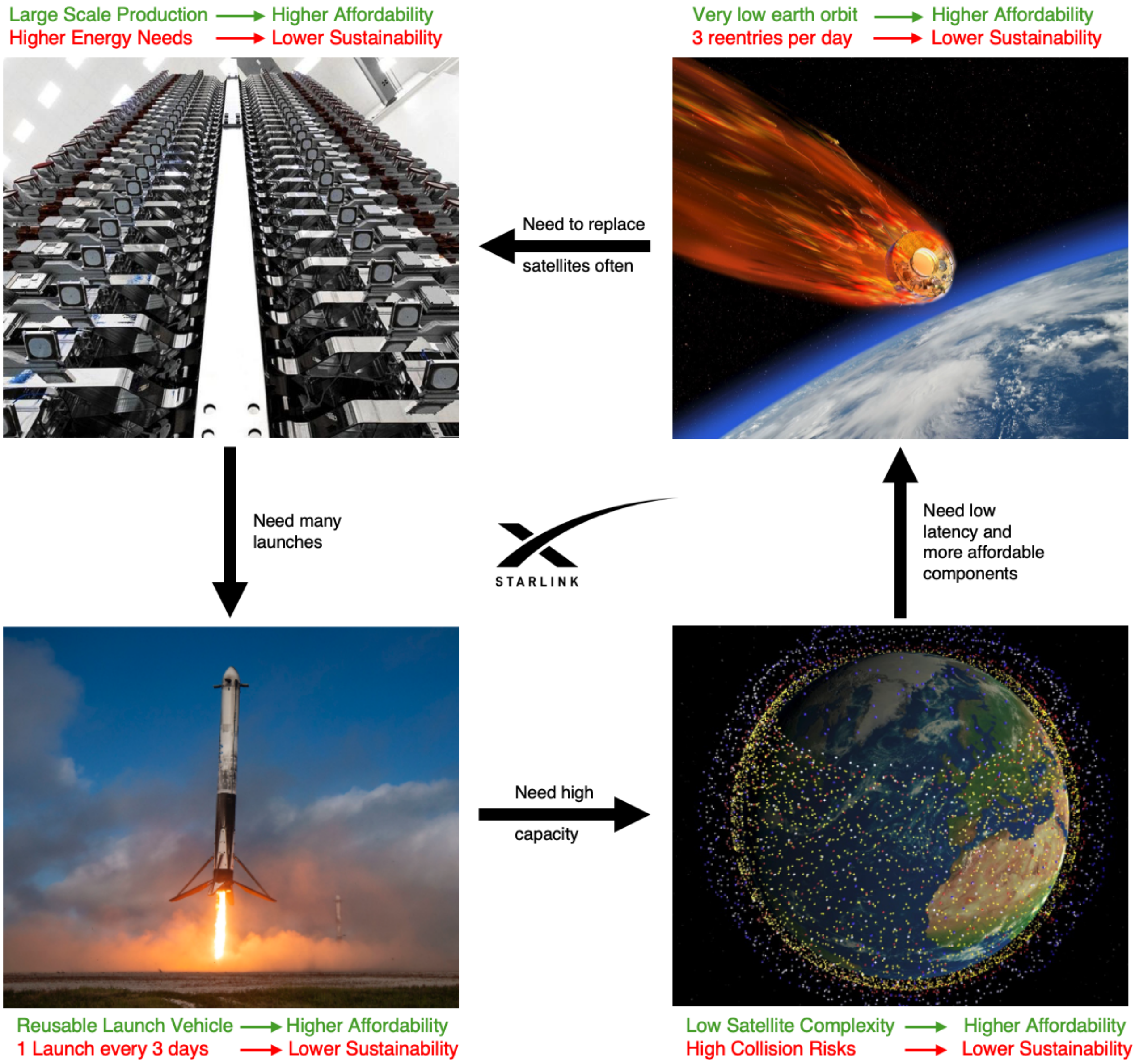

Figure 28: Case of the Starlink mega-constellation as an example of mission with high affordability but lower sustainability than old space mission due to scale. Own figure.

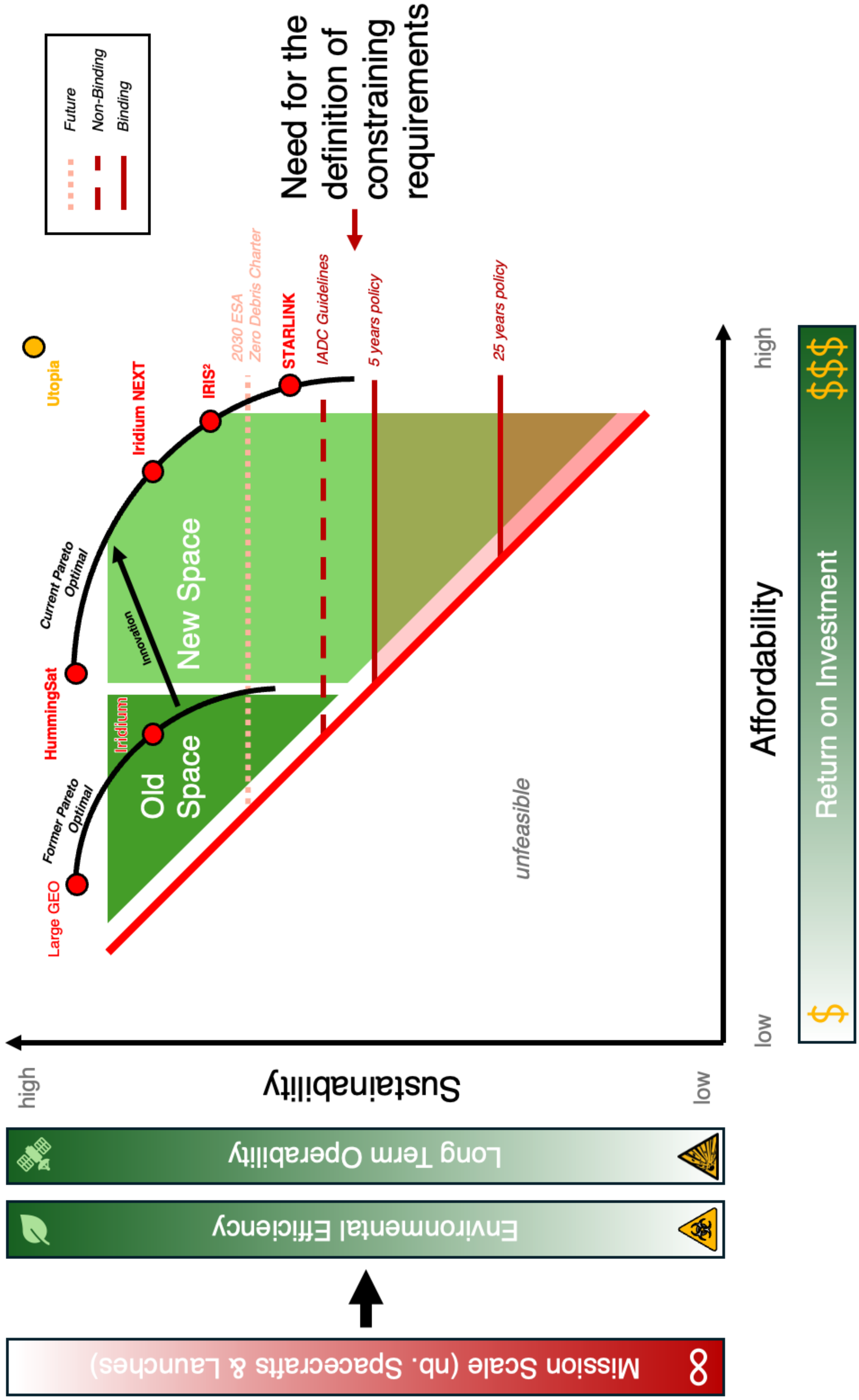

Figure 29: Qualitative representation of the trade-off between sustainability and affordability for the selection of a space mission concept, and the related transition from *Old Space* to *New Space Economy*. Own figure.

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4 System Requirements

We have now performed a comprehensive stakeholder analysis and we have an overview of the current State-of-the-Art. We can therefore initiate the system design phase, starting with the requirements. The system requirements are directly derived from the Stakeholder Value Network (See figure 11, p.19).

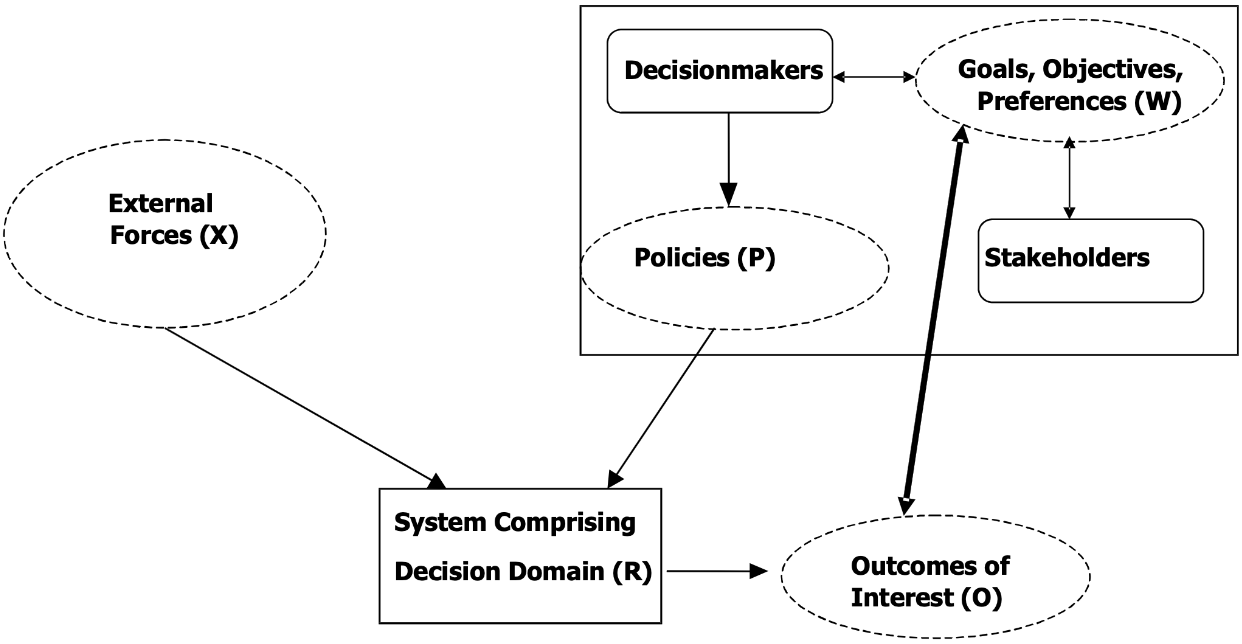

Figure 30: A framework for decision support. Figure from Marchau et al. [12].

The figure 30 provides the framework used in engineering systems design, and we can see that - indeed - the stakeholders play a crucial role and are a mandatory step to define relevant requirements. We will follow this framework, starting with the definition of the goals (W on the Figure) - also called stakeholder expectations, then we will be able to derive the Outcomes of Interest for our system (also often called Figures of Merit or Key Performance Indicators). Finally, with these Outcomes of Interest, we will define minimum acceptable values to constrain the system, which will serve as our requirements.

In addition to identifying the expectations of the different stakeholders to define meaningful requirements, the weights that we computed in the stakeholder analysis will play a very important role throughout the definition of the requirements. Indeed, the relative importance of the different stakeholders will be communicated along the different steps of the process to have weights applied of the Outcomes of Interest that are directly derived from the stakeholders' weights. These weights are especially important to make an informed decision when selecting the most suited trade-off (i.e. selection of a solution among Pareto Optimal solutions).

4.1 Goals, Objectives, Preferences

Now that we have identified the different stakeholders, how they interact with one another, and how important each community of stakeholders is, we can determine the expectations of each cluster. These expectations represent the first step in the definition of requirements and are crucial to make sure that the requirements cover all needs, to define the most possibly relevant tradespace.

Determining these goals is once again very qualitative by nature and is quite uncertain. A systematic approach is adopted, by iteratively filling the following:

Stakeholder Expectations Identification Template (From Maier et al. [11])

GOAL_XX: As a **(CLUSTER)**, I want **(GOAL)** so that **(REASON).**

Defining goals cluster-wise and not for individual stakeholders is much simpler and greatly reduces the probability of errors, which directly shows how valuable the clustering is in the stakeholder analysis process to effectively manage complexity. Applying this with the previously created SVN (See figure 11, p.19), the following list is created,

- *GOAL_01*: As a **member of the Cluster 1**, I want **a system that is pedagogically interesting** so that **it fits correctly in the master's degree**.
- *GOAL_02*: As a **member of the Cluster 1**, I want **a well documented system with clear decisions justification** so that **I can grade the project**.
- *GOAL_03*: As a **member of the Cluster 1**, I want **an applicable feedback/case study for the sustainability course** so that **I can improve the next iteration of the course**.
- *GOAL_04*: As a **member of the Cluster 2**, I want **a system ready to be tested and iterated upon at every design session of the course ENG-411** so that **I can have a real case study for the paper "Space Sustainability in Systems Engineering"**.
- *GOAL_05*: As a **member of the Cluster 2**, I want **a system that is modular and seemlessly integrable in the concurrent engineering process** so that **it can be integrated in the course ENG-411 with the lowest risk of overall failure**.
- *GOAL_06*: As a **member of the Cluster 2**, I want **a system that is comprehensive** so that **multiple points can be simultaneously studied and I can get an overview on what performs better**.
- *GOAL_07*: As a **member of the Cluster 2**, I want **a system that is adaptive** so that **it can integrate the feedback of a design session for the next one and continuously improve**.
- *GOAL_08*: As a **member of the Cluster 2**, I want **a system that is flexible** so that **it can avoid hazards or take profit of opportunities that arise during a design session**.
- *GOAL_09*: As a **member of the Cluster 3**, I want **to gain insight on how to design safer and more resilient SATCOM systems** so that **I can ensure the integrity of Mission Critical Communications**.
- *GOAL_10*: As a **member of the Cluster 3**, I want **to gain insight on new trends for satellites design processes** so that **I can design a more competitive system**.
- *GOAL_11*: As a **member of the Cluster 4**, I want **a system that is the easiest to integrate in my current design processes** so that **I can integrate it despite the constraints that my nature imposes**.
- *GOAL_12*: As a **member of the Cluster 5**, I want **an innovative system** so that **I can improve my current processes**.
- *GOAL_13*: As a **member of the Cluster 5**, I want **a system that is highly modular** so that **it is as simple as possible to integrate it into my complex structure**.
- *GOAL_14*: As a **member of the Cluster 5**, I want **a set of multiple solutions that offer different trade-offs** so that **select the one that corresponds the best to my needs**.

Using the weights of the different clusters, that are derived from the model used in the stakeholder analysis, we can infer the ones of the goals. To this end, we will simply allocate the weight of each cluster among its respective goals. For some cases, like the Cluster 3, where the cluster is small and the goals obviously reflect the objectives of individual stakeholder, we will allocate the weights that we computed for the individual stakeholders of the cluster. Moreover, certain goals are extremely similar, hence they are merged, with a new index. The goals that are merged into one are:

- **GOAL_15**, composed of:
  - *GOAL_01*
  - *GOAL_02*
  - *GOAL_03*
- **GOAL_16**, composed of:
  - *GOAL_05*
  - *GOAL_11*
  - *GOAL_13*
- **GOAL_17**, composed of:
  - *GOAL_10*
  - *GOAL_12*
- **GOAL_18**, composed of:
  - *GOAL_06*
  - *GOAL_09*
  - *GOAL_14*

Hence we obtain the following weights allocation (See figure 31), and merging the similar goals together, we get the simplified set (See figure 32, p.42).

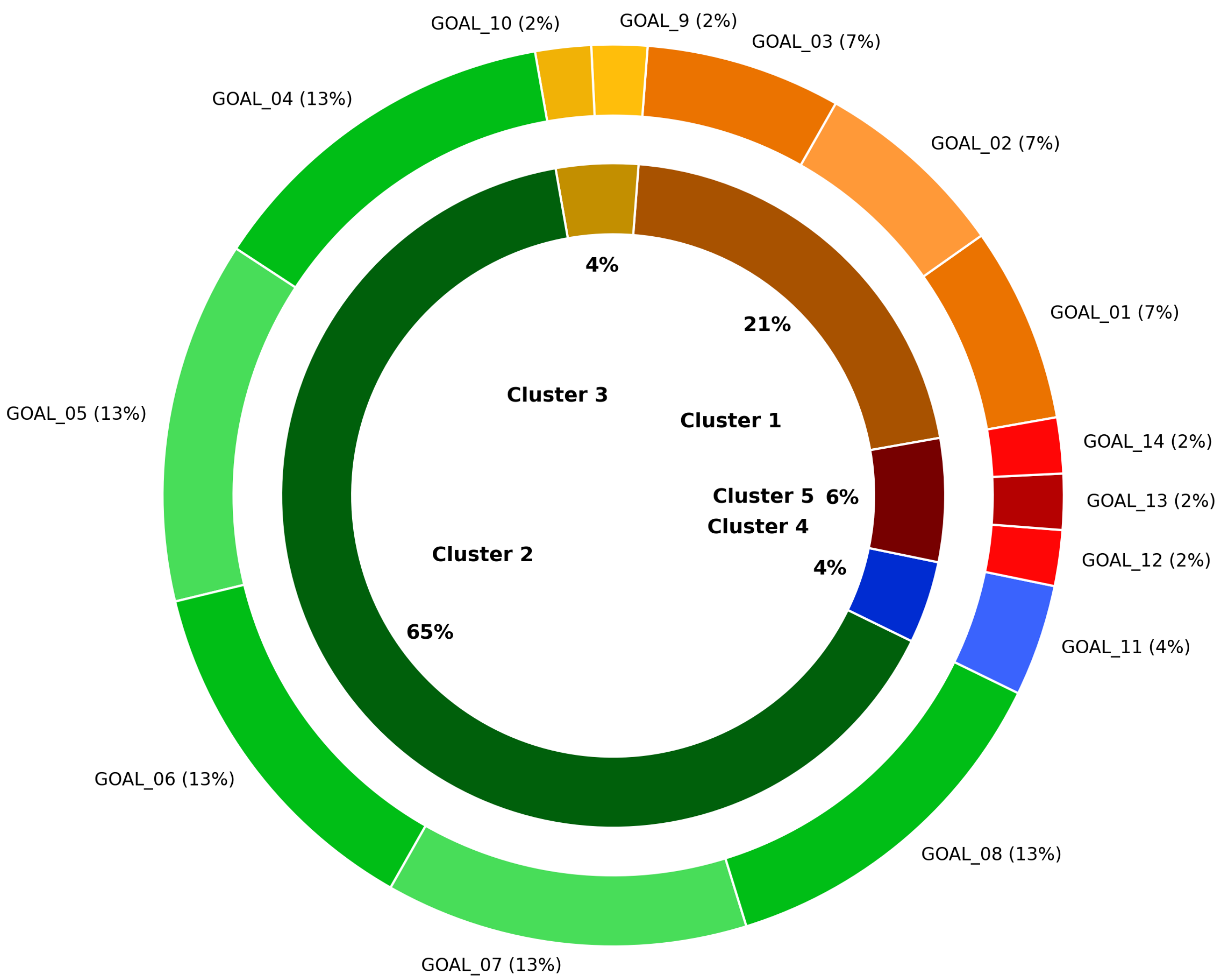

Figure 31: Weights of the goals, with their assigned stakeholders or clusters. Similar colors indicating parent-child relationships. Own figure.

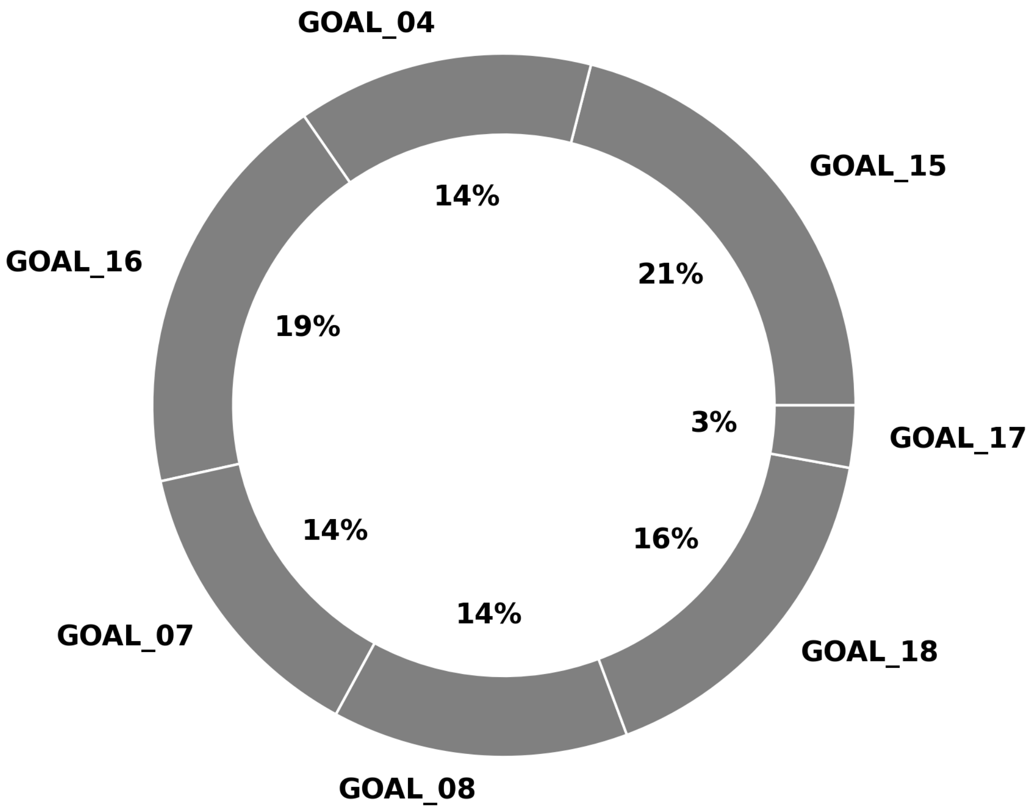

Figure 32: Weights of the compact set of goals. Own figure.

4.2 Outcomes of Interest

From the goals that were previously defined, we want to create a list of Outcomes of Interest (OOI). These OOIs will serve as the basis for the definition of the requirements and are therefore themselves constrained by a few requirements:

- **REQ_OOI_1:** The Outcomes of Interest should be assigned to a SI unit or currency if cost.
- **REQ_OOI_2:** A scoring system with a clear rationale shall be provided if the OOI is not assigned to a SI unit or currency.
- **REQ_OOI_3:** The OOI shall be a child of at least one GOAL.
- **REQ_OOI_4:** If a unit is provided, the calculation/measurement method shall be specified.
- **REQ_OOI_5:** The boundaries of feasible values shall be specified, with an upper bound and a lower bound.
- **REQ_OOI_6:** The optimisation type shall be specified, i.e. maximisation or minimisation.

From these requirements we can use the following template to be compliant,

Outcomes of Interest Definition Template

- **OOI_XX: XXX**
  - Unit: $[X]$
  - Parent goal(s): GOAL_XX
  - Calculation method: XXX
  - Upper bound: XXX
  - Lower bound: XXX
  - Optimisation type: XXX
  - Explanation: XXX. (If applicable) The rationale is given by:
    - **100%:** *XXX*
    - **66%:** *XXX*
    - **33%:** *XXX*
    - **0%:** *XXX*

Finally, we can derive the following Outcomes of Interest for our system,

- **OOI_01: System readiness**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_04
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: This OOI aims to evaluate at what point the system is ready for operation at the start of the design session. The rationale is given by:
    - **100%:** *The system was immediately ready for operations without any changes required before the start of the session. Seemless integration with the concurrent engineering software.*
    - **66%:** *A few changes were needed at the start of the session before being able to operate. Under 10 minutes of preparation.*
    - **33%:** *Many changes were needed at the start of the session before being able to operate. Over 10 minutes of preparation.*
    - **0%:** *Impossible to operate the system, system not ready.*

- **OOI_02: System adaptibility**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_07
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: This OOI aims at measuring how much the system is capable of being adapted from a session to the next. To assess this, we qualitatively evaluate how much "effort" (Time + Complicatedness) was needed to adapt the system and integrate the feedback from the previous design session. The rationale is given by:
    * **100%:** *The identified issues were solved very rapidly with very low effort.*
    * **66%:** *It was either time consuming or hard to adapt the system to correct the identified issues.*
    * **33%:** *It was very time consuming and hard to adapt the system to correct the identified issues.*
    * **0%:** *The system could not be adapted before the next design session.*
- **OOI_03: System flexibility via safety measures**
  - Unit: $[-]$ (Unitless, index)
  - Parent goal(s): GOAL_08
  - Calculation method: Ratio of protected hazards and identified hazards
  - Upper bound: 1
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: This OOI aims at capturing how flexible the system was during the design sessions, whether it was able to perform with the dynamics that are brought by concurrent engineering. Flexibility is correlated with safety (See figure 18, p.27) and we know how to measure safety, therefore we will use it to assess a part of this property. It is computed as the ratio of the hazards for which we have set measures, and the number of identified hazards. The number of identified hazards will increase with design sessions, hence the safety index of early iterations will get lower, and we use the equation,
  $$\frac{\text{Number of mitigated hazards}}{\text{Number of identified hazards}} \tag{5}$$
- **OOI_04: System flexibility via modular design**
  - Unit: $[-]$ (Unitless, index)
  - Parent goal(s): GOAL_08
  - Calculation method: SMI [9]
  - Upper bound: 1
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: This OOI is serving the same objective as OOI_03. To increase the chances of capturing the flexibility property of the system, we measure another correlated ility (See figure 18, p.27) that we can quantitatively measure, i.e. modularity. Here we will compute it using the Singular value Modularity Index, from De Weck [9].
- **OOI_05: Documentation comprehensiveness**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_15
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: This OOI intends to represent how complete the documentation of the system at each design session is. The rationale is given by:
    * **100%:** *A full documentation of the system before the design session is provided, with complete formatting. A full feedback form is filled after the design session to keep track of the events and failures that arised in operation.*
    * **66%:** *Most of the documentation exists, but the formatting is precarious and some information are missing, it is not perfectly clear. The feedback is not totally formatted, it is not perfectly clear.*
    * **33%:** *Only a concept of the system is provided, the feedback documentation is very lacunar.*
    * **0%:** *No documentation nor any trace of feedback.*

- **OOI_06: System modularity**
  - Unit: $[-]$ (Unitless, index)
  - Parent goal(s): GOAL_16
  - Calculation method: SMI [9]
  - Upper bound: 1
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: We want to capture the modularity of the system, which is given by the Singular value Modularity Index from De Weck [9].
- **OOI_07: System's DSM sparsity**
  - Unit: $[-]$ (Unitless, index)
  - Parent goal(s): GOAL_16
  - Calculation method: NZF [9]
  - Upper bound: 0.5
  - Lower bound: 0
  - Optimisation type: Minimisation
  - Explanation: We add a second metric for the modularity of the system, which measure the sparsity of the DSM through the Non-Zero Factor from De Weck [9]. This second metric is added to capture a possible "bus-modular" architecture as having a higher merit than "integral", and therefore penalise it less.
- **OOI_08: Innovation**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_17
  - Calculation method: Comparison with State-of-the-Art
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: We desire a system that is innovative, which is itself defined by being more advanced than the State-of-the-Art in the applicable subject. From the State-of-the-Art analysis that was performed and the interviews with the relevant stakeholders, we are able to qualitatively assess how innovative the system is. The rationale is given by:
    * **100%:** *More advanced than the State-of-the-Art level.*
    * **66%:** *At the State-of-the-Art level.*
    * **33%:** *Lower than the State-of-the-Art level.*
    * **0%:** *System fail, no operation.*
- **OOI_09: System comprehensiveness - Integration of environmental impact**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_18
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: We defined sustainable space systems with 4 main characteristics, with one being a low environmental impact. Therefore to measure the comprehensiveness of the system, we want to ensure that we cover the 4 characteristics, and here we measure how much we are covering the environmental impact. The rationale is given by:
    * **100%:** *The environmental impact is fully covered and a positive impact can be observed.*
    * **66%:** *The environmental impact is covered but no major positive impact can be observed.*
    * **33%:** *The environmental impact is mentioned but very partially covered.*
    * **0%:** *The environmental impact is not mentioned.*

- **OOI_10: System comprehensiveness - Integration of long-term operability**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_18
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: Following the path of the OOI_09, we are covering long-term operability. The rationale is given by:
    * **100%:** *The long-term operability is fully covered and a positive impact can be observed.*
    * **66%:** *The long-term operability is covered but no major positive impact can be observed.*
    * **33%:** *The long-term operability is mentioned but very partially covered.*
    * **0%:** *The long-term operability is not mentioned.*
- **OOI_11: System comprehensiveness - Integration of resilience**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_18
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: Following the path of the OOI_09, we are covering resilience. The rationale is given by:
    * **100%:** *Resilience is fully covered and a positive impact can be observed.*
    * **66%:** *Resilience is covered but no major positive impact can be observed.*
    * **33%:** *Resilience is mentioned but very partially covered.*
    * **0%:** *Resilience is not mentioned.*
- **OOI_12: System comprehensiveness - Integration of safety**
  - Unit: Percentage based on rationale
  - Parent goal(s): GOAL_18
  - Calculation method: Observation
  - Upper bound: 100
  - Lower bound: 0
  - Optimisation type: Maximisation
  - Explanation: Following the path of the OOI_09, we are covering safety. The rationale is given by:
    * **100%:** *Safety is fully covered and a positive impact can be observed.*
    * **66%:** *Safety is covered but no major positive impact can be observed.*
    * **33%:** *Safety is mentioned but very partially covered.*
    * **0%:** *Safety is not mentioned.*

We have a redundant OOI for modularity (OOI_04 and OOI_06), therefore we merge it into one (OOI_13). Using the same method as for the definition of the goals' weights, we obtain the OOIs' weights (See figure 33, p.47).

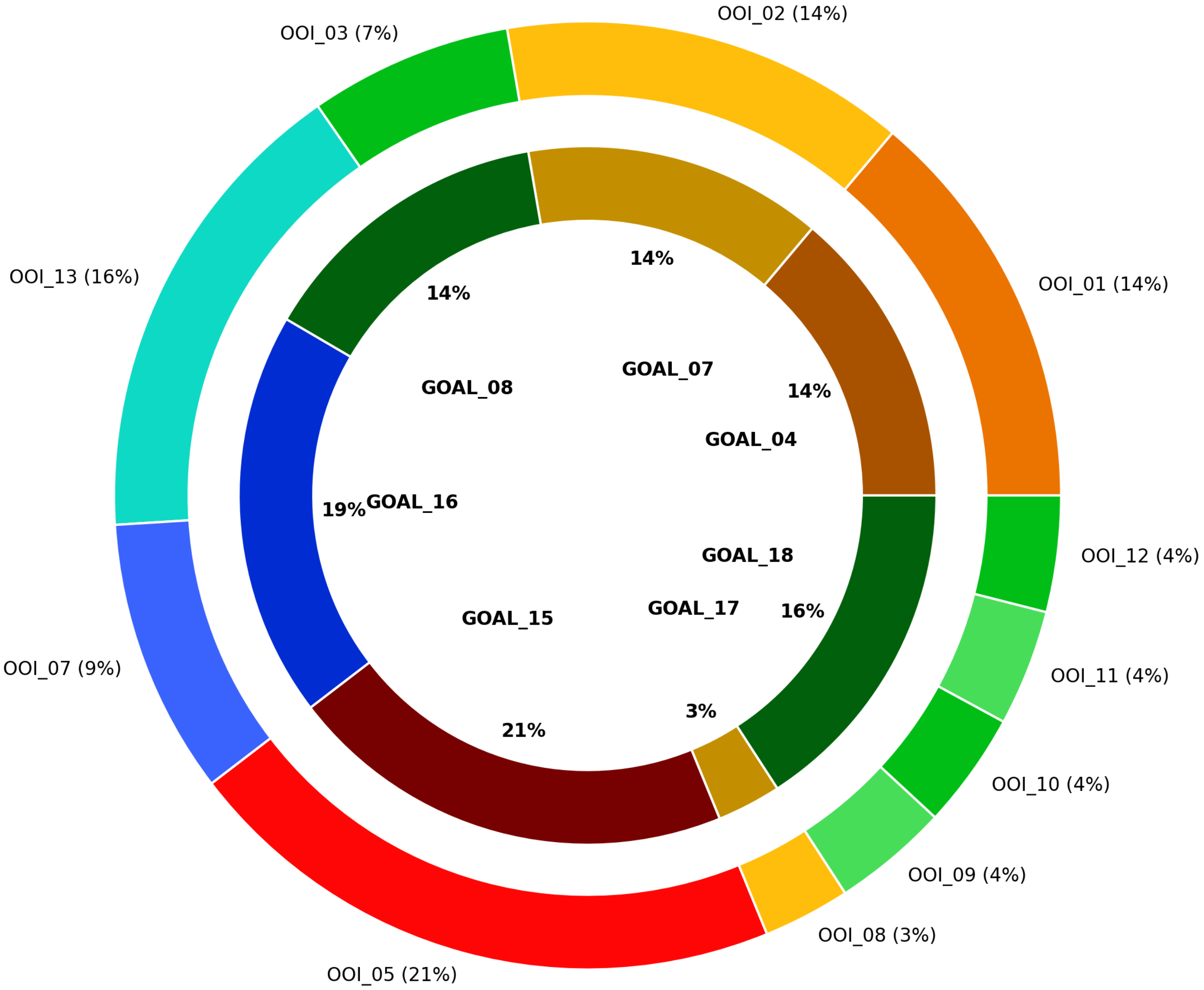

Figure 33: Weights of the Outcomes of Interest, with their assigned goals. Similar colors indicating parent-child relationships, with OOI_13 belonging to 2 different goals. Own figure.

4.3 Requirements List

Using the previously defined Outcomes of Interest, we can set targets to reach by the end of the project, which sets our requirements list. Most of these are set as reference targets to make sure that all Outcomes of Interest are covered and reach an acceptable state, but the higher the better. Also, some OOIs like modularity are not present in the requirements (or at least not with the same definition) because it would not be reasonable to specify quantitative targets on these. Indeed, if we take the example of modularity, a tradespace should be defined to determine the different alternatives that we have and the best performance of each architecture, but this could be an entire project on its own, hence we will simply define a baseline architecture that seems acceptable based on past experience, quantify its modularity and then move directly to the subsystems specification.

- **REQ_01:** System readiness
  - **Parent Outcome of Interest:** OOI_01
  - **Description:** The system shall have a final readiness level of 100%, enabling Off-The-Shelf integration in the concurrent engineering process for the design of space missions.
- **REQ_02:** System flexibility via safety measures
  - **Parent Outcome of Interest:** OOI_03
  - **Description:** All the identified hazards shall have an associated mitigation.
- **REQ_03:** System modularity
  - **Parent Outcome of Interest:** OOI_13
  - **Description:** The system's modules shall be specified using a Newman Eigenvectors method applied on the DSM of the system architecture.
- **REQ_04:** Documentation comprehensiveness
  - **Parent Outcome of Interest:** OOI_05
  - **Description:** The final documentation comprehensiveness shall be 100%.
- **REQ_05:** Innovation
  - **Parent Outcome of Interest:** OOI_08
  - **Description:** The system shall have a final innovation score of at least 66%.
- **REQ_06:** System comprehensiveness - Environmental impact
  - **Parent Outcome of Interest:** OOI_09
  - **Description:** The final score for the integration of environmental impact shall be 100%.
- **REQ_07:** System comprehensiveness - Operability
  - **Parent Outcome of Interest:** OOI_10
  - **Description:** The final score for the integration of operability shall be 100%.
- **REQ_08:** System comprehensiveness - Resilience
  - **Parent Outcome of Interest:** OOI_11
  - **Description:** The final score for the integration of resilience shall be at least 66%.
- **REQ_09:** System comprehensiveness - Safety
  - **Parent Outcome of Interest:** OOI_12
  - **Description:** The final score for the integration of safety shall be at least 66%.

4.4 Summary of Objectives Definition

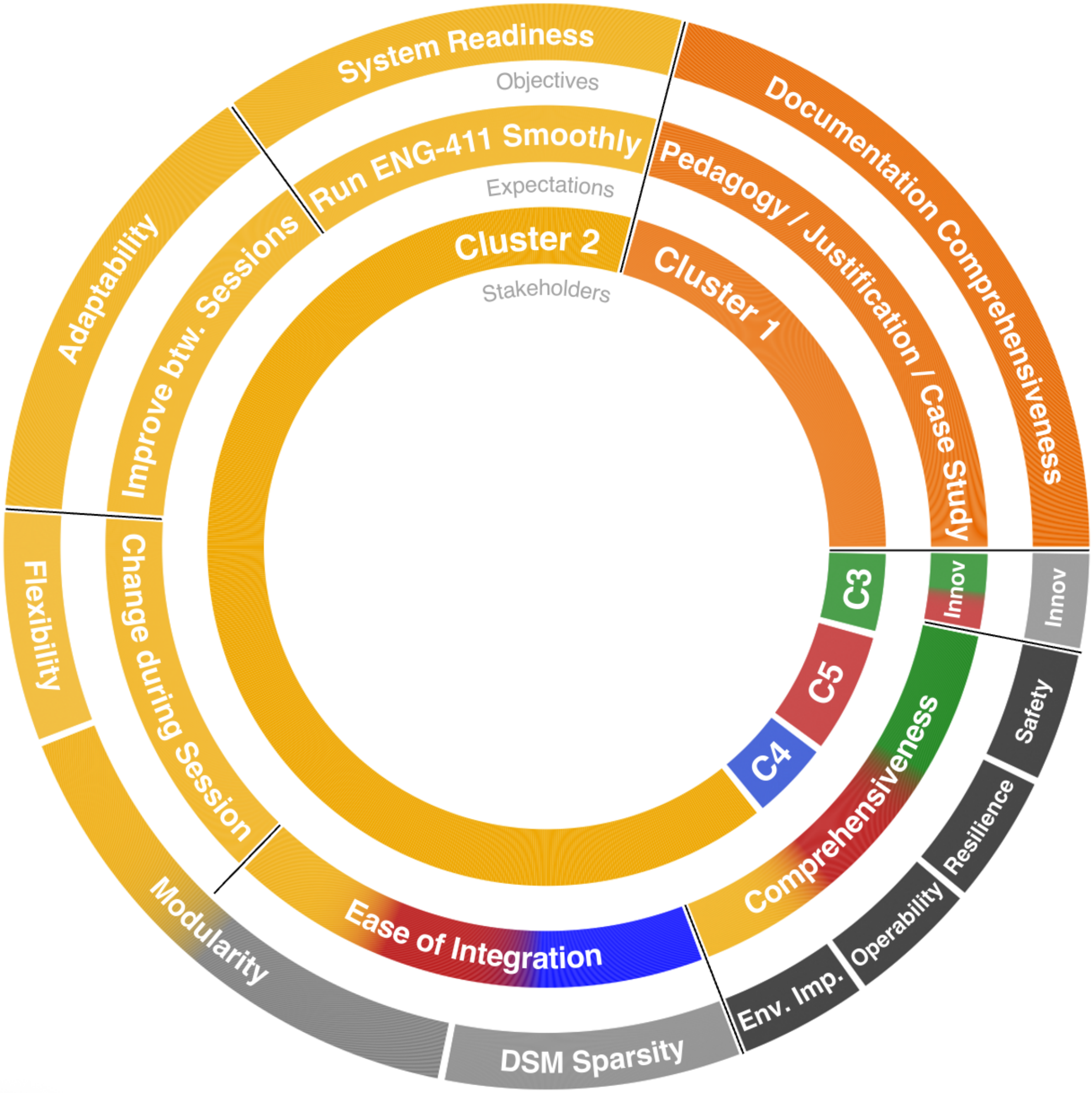

Figure 34: Relationships between the stakeholder analysis results and the final objectives set.

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5 System Architecture

In this section, we are going to establish the architecture of the system. This step consists in defining components and interfaces in a way that integrates desired ilities in the system. These ilities, previously defined in the objectives (See figure 34, p.49), ensure compliance with the stakeholder expectations. This section will mostly focus on modularity and DSM-based architecture assessment to effectively manage complexity, and other ilities like flexibility will be integrated in further steps. The reason for a delayed integration of flexibility or adaptability is that design sessions will enable an iterative identification of failure points and a better definition of mitigations, whereas modularity is frozen early on for simplicity purposes.

Before the integration of modularity, we will define the components with a functional decomposition to make sure that the core function of the system is integrated. Then a conceptual model will enable the definition of the interfaces and the creation of the DSM for modularity assessment. Ultimately, a Multi-Domain Matrix of the system will represent the levels of decomposition with component to subsystem and function to component relationships, ensuring an effective management of complexity.

5.1 Components Definition

The first step in the creation of the system architecture is the definition of the components. At this point, we need to ensure that all the required functions are fulfilled by the different components in order to allow compliance with the system requirements. We will therefore start by identifying the different functions of the system, and then use a domain mapping matrix to show that all functions are covered.

5.1.1 Functional Decomposition

Concurrent engineering is all about continuous information loops that make the system converge towards a desirable state. Hence it is critical to design a system that integrates into the existing information network, and create interfaces with other subsystems that will naturally add a sustainability objective to the set for the overall system. We also want to define components that make the system comprehensive (See figure 34, p.49), i.e. that serve all the different characteristics of a sustainable space system (See figure 27, p.35). Hence we have the following functions:

1. Evaluate the overall sustainability of the mission.
2. Evaluate the environmental impact of the mission.
3. Ensure the long term operability of the space environment.
4. Assess the safety of the mission.
5. Assess the resilience of the mission.

5.1.2 Functions to Components Domain Mapping Matrix

Now that we have identified the different functions that our system needs to fulfill, we can define the components to enable it:

- High-level life-cycle assessment
- Trade-off analysis for launcher selection
- External forces analysis
- System analysis for hazards identification
- Real Options Analysis for End-of-Life strategy
- Weighted sum for mission sustainability score

We can observe on the following domain mapping matrix (See figure 35, p.52) that all the functions are covered by the components that we defined, hence the system's functionality is partially ensured. It is important to note that the condition of having at least one component per function is not sufficient and requires an additional qualitative assessment. For instance the condition would be met by having the weighted sum alone, but since it requires the outputs from the others, it cannot be alone. It is similar for the LCA that needs to be accompanied by the assessment of the launcher in order to cover all aspects of the operations on Earth, although they both have the same function (the difference is the scope).

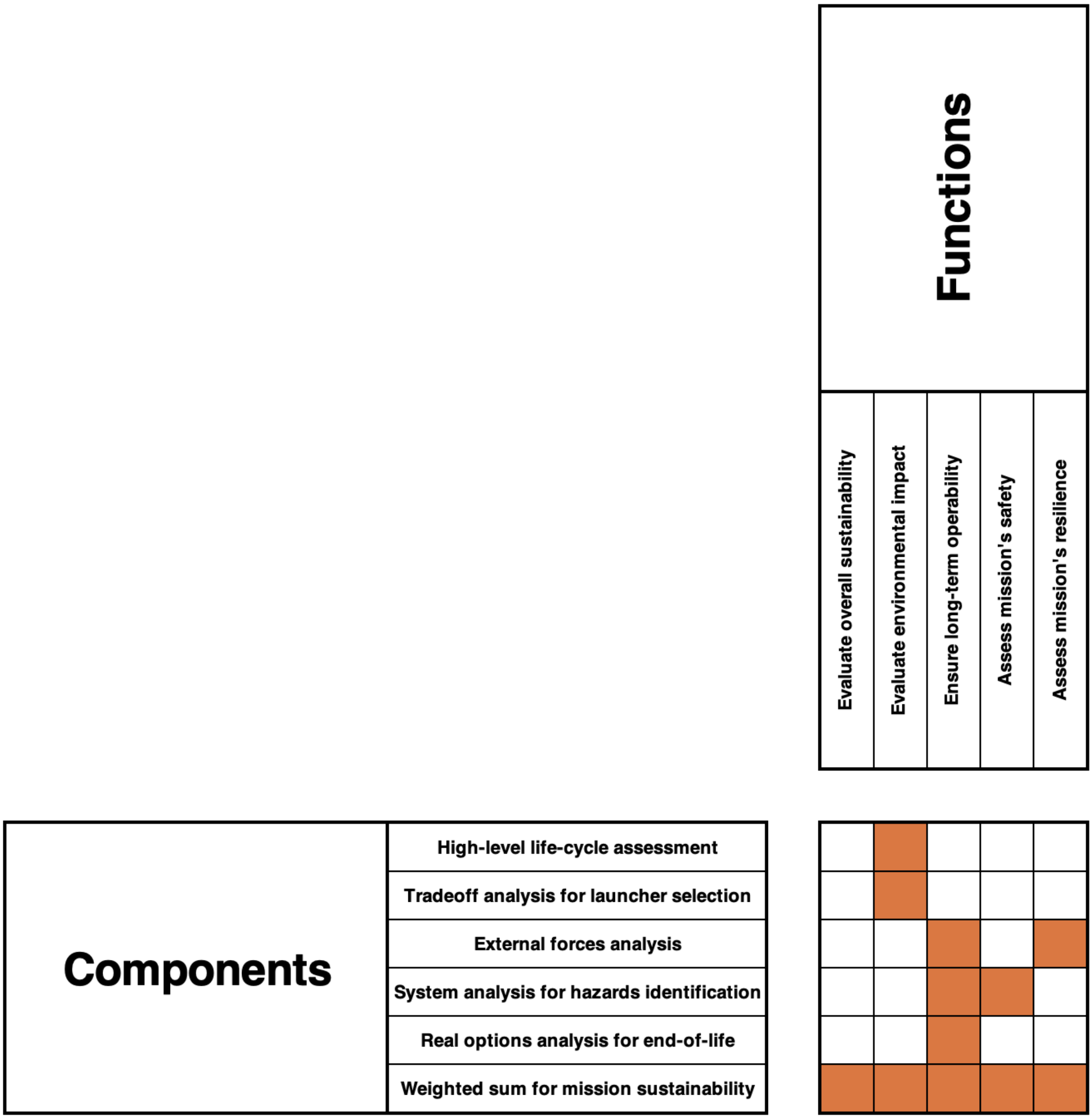


Figure 35: Domain Mapping Matrix from the domain of functions and the domain of components. All functions being related to at least one component partially ensures system functionality.

5.2 Conceptual Model

Now that we have defined the components of the system, we can establish the interfaces and derive the conceptual model. Now we want to define other roles of the CDF with which interfaces exist. Here we want to have the minimum amount of them while still maintaining a reasonable quality, to make the role as modular as possible in the concurrent engineering process, and to reduce the complexity of the sustainability role.

5.2.1 Mass Contribution Breakdown for Complexity Reduction

In the requirements for the system, we have a one for sparsity and another for modularity, hence we want to design a system with independent processes and also minimise the interfaces with others to manage complexity efficiently. The Life-Cycle Assessment is clearly the component that is critical here. Indeed, creating interfaces with all the subsystems would increase the accuracy of the results but then it would also make it very complex in terms of communications and the analysis would get increasingly complex. Hence we want to identify the principal mass components to reduce the complexity while maintaining a reasonable amount of accuracy.

The figure 36 shows us that 3 components take more than 80% of the satellite's mass. This percentage increases even more when having missions at higher altitudes than LEO. Hence it seems that simplifying the LCA to only take into account power, structure, and propellant is a reasonable reduction in complexity while keeping a high level of accuracy. This analysis is viable because most LCA outcomes are normalised by the mass and no major differences in orders of magnitudes are noticeable for the discarded subsystems.

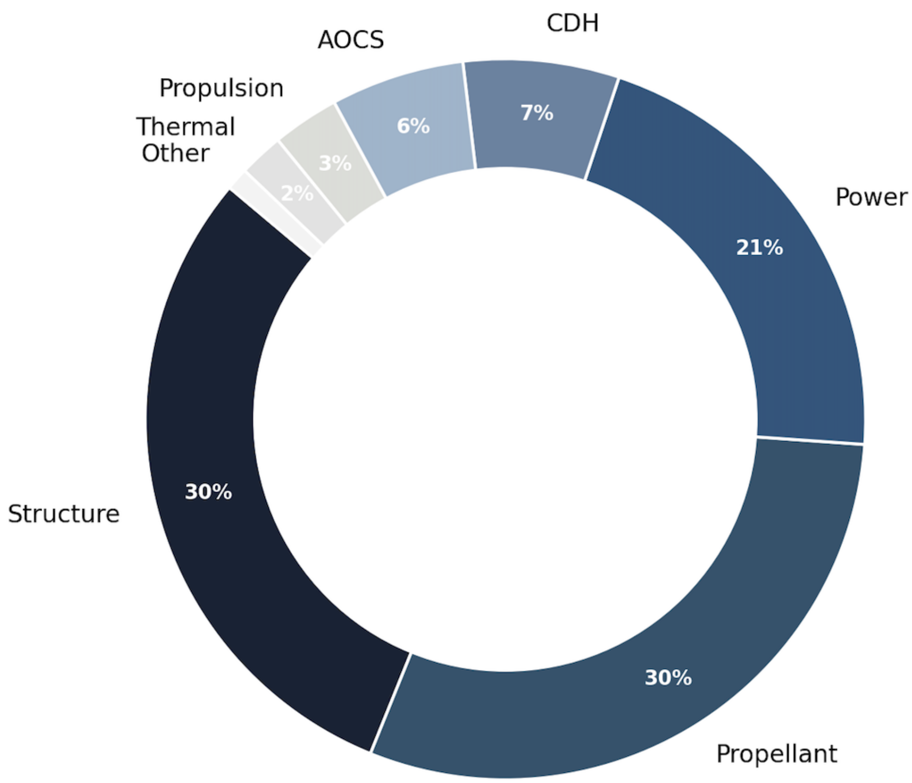


Figure 36: Typical mass allocation between subsystems in a satellite (LEO) (Data from Delessert [4]). Note that for higher altitudes, the main change that can be observed is a large increase of propellant mass.

Using this mass allocation as reference, we can define the following parameters as the most important:

- Solar panel area
- Solar panel technology
- Structure main material(s)
- Structure mass
- Propellant type
- Propellant mass
- Battery type
- Battery mass

5.2.2 Object-Process Model

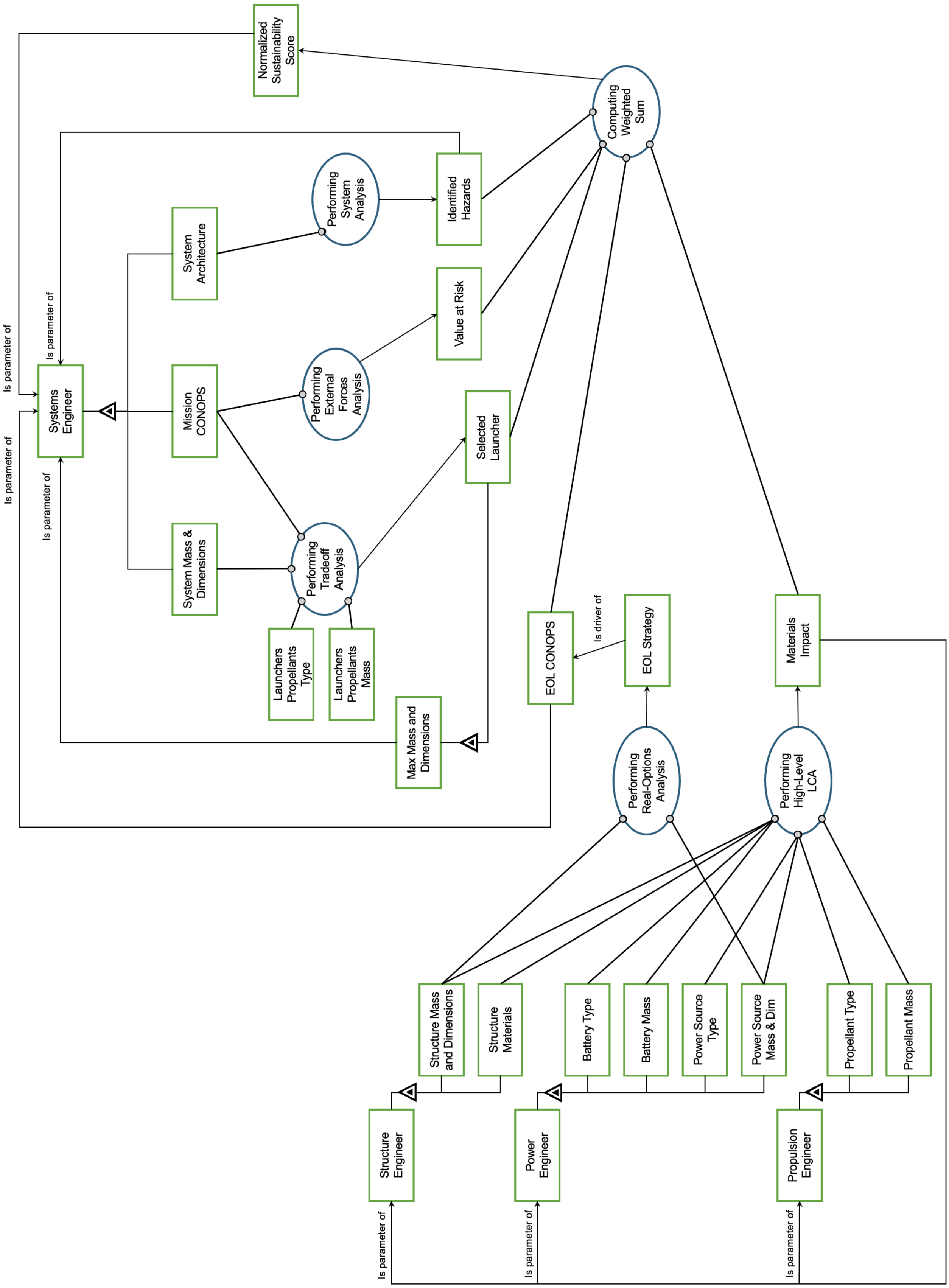


Figure 37: Conceptual Model of the System. Compliant with ISO 19450:2024 for OPM, see appendix B.

5.3 Architecture Modeling

Now that we have established the conceptual model of the system, we want to evaluate the architecture to verify the modularity and efficiently manage complexity. In order to quantitatively assess the architecture, we need to translate the previous OPM (See figure 37, p.54) into a Design Structure Matrix, which will allow to perform network analysis techniques. The following DSM (See figure 38) shows the adjacency matrix form of the system.

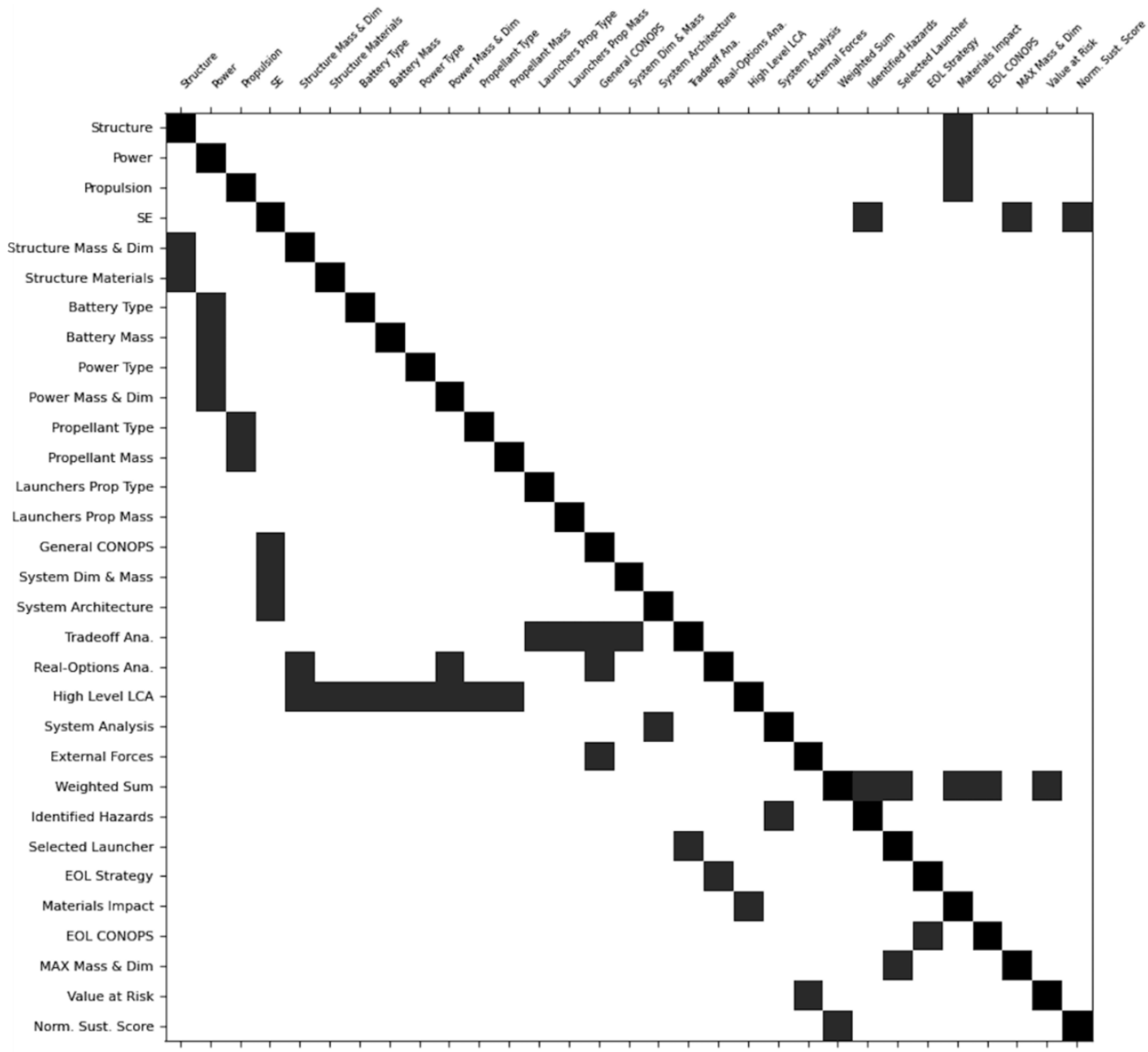


Figure 38: Design Structure Matrix of the system. Own figure.

5.4 Architecture Modularisation

We now have a form of the system that enables to apply network analysis. Here we want to objectively identify the modules of the system. To this end, we will apply the Newman Eigenvectors method [15] for spectral clustering of the DSM. Before applying the method, we need to symmetrise the matrix, because spectral clustering is much more stable and robust on symmetric matrices. Indeed, small perturbations in a very non-symmetric matrix can cause large shifts in eigenvectors, which is our case. Hence we simply apply the equation 6 and use the following symmetric DSM (See figure 39) for further analysis.

$$DSM_{sym} = DSM + DSM^T \tag{6}$$

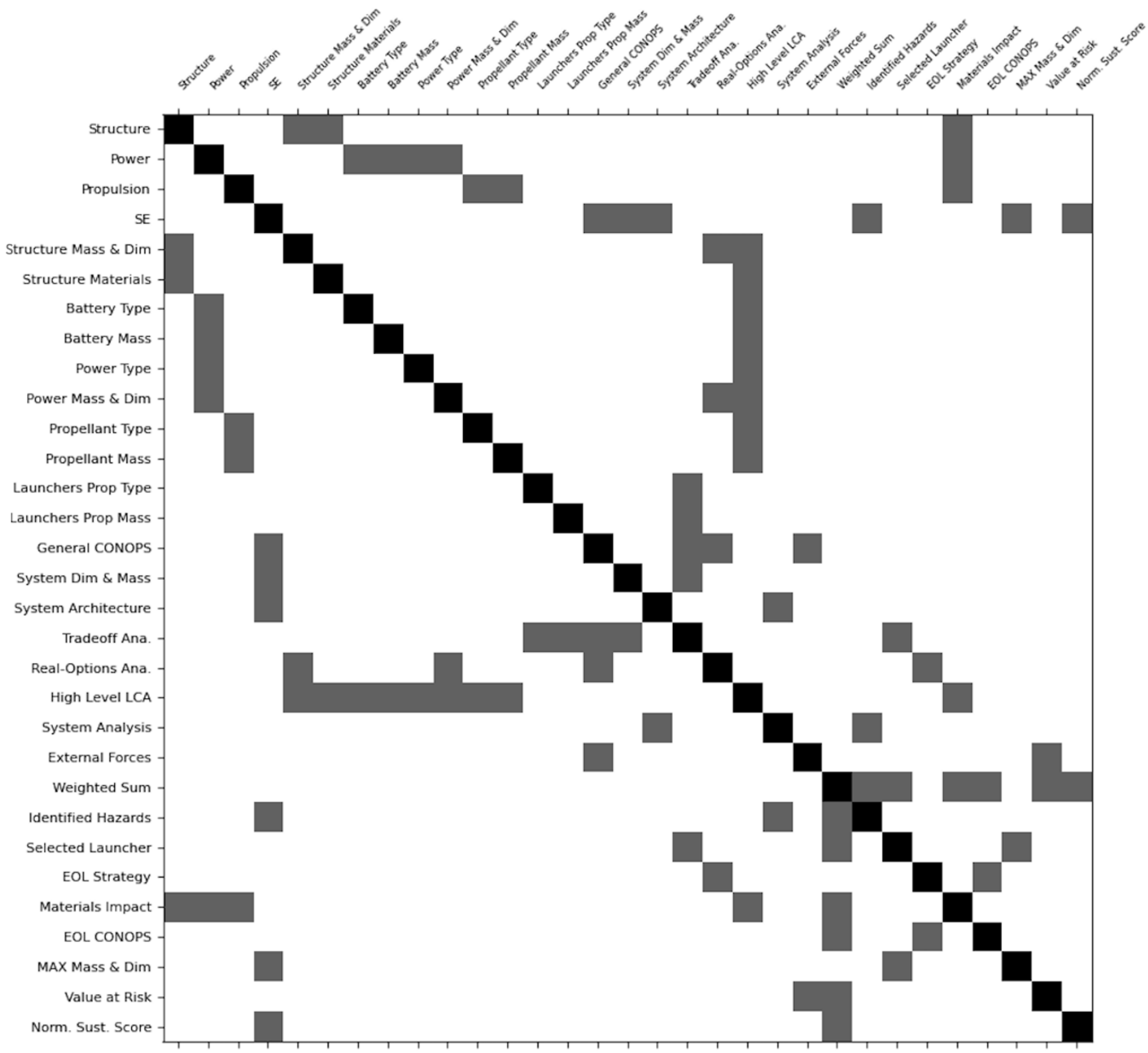


Figure 39: Symmetrised Design Structure Matrix of the system. Own figure.

Now applying the clustering on the previous DSM (See figure 40, p.57), we obtain four subsystems. Note that the composition of these subsystems is debatable and is obtained through a completely objective analysis, but the most important outcome of this analysis is the identification of the main processes of the system. We can for example observe that the External Forces Analysis (for resilience assessment) is grouped with the launcher selection, which is mainly due to the fact that they both take the mission CONOPS as input, but we will place it in the single score for further steps because it seems qualitatively more relevant. This analysis also enables to identify which other roles of the CDF are the most important for each process, both as input and as output. It is also expected to observe that we get back to the components that we defined after the functional decomposition, with the addition of their parameters and other elements.

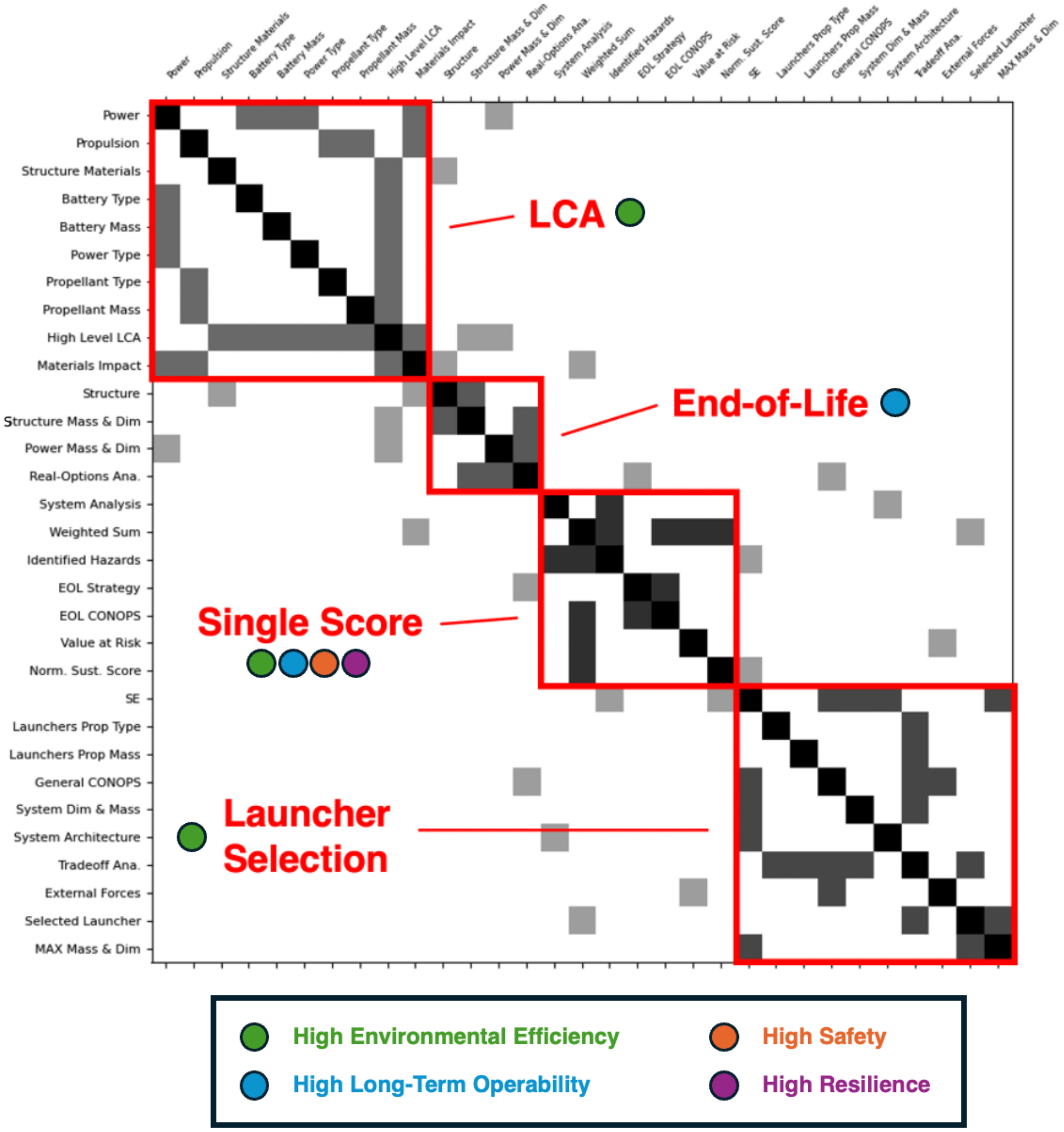


Figure 40: Modularised Design Structure Matrix resulting from the Newman eigenvectors method [15]. Own figure.

After having identified the different modules of the system, we can also compute the indices for the sparsity and the modularity of the system (See table 2) that were defined in the Outcomes of Interest (See OOI_06 and OOI_07, p.45).

Size of DSM N	Non-Zero Fraction for Sparsity	Singular value Modularity Index
31	0.05	0.36

Table 2: Modularity metrics of the system's architecture. Computed using mathematical definition of metrics from De Weck [9].

This assessment alone does not allow us to draw meaningful conclusions directly, but by comparing with other systems (See figure 41), we can observe that the sparsity is very good, nearly dominating all other systems, and about average in terms of pure modularity. The low sparsity is mostly due to the fact that it is an informatical system (processes and exchanges of information), instead of a physical one, which leads to a low "interface density".

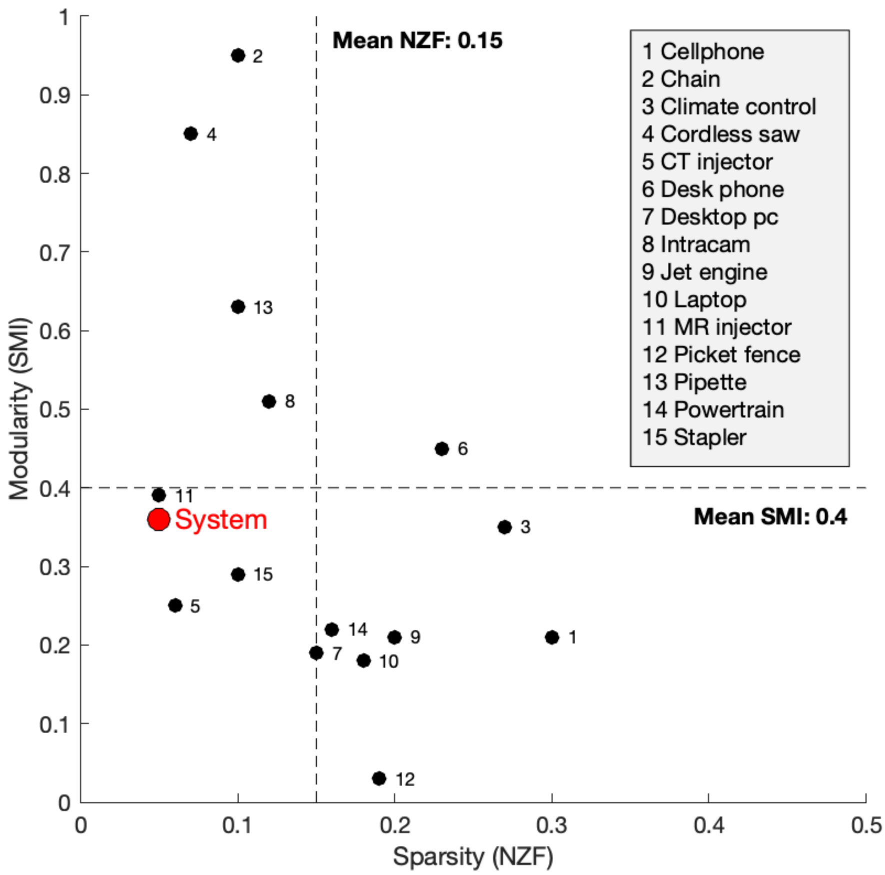


Figure 41: Modularity (SMI) versus Sparsity (NZF). A higher SMI means more modular, and a lower SMI means more integral. A low NZF means more sparse, and a high NZF means denser. Figure from De Weck [9] to which the studied system is added.

5.5 System Multi-Domain Matrix

We have now defined all the different elements of the system architecture. All of these elements are interconnected and not separate sets. The Multi-Domain Matrix shown below is the tool that was used to ensure the total traceability from functions to the different levels of decomposition. This tool also helps to visualise the value brought by the modularisation step, where the dimensionality of the system DSM went from 31 to 4.

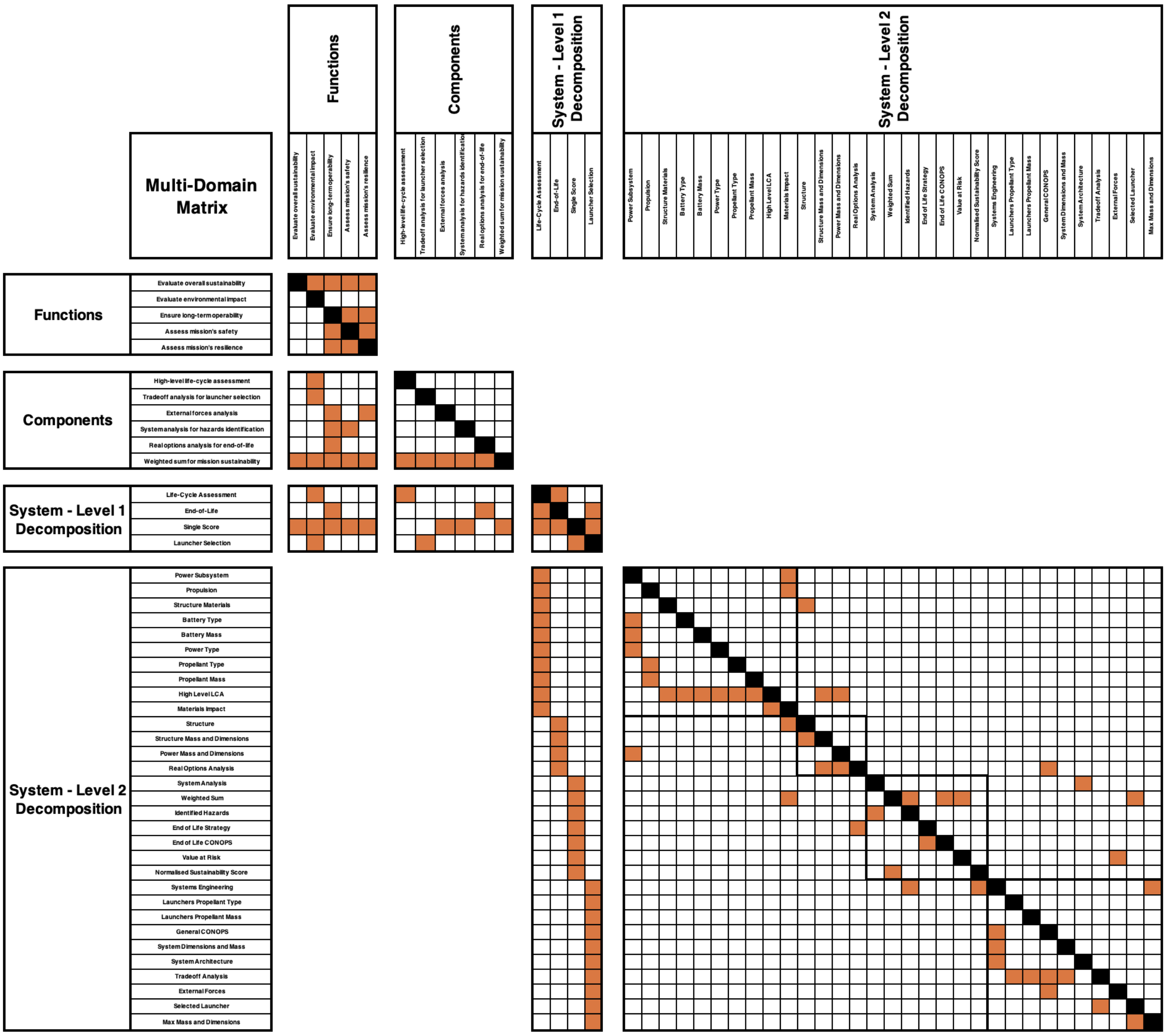


Figure 42: Multi-Domain Matrix of the system, representing the four domains used to define the system architecture - functions, components, and the two levels of decomposition. Purpose of illustration of the tool, not readability. Own figure.

5.6 Low Level Requirements

Now that we have finalised the definition of the system architecture, we want to establish a set of low level requirements for the different components. These requirements enable to design the components for integrability and ensure compliance with the higher level system requirements. We will define the set for the components, but they can be traced to the subsystems using the previously defined Multi-Domain Matrix (See figure 42, p.59). Hence we have,

- **REQ_LCA_01:** The system shall return a value that represents the materials impact of the entire system.
- **REQ_LCA_02:** The value that represents the materials impact of the entire system (from REQ_LCA_01) shall be comprised between 0 and 1, where zero represents the worst environmental impact and 1 is the best environmental impact.
- **REQ_LCA_03:** The system shall return a value that represents the materials impact of the structure subsystem.
- **REQ_LCA_04:** The value that represents the materials impact of the structure subsystem (from REQ_LCA_03) shall be comprised between 0 and 1, where zero represents the worst environmental impact and 1 is the best environmental impact.
- **REQ_LCA_05:** The system shall return a value that represents the materials impact of the power subsystem.
- **REQ_LCA_06:** The value that represents the materials impact of the power subsystem (from REQ_LCA_05) shall be comprised between 0 and 1, where zero represents the worst environmental impact and 1 is the best environmental impact.
- **REQ_LCA_07:** The system shall return a value that represents the materials impact of the propulsion system.
- **REQ_LCA_08:** The value that represents the materials impact of the propulsion subsystem (from REQ_LCA_07) shall be comprised between 0 and 1, where zero represents the worst environmental impact and 1 is the best environmental impact.
- **REQ_EXT_FORCES_01:** The system shall return a value ranging between zero and one, where 1 represents an equal value under normal or degraded conditions, and 0 represents a failure of the system under degraded conditions.
- **REQ_SCORE_01:** The system shall return a value ranging between zero and one, where 1 represents the most sustainable system that can be designed at the current state-of-the-art and 0 is the threshold from which the system is considered not sustainable at all.
- **REQ_EOL_01:** The system shall provide a Concept of Operations for the End-of-Life strategy.
- **REQ_EOL_02:** The system shall return a score comprised between zero and one, where 1 represents the strategy with the highest merit in terms of debris risk, and zero the lowest.
- **REQ_TRADEOFF_ANALYSIS_01:** The system shall provide a launcher for the mission, which is compliant with the needed mass.
- **REQ_TRADEOFF_ANALYSIS_02:** The system shall return the maximum mass that the selected launcher may support.
- **REQ_TRADEOFF_ANALYSIS_03:** The support shall return a value ranging between zero and one, where 1 represents the best launcher in terms of environmental impact and 0 is the worst.
- **REQ_SAFETY_01:** The system shall return a value ranging between zero and one, where 1 represents a totally safe system where all hazards are mitigated, and zero represents a very unsafe system that jeopardises the overall function.

6 Subsystems Specification

6.1 High-Level Life-Cycle Assessment

6.1.1 Conceptual Model

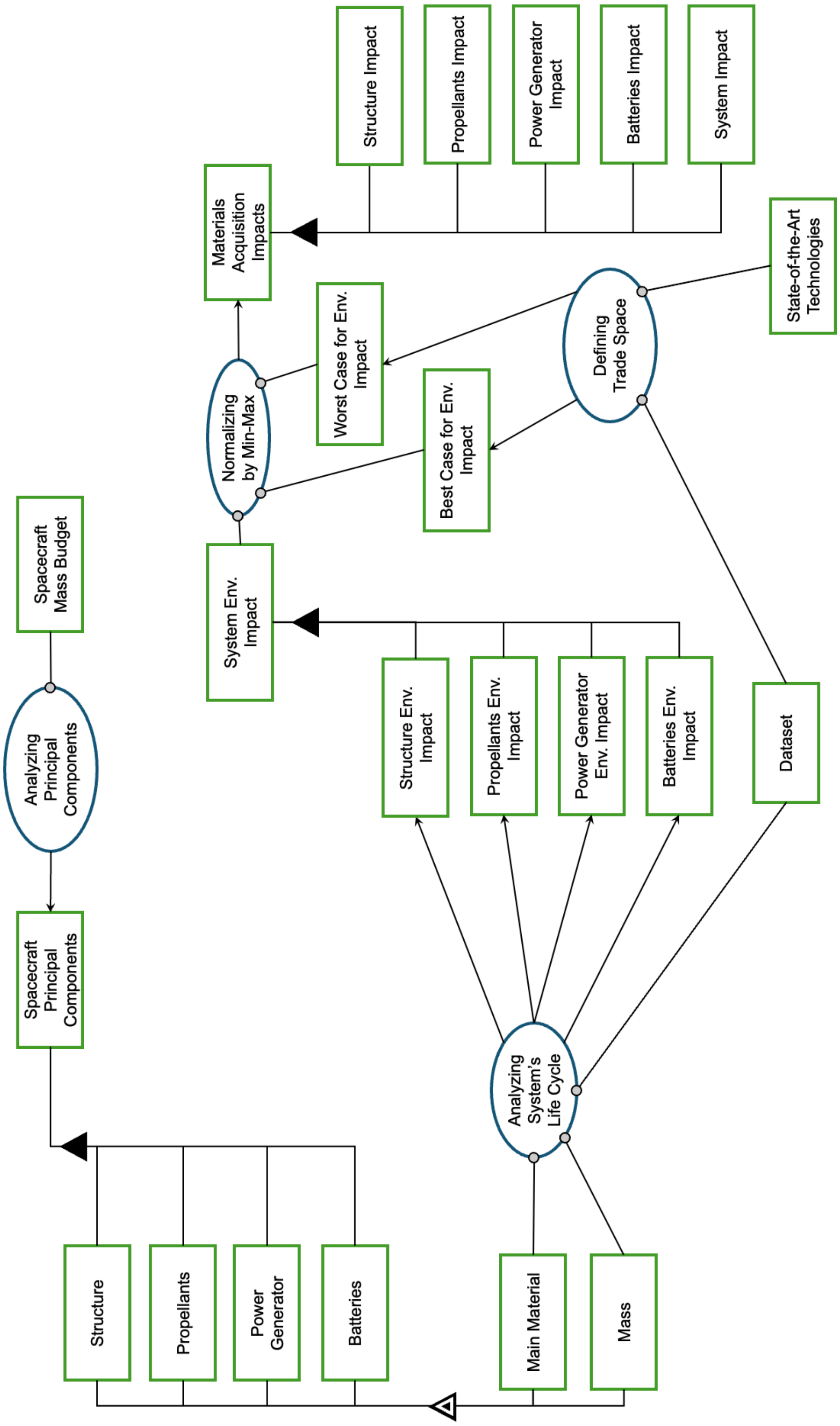


Figure 43: Object-Process Model of the High-Level Life-Cycle Assessment. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

6.1.2 Feasibility and Risks of a Traditional LCA in Early Design

Life-Cycle Assessment is a method used to evaluate the environmental impact of a system from the extraction of materials to the disposal. It is mostly used to evaluate systems that are already designed and manufactured, as a reference for future improvements. In our case, we want to determine if it is feasible to integrate this method as a design tool, especially in very early design of space missions.

At such a high-level, we are at a stage where trade-offs between technologies are performed for each subsystem. Hence no details such as the specific components nor the suppliers are known. For the simplicity and robustness of this feasibility study, we will limit ourselves to the use of the Carbon Footprint (i.e. kg-CO_2-eq). Therefore we can draw from this that the database that would be required at this stage to perform a Life-Cycle Assessment would be similar to the Table 3. The goal of the further steps are now to assess if such a database is feasible to produce, given that this one was AI generated as an hypothesis and no data is verified.

Component	Parameter	kg-CO_2-eq per unit
Solar Panels	Si Monocrystalline	~50 kg-CO_2/m²
	Si Polycrystalline	~40 kg-CO_2/m²
	GaAs (Gallium Arsenide)	~80-120 kg-CO_2/m²
	Thin-Film (CIGS, CdTe)	~20-30 kg-CO_2/m²
Battery	Li-Ion (LFP)	~80-120 kg-CO_2/kg
	Li-Ion (NMC)	~120-180 kg-CO_2/kg
	Li-Ion (LCO)	~150-200 kg-CO_2/kg
Structure	Aluminum Alloy	~10-15 kg-CO_2/kg
	Titanium Alloy	~30 kg-CO_2/kg
	Carbon Fiber Composite	~20 kg-CO_2/kg
	Stainless Steel	~6 kg-CO_2/kg
Propulsion System	Hydrazine	~30 kg-CO_2/kg
	Xenon (Electric Propulsion)	~15 kg-CO_2/kg
	Green Propellants (e.g., ADN)	~10-20 kg-CO_2/kg

Table 3: Lifecycle CO_2 emissions by satellite component. Created by Chat-GPT. Unverified data and purpose of illustration of the database that would be needed to perform a traditional LCA.

At this point, we know that the two main parameters that are unknown are the specific components of a technology and the supplier of that technology. Hence we want to determine the sensitivity of the Carbon Footprint to a variation in these parameters, and if this sensitivity is low enough, we can say that the traditional LCA is feasible.

We will start by the supplier parameter with the example of a generic aluminum alloy for the structure subsystem, as it is a material for which an larger amount of data is publicly available (larger than for other technologies). The figure 44 (page 63) shows that for a similar material (here aluminum), the location of production has a very large impact on the final carbon footprint. This variation is due to the different sources of energy, where electricity produced from coal yields a much higher carbon footprint than nuclear power for example. The aluminum with the highest carbon footprint is produced in Asia (excluding China) and the one with the lowest comes from Europe, with a nearly 300% increase from the lowest to the highest.

Such a high variation cannot be neglected and it is clear that the location of production is a major parameter of the final carbon footprint. Therefore, we can conclude that returning the carbon footprint with a reasonable accuracy, given that we only have the technology as input and not the supplier, is unfeasible.

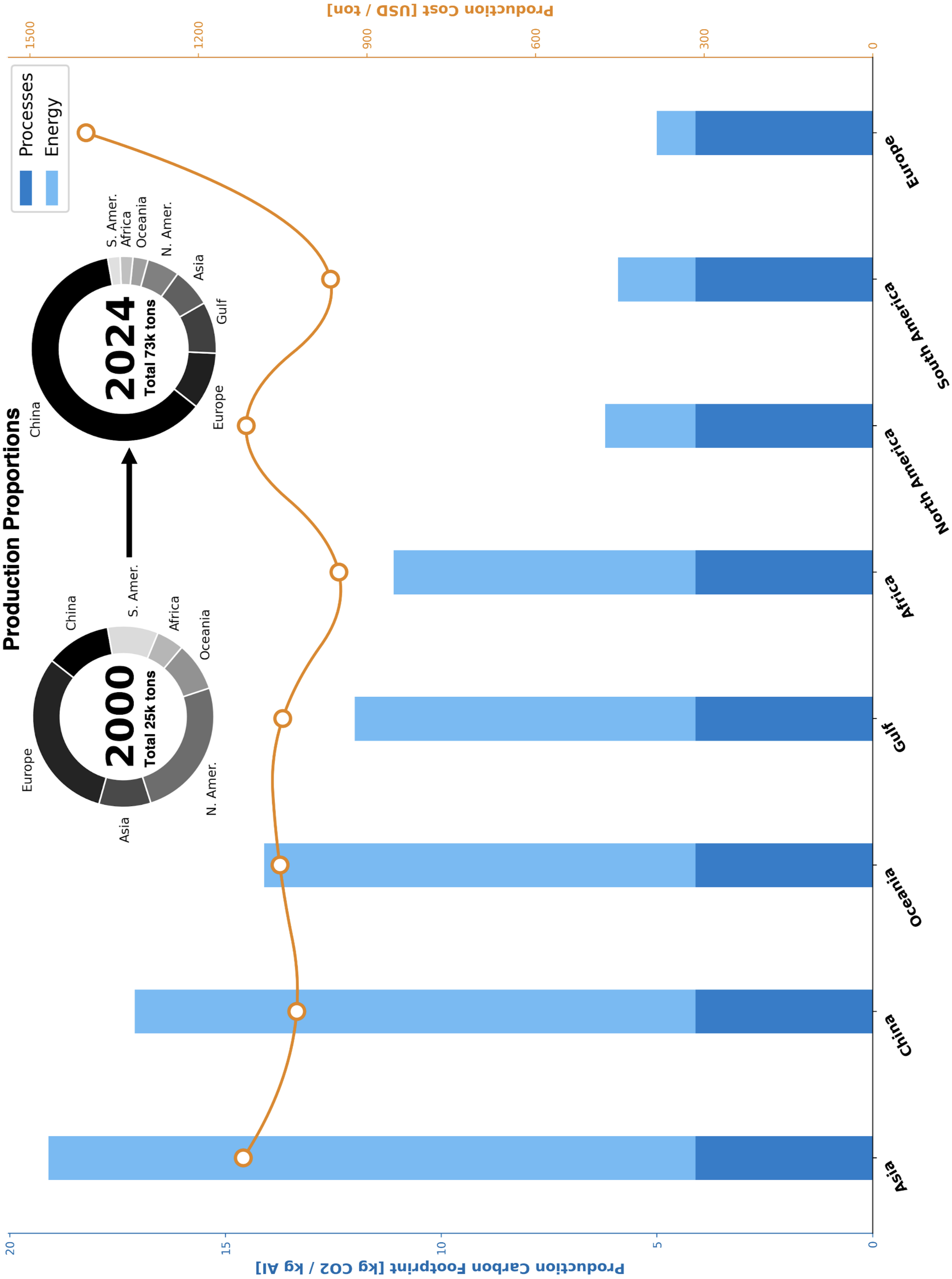


Figure 44: Carbon footprint and production cost of aluminum, by region and on average. Asia is excluding China, and Europe is including Russia. Data for carbon footprint from Saevarsdottir et al. [17], data for prodution cost partly from Thunder Said Energy [6] and completed with ChatGPT for missing points (ChatGPT mentions sources that are not free of charge but similar data to Thunder Said Energy [6] correspond), and proportions data from International Aluminium [2]. Own figure.

6.1.3 Energy Consumption as a More Reliable Indicator

We have previously concluded that the carbon footprint is not an indicator that can reliably be used in such an early design phase. However, as can be observed on figure 44 (page 63), the carbon footprint due the production process itself is very stable across locations, showing a standardisation of the process. We can also see that the variation mostly comes from the carbon footprint of the energy that is used.

Given that the process is similar in all locations, we can reliably say that they all consume a similar amount of energy, and that the variation that can be observed from the energy side is nearly only due to a variation of the carbon footprint of the energy source. We can conclude that the variation is due to the impact of the energy source and that the required energy for production is stable across locations.

The second unknown parameter that we had was the exact components of a technology. Given that in engineering systems, a technology refers to system architecture, the components will stabilise with the maturity of the technology. Indeed, the evolution of a technology follows the s-curve model (See figure 45), which stabilises once the maturity is high. This stability is actually reflecting the fundamental limit of performance for a technology, with an "optimal" configuration. Therefore the components for a same mature technology are fairly similar across all alternatives and this parameter should hence not extensively affect the carbon footprint for the production.

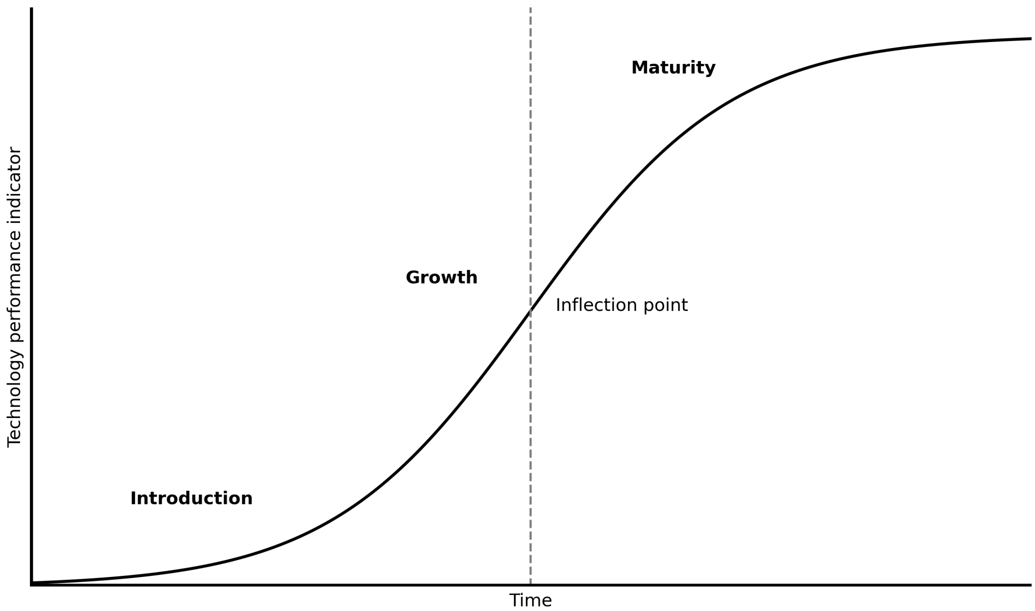


Figure 45: Typical technology s-curve. Figure reproduced from Priestley [16].

From this, we can draw the conclusion that the energy consumption for the production of a technology (See blue factor in equation 7) is the most advanced parameter that can reliably be accounted in an early design phase. Hence the table that was presented as the needed database (See table 3, p.62, and olive parameter of Equation 7) is not feasible, but by changing the unit to kWh per unit, it becomes viable. Of course, we have lost some accuracy in the process by deciding to avoid choosing the supplier at this stage, because it would not be relevant. Therefore this constitutes the first part of the LCA as a design process, which should be finalised in later phases when the suppliers and locations of production are chosen. An improvement for the selection of suppliers in terms of sustainability can be reached through policymaking and standardisation (See red parameter of equation 7).

$$\left[\frac{kg.CO_2.eq}{kg}\right]_{\text{Production}} = \left[\frac{kg.CO_2.eq}{kWh}\cdot\frac{kWh}{kg}\right]_{\text{Energy}} + \left[\frac{kg.CO_2.eq}{kg}\right]_{\substack{\text{Processes}\\\text{(constant)}}} \quad (7)$$

6.1.4 Identified Needs and Research Gaps for Future Advancements

We have assessed the feasibility of a traditional LCA in an early design phase and concluded that the energy consumption of the production of each technology would be a much more reliable indicator. However, this does not constitute the end of the research, because we now know what we need (See table 4), but we don't have it. Indeed, the energy consumption of each production process is not known, especially for space technologies. Hence a first research gap is identified to enable the integration of a high-level "LCA" as an early phase design tool. The table 4 should be completed, through an analysis of standard production processes and LCA projects of the various technologies. These LCA projects should be preceded by a definition of standard procedures to perform the LCA, aiming at coherent and reproducible results.

Component	Parameter	kWh per unit
Solar Panels	Si Monocrystalline	. . . kWh/m²
	Si Polycrystalline	. . . kWh/m²
	GaAs (Gallium Arsenide)	. . . kWh/m²
	Thin-Film (CIGS, CdTe)	. . . kWh/m²
Battery	Li-Ion (LFP)	. . . kWh/kg
	Li-Ion (NMC)	. . . kWh/kg
	Li-Ion (LCO)	. . . kWh/kg
Structure	Aluminum Alloy	. . . kWh/kg
	Titanium Alloy	. . . kWh/kg
	Carbon Fiber Composite	. . . kWh/kg
	Stainless Steel	. . . kWh/kg
Propellants	Hydrazine	. . . kWh/kg
	Xenon (Electric Propulsion)	. . . kWh/kg
	Green Propellants (e.g., ADN)	. . . kWh/kg

Table 4: Empty database for the evaluation of the power consumption required for the production of the accounted technologies in the main system trade-offs.

As previously described, the assessment that is performed with the table 4 is only the first half of the process (See equation 7, p.64). The second half should be integrated in the supplier selection process, which comes in later phases. This integration needs to be constrained by policies and requirements to enable progress in the right direction. These policies should relate about controlling the energy sources used for production, which can be firstly approximated through the country of origin. An obligation for the suppliers to provide a standardised summary of their energy sources and COTS components could also be a potential path.

To summarise, the following research paths are critical to reach a feasible state for the integration of LCA in early design processes of space missions:

- Definition of a standard LCA procedure (for this specific application) for results that are coherent, reproducible, and reliable.
- LCA projects relying on the previously defined standard procedure, all serving the purpose of filling the gaps in the database (See table 4 as a simplified reference).
- Projects for the integration of environmental impact criteria in the supplier selection process, in a direction that facilitates policymaking.

6.1.5 Example of Application for the Course ENG-411

In the course ENG-411, a high-level LCA was integrated. We drew the conclusion after the course that the process that is presented in this example is not feasible because the database that was used did not exhibit enough certainty. However, for the sake of integration, this example is still relevant and very close to what would be feasible. Indeed, the inputs and outputs would take the same form and hence the whole system is not impacted by the nature of the database that is used.

Therefore, in this example, the unit of reference will be $kg - CO_2 - eq$ and the database that is used is the table 3 (page 62). For each subsystem, the carbon footprint that is returned is simply the normalised footprint of the technology (relative to the alternatives). On the other hand, the carbon footprint for the whole spacecraft is determined using a weighted sum, where the weights are the masses of the different components (weights do not necessarily sum up to 1 in this case). Then the normalised score is based on boundaries that are defined as best and worst cases for the given system mass.

We want to get a score that is comprised between 0 and 1 to estimate the overall sustainability of the system. To this end, the normalisation method that we can use is the min-max. This method requires to define boundaries that are relevant to the studied case.

To establish a score that results from the previously defined min-max normalisation, we want to have boundary values to define a relevant range of values. The following graph is used to define these boundaries. It was created using the carbon footprint database (See table 3, p.62) and the typical mass allocation of satellites from Delessert [4]. However, it does not account for the performance variations between technologies, hence assuming that for an equal performance, they have equal mass. This is not a true statement but can be used as a first approximation to produce rough estimates of boundaries, which is sufficient for our example.

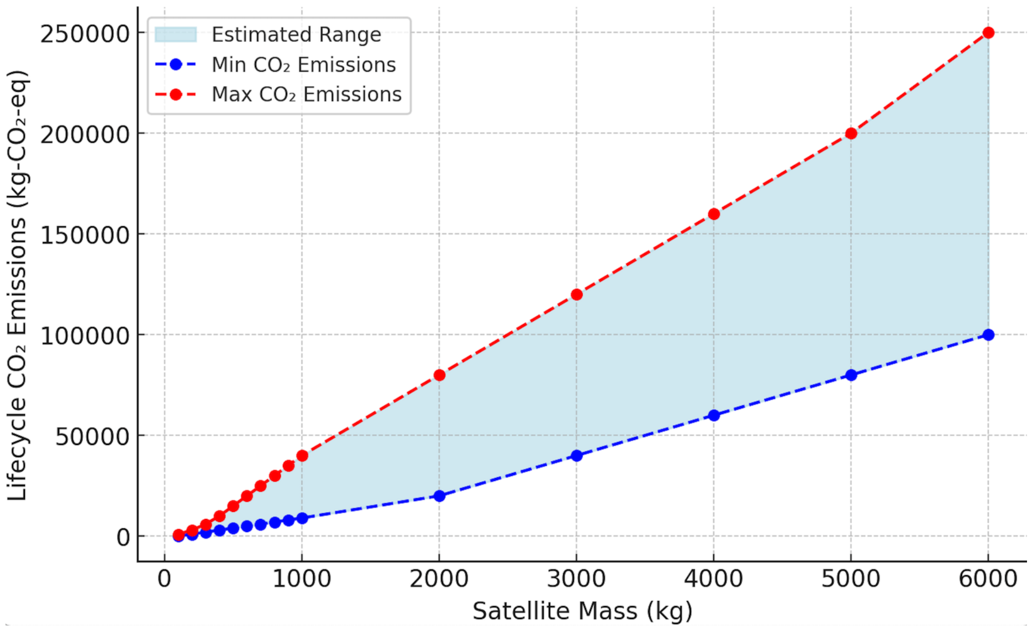


Figure 46: First approximation of carbon footprint range for different satellite mass. Created with Chat-GPT. Non linearities represent technology shifts and hence changing mass proportions. For example, smaller satellites do not have a propulsion subsystem.

With the values that are computed for each subsystem, and the boundaries that we have from figure 46 and figure 47 (page 67), we can obtain the four required scores. A detail arises for the power subsystem, for which we have to combine the result of solar panel (m^2) and the battery (kg). It is also debatable whether we should provide the separate values for better feedback. For requirements compliance purposes, we will return the non-weighted average of the two normalised scores. A final step before normalising the score for the whole satellite is to divide the obtained carbon footprint by the proportion of mass of the satellite that we account for (In the case of figure 36 p.53, we would divide by 0.81), then simply use the satellite mass to find the range on figure 46.

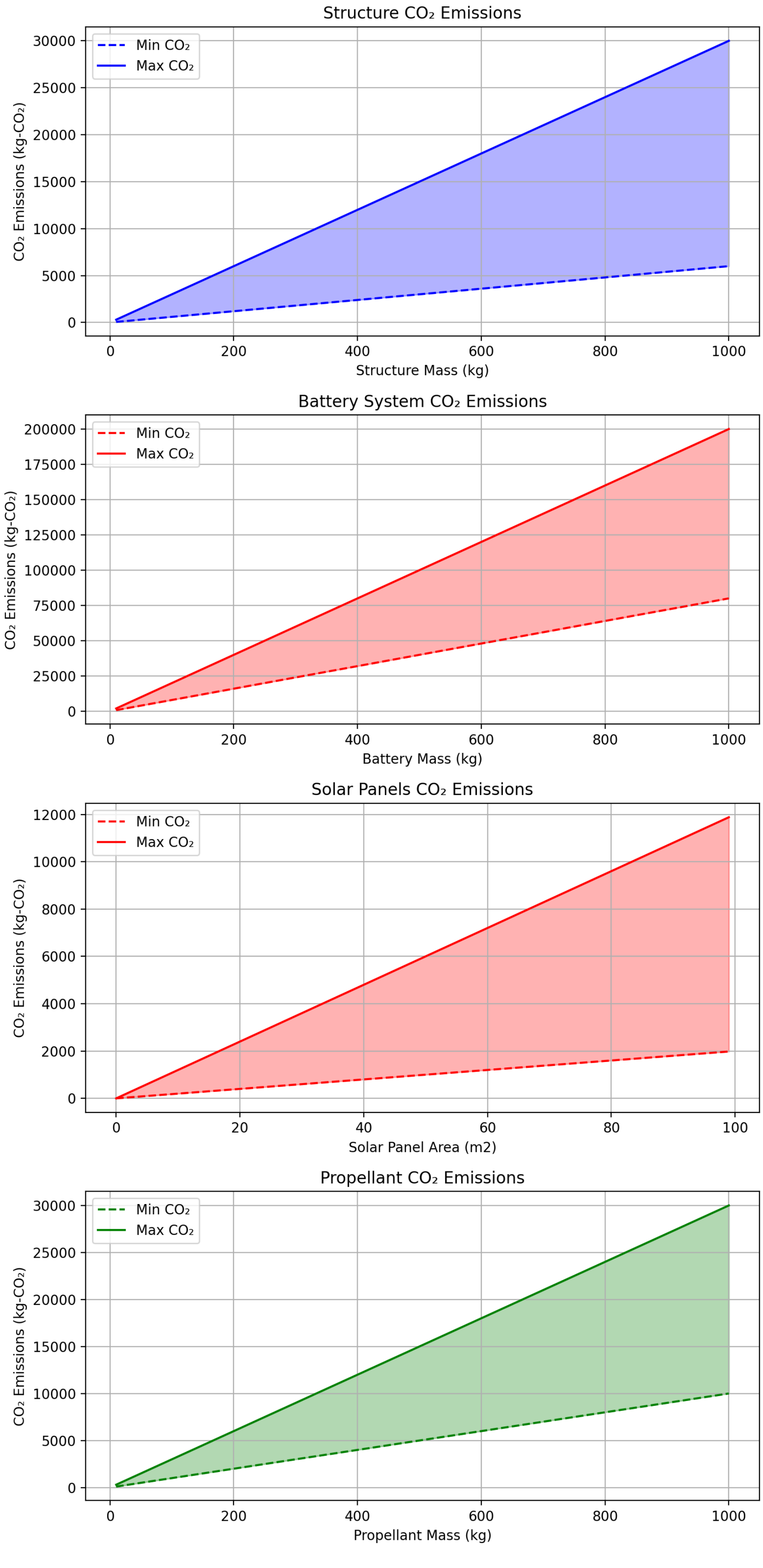


Figure 47: First approximation of carbon footprint range for different subsystem mass. Created using table 3, p.62.

6.1.6 Requirements Verification

Requirements were defined for the high-level LCA subsystem. As can be observed below, all requirements are verified and hence the subsystem can be integrated.

- **REQ_LCA_01:**
  - **Description:** The system shall return a value that represents the materials impact of the entire system.
  - **Verification:** The table 3 (page 62) enables to sum the different carbon footprints of technologies and evaluate the materials impact of the entire system. Hence this requirements is verified.
- **REQ_LCA_02:**
  - **Description:** The value that represents the materials impact of the entire system (from REQ_LCA_01) shall be comprised between 0 and 1, where 0 represents the worst environmental impact and 1 is the best environmental impact.
  - **Verification:** The figure 46 (page 66) allows to obtain boundary values to normalise the carbon footprint of the system by a min-max method, which by nature returns a value between zero and one. Hence this requirements is verified.
- **REQ_LCA_03:**
  - **Description:** The system shall return a value that represents the materials impact of the structure subsystem.
  - **Verification:** The table 3 (page 62) enables to sum the different carbon footprints of technologies and evaluate the materials impact of the structure subsystem. Hence this requirements is verified.
- **REQ_LCA_04:**
  - **Description:** The value that represents the materials impact of the structure subsystem (from REQ_LCA_03) shall be comprised between 0 and 1, where zero represents the worst environmental impact and one is the best environmental impact.
  - **Verification:** The figure 47 (page 67) allows to obtain boundary values to normalise the carbon footprint of the structure subsystem by a min-max method, which by nature returns a value between zero and one. Hence this requirements is verified.
- **REQ_LCA_05:**
  - **Description:** The system shall return a value that represents the materials impact of the power subsystem.
  - **Verification:** The table 3 (page 62) enables to sum the different carbon footprints of technologies and evaluate the materials impact of the power subsystem. Averaging the result of solar panels and batteries yields a single value. Hence this requirements is verified.
- **REQ_LCA_06:**
  - **Description:** The value that represents the materials impact of the power subsystem (from REQ_LCA_05) shall be comprised between 0 and 1, where zero represents the worst environmental impact and one is the best environmental impact.
  - **Verification:** The figure 47 (page 67) allows to obtain boundary values to normalise the carbon footprint of the power subsystem by a min-max method, which by nature returns a value between zero and one. Averaging the result of solar panels and batteries yields a single value. Hence this requirements is verified.
- **REQ_LCA_07:**
  - **Description:** The system shall return a value that represents the materials impact of the propulsion system.
  - **Verification:** The table 3 (page 62) enables to sum the different carbon footprints of technologies and evaluate the materials impact of the propulsion subsystem. Hence this requirements is verified.

- **REQ_LCA_08:**
  - **Description:** The value that represents the materials impact of the propulsion subsystem (from REQ_LCA_07) shall be comprised between 0 and 1, where zero represents the worst environmental impact and one is the best environmental impact.
  - **Verification:** The figure 47 (page 67) allows to obtain boundary values to normalise the carbon footprint of the propulsion subsystem by a min-max method, which by nature returns a value between zero and one. Hence this requirements is verified.

6.2 Launcher Selection

6.2.1 Conceptual Model

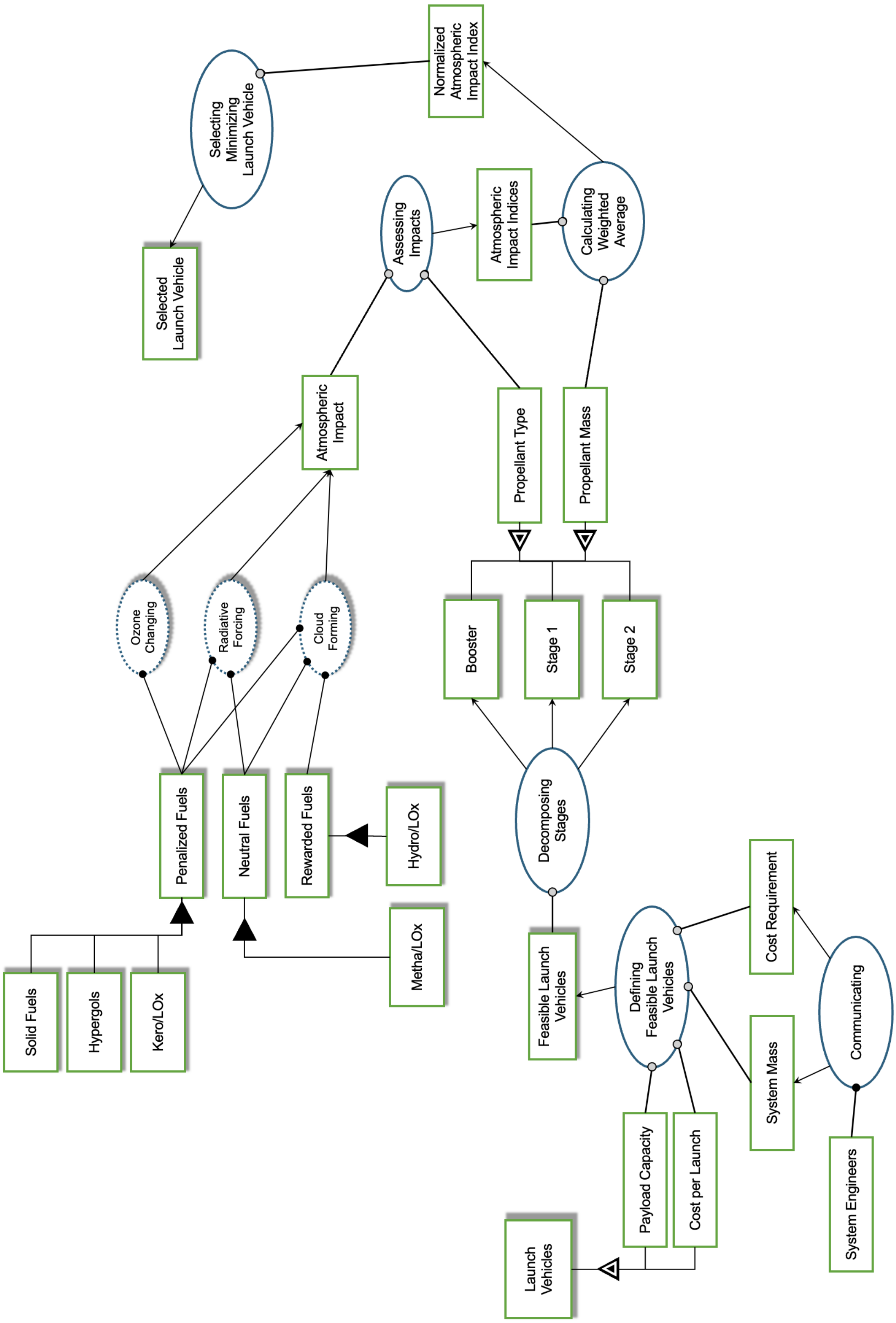


Figure 48: Object-Process Model of the Launcher Selection System. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

6.2.2 Atmospheric Impact Index

In the previously defined conceptual model for the launcher selection (See figure 48, p.70), it is stated that we assess the impact of the launcher on the atmosphere using the propellants of the rocket as reference. The atmospheric impact of launchers is a topic that is quite unknown. Some tools attempt to assess quantitatively these effects, but they require too much information to be used and to be relevant at our level. We know from Sirieys et al. [18] that the most impactful parameter for the atmospheric impact of a launcher is its propellants.

We know what the main negative impacts of each propellant occur through three different phenomena. These phenomena are ozone depletion and radiative forcing in the Stratosphere, as well as cloud formation in the Mesosphere (See figure 49).

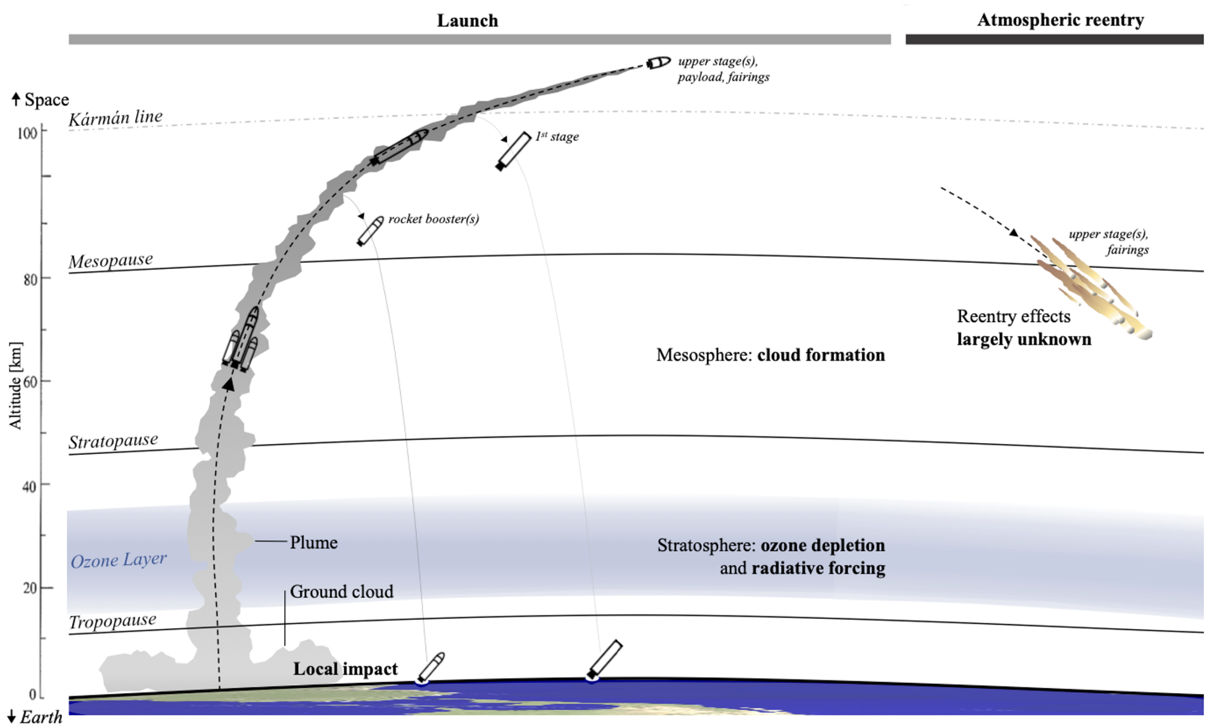


Figure 49: Trajectory of a typical launch vehicle. Figure from Sirieys et al. [18].

From the information that we have, we establish an index for each of the propellants (See table 5). We are then able to tailor the assessment to any launch vehicle using its propellants composition and performing a weighted average based on mass (See equation 8). An implementation of the index can be observed on figure 50 (page 72) with the currently operational launchers and the future ones.

Propellant Type	Ozone Changing	Radiative Forcing	Cloud Forming	Impact	Normalised Impact
Solid	YES	YES	YES	-3	0
Hypergols	YES	YES	YES	-3	0
Kero/Lox	YES	YES	YES	-3	0
Metha/Lox	NO	YES	YES	-2	0.5
Hydro/Lox	NO	NO	YES	-1	1

Table 5: Known atmospheric impact of typical launcher propellants, and their associated normalised impact for quantitative assessment. Information from Sirieys et al. [18].

$$AtmoImpactIndex = \frac{0.5 \cdot M_{metha} + M_{hydro}}{M_{solid} + M_{hyper} + M_{kero} + M_{metha} + M_{hydro}} \tag{8}$$

6.2.3 Example of a Generic Result for the Trade-off Analysis

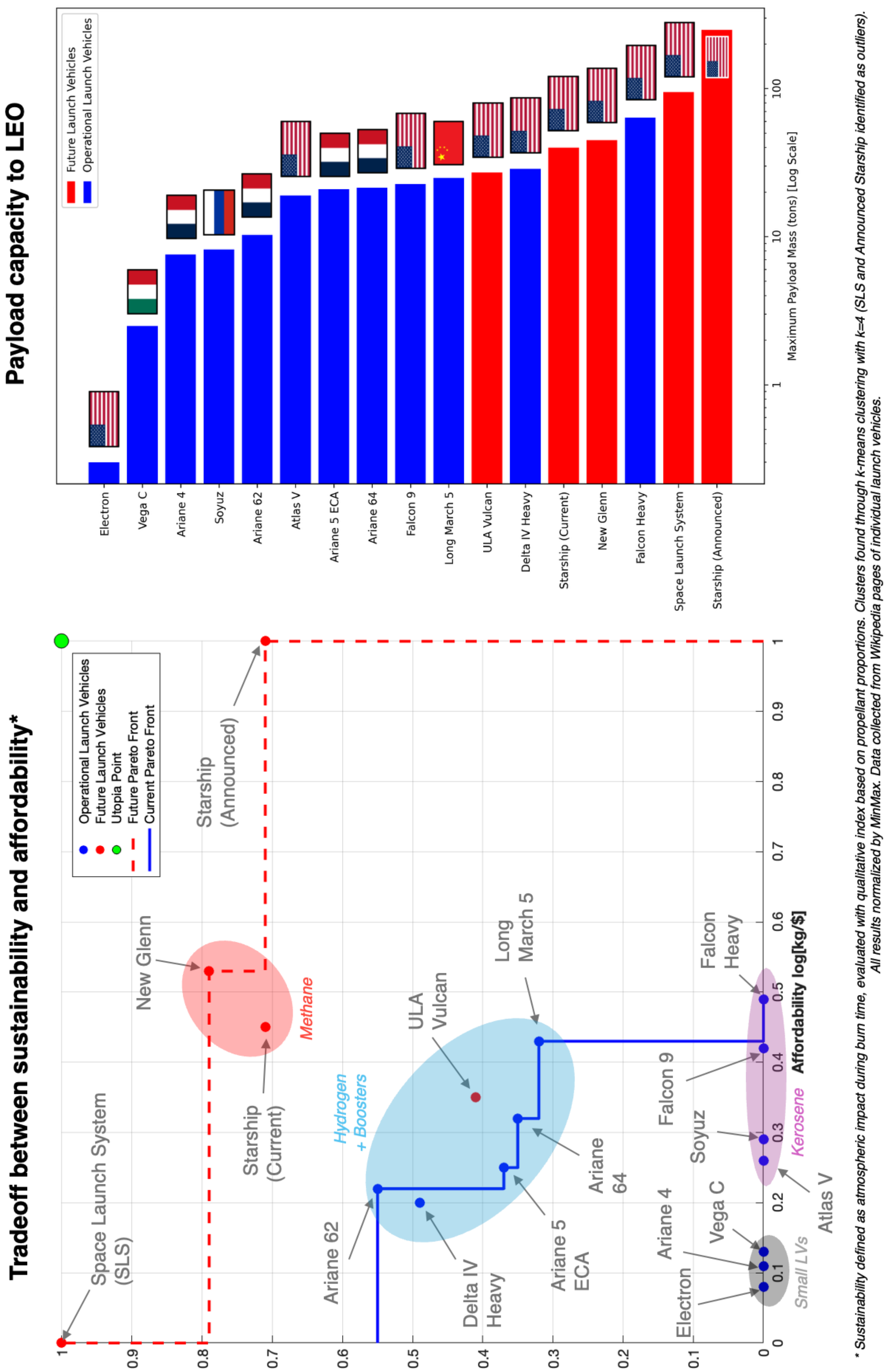


Figure 50: Decision support for launch vehicle selection. Calculation details can be found in appendix E.

6.2.4 Requirements Verification

Requirements were defined for the launch vehicle selection subsystem. As can be observed below, all requirements are verified and hence the subsystem can be integrated.

- **REQ_TRADEOFF_ANALYSIS_01:**
  - **Description:** The system shall provide a launcher for the mission, which is compliant with the needed mass.
  - **Verification:** The bar chart of the figure 50 (page 72), in increasing payload capacity order, allows to discard unfeasible solutions. The scatter plot then allows to select a launcher along with the systems engineers. Hence this requirement is verified.
- **REQ_TRADEOFF_ANALYSIS_02:**
  - **Description:** The system shall return the maximum mass that the selected launcher may support.
  - **Verification:** The bar chart of the figure 50 (page 72) explicitely provides the payload capacity of each launcher. Hence this requirement is verified.
- **REQ_TRADEOFF_ANALYSIS_03:**
  - **Description:** The system shall return a value ranging between 0 and 1, where one represents the best launcher in terms of environmental impact and 0 is the worst.
  - **Verification:** The y-axis of the scatter plot on figure 50 (page 72) provides the score of the different launchers. This score is bounded by zero and one. Hence this requirement is verified.

6.3 End-of-Life Strategy

6.3.1 Conceptual Model

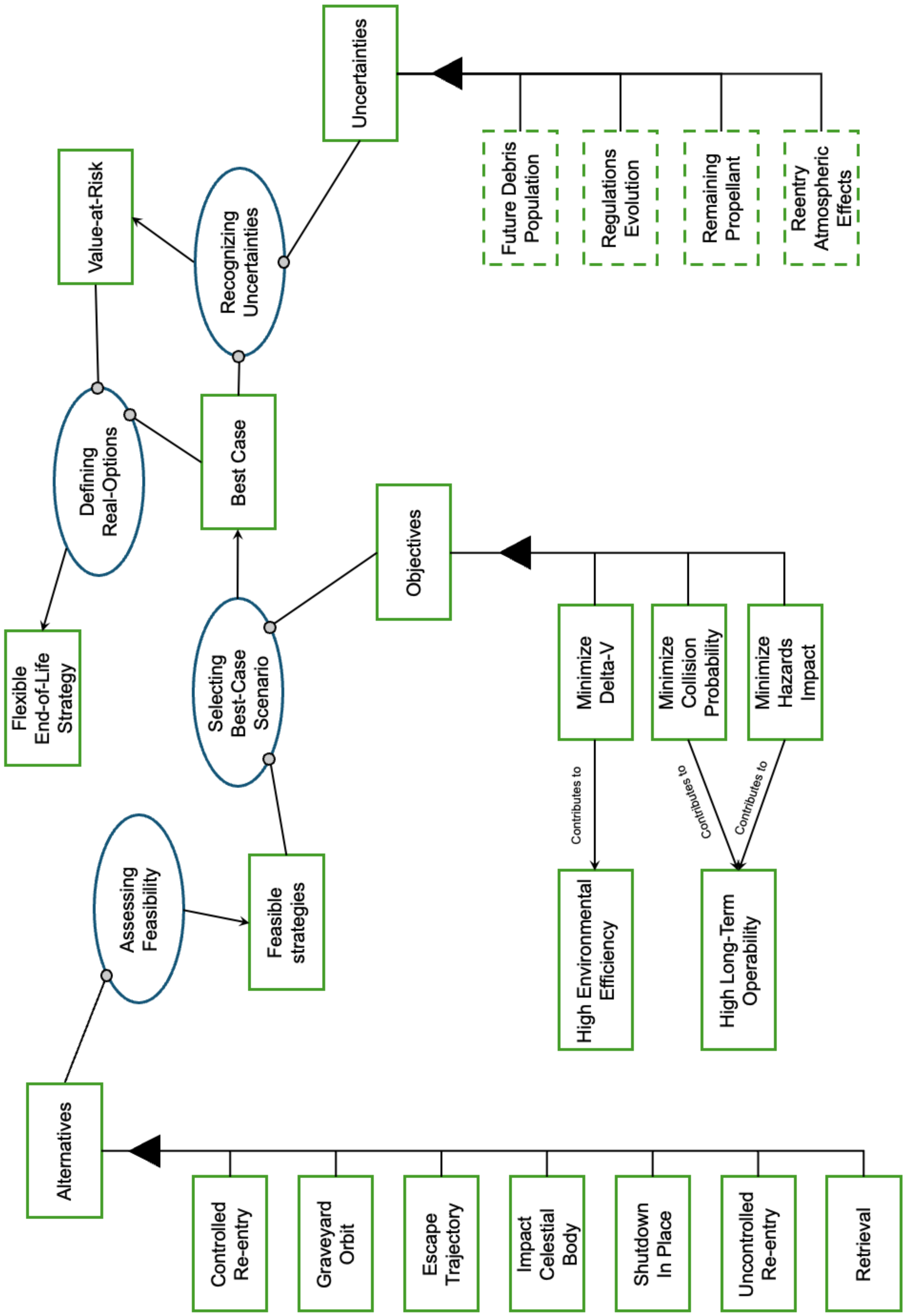


Figure 51: Object-Process Model of the End-of-Life strategy definition. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

6.3.2 Real-Options Analysis

The traditional method for selecting the End-of-Life strategy is to simply perform a trade-off between the different alternatives, select one, and compute the required Delta velocity (Δv). This method becomes less and less robust with time because some uncertainties become more impactful. For instance, increasing debris population or future regulations are more and more important. These uncertainties cannot be ignored if the long-term operability of the space environment needs to be ensured.

Recognising these uncertainties is especially crucial in the selection of the End-of-Life strategy because it is planned for the end of the mission, usually being after at least 5 years of operations, without accounting the time between mission planning and commissioning.

Real-Options Analysis (ROA, from Neufville [14]) offers a solution to this matter by introducing flexibility in systems to make them more robust to inevitable uncertainty. The ultimate goal of such an analysis is to *cut downside risks* and also to *expand upside potential* (See figure 52).

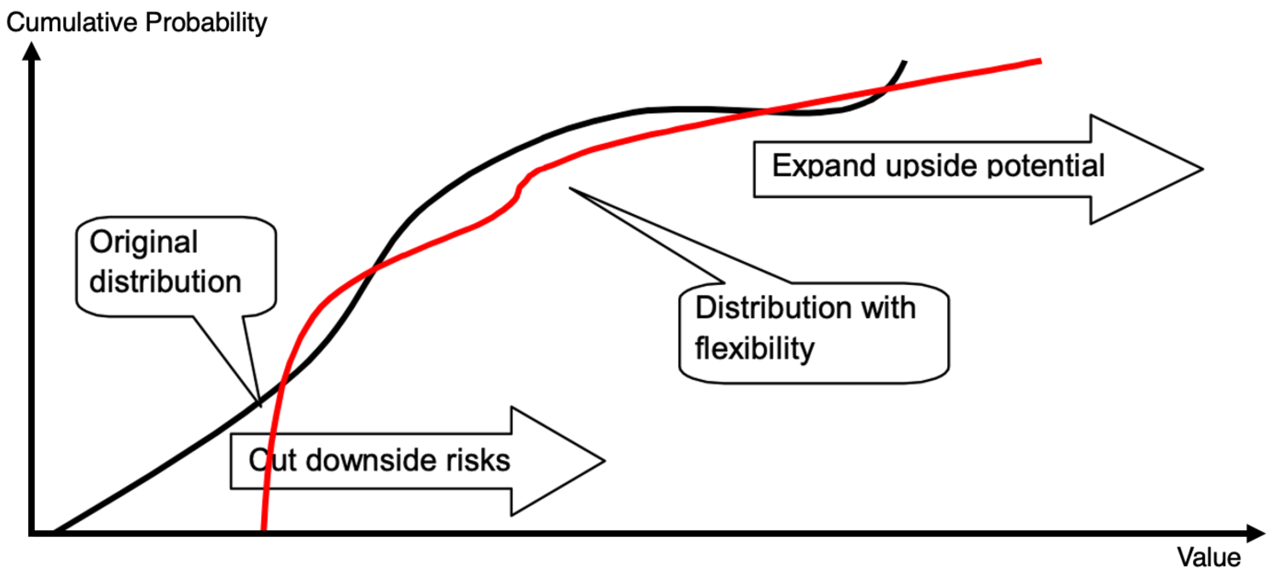


Figure 52: Sources of value for flexibility. Figure from Neufville [14].

To obtain such a result, three steps need to be performed:

1. Select a base case
2. Recognise uncertainties
3. Define real-options

The first step is rather simple in our case, because we use the result from the traditional definition of the End-of-Life strategy, which is assumably the "best strategy". To select this strategy, we can simply take 2 parameters into account, the Delta velocity (Δv) and the collision risk. To summarise, we want to place the spacecraft in a safe zone where it has a low risk of collision while having the lowest possible Delta velocity (Δv). For example, this process yields reentry for LEO missions and graveyard orbit for GEO missions.

For the second step, uncertainties will be common to nearly all cases for the definition of the End-of-Life strategy:

- Future debris population (See figure 53, p.76)
- Regulations evolution
- Remaining propellant
- Reentry atmospheric impact (See figure 49, p.71)

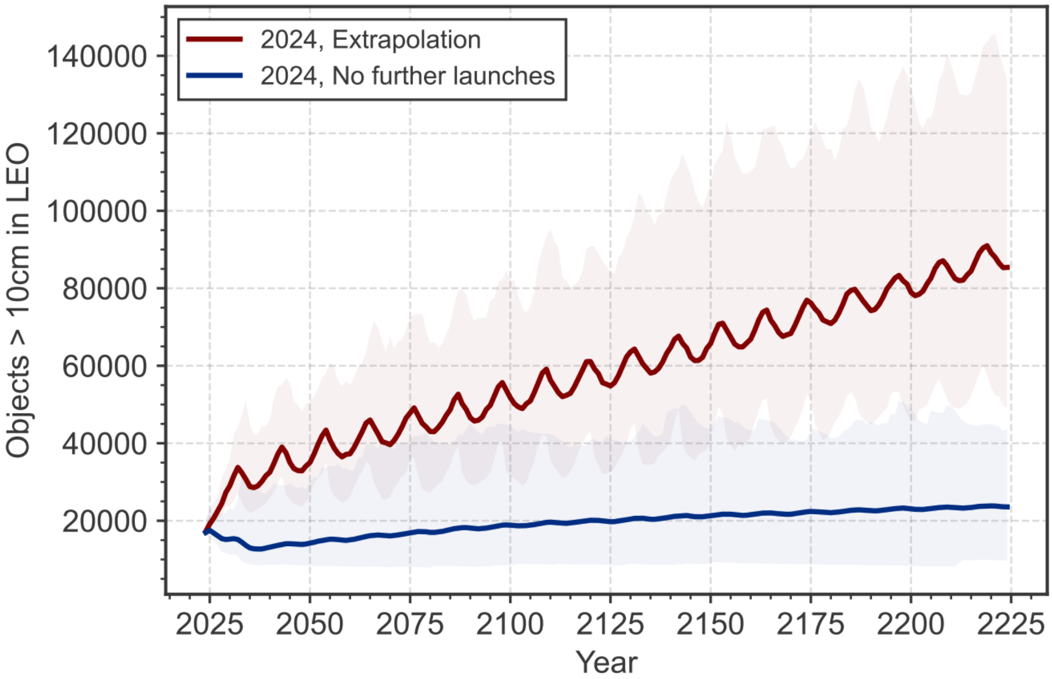


Figure 53: Number of objects larger than 10cm in LEO in the simulated scenarios of long-term evolution of the environment. The very high variance shows the high level of uncertainty. Figure from IADC [1].

Reentry is also a topic that cannot be ignored anymore. It is a matter that is similar to the one of the atmospheric impact of launches, because it is the shift in scale that raises issues. Over the past few years, the number of yearly re-entered objects has quadrupled (See figure 54), but the actual atmospheric impact of a reentry is still unknown. The current philosophy is to make satellites demisable so that the safety of the population is ensured, but there might be a scenario in which we discover that demising strategies are extremely damaging for the atmosphere.

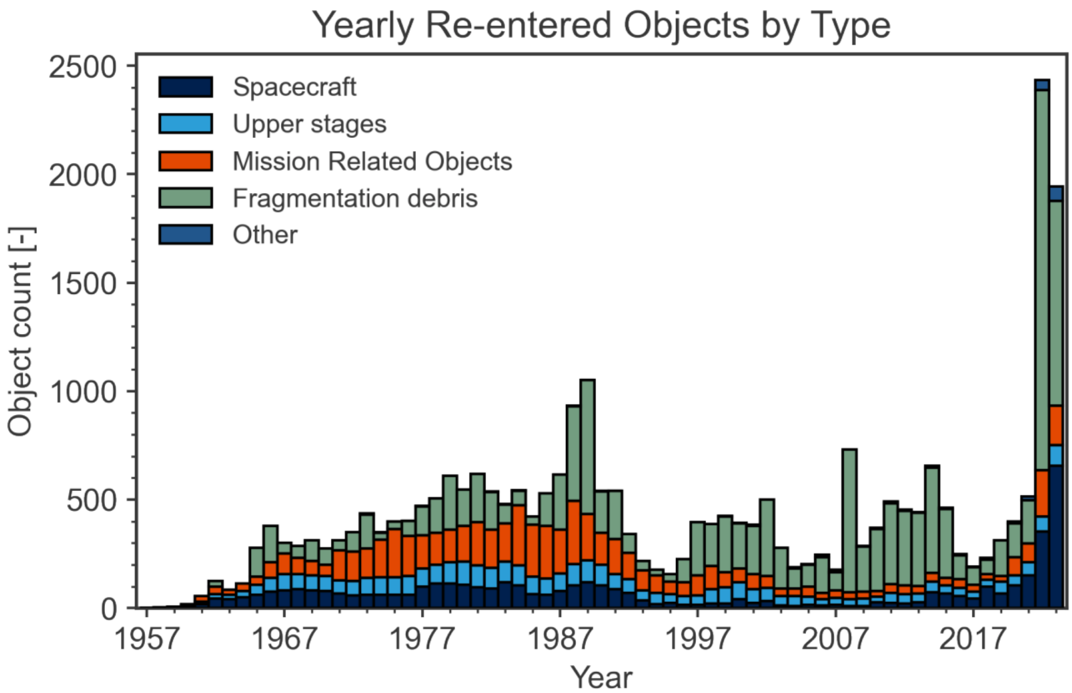


Figure 54: Re-entries of catalogued objects by object type. Figure from IADC [1].

The third step of the real options analysis consists in defining a decision tree to propose reactions to the possible scenarios defined by the previous uncertainties. These reactions both mitigate risks and take advantage of more favorable scenarios.

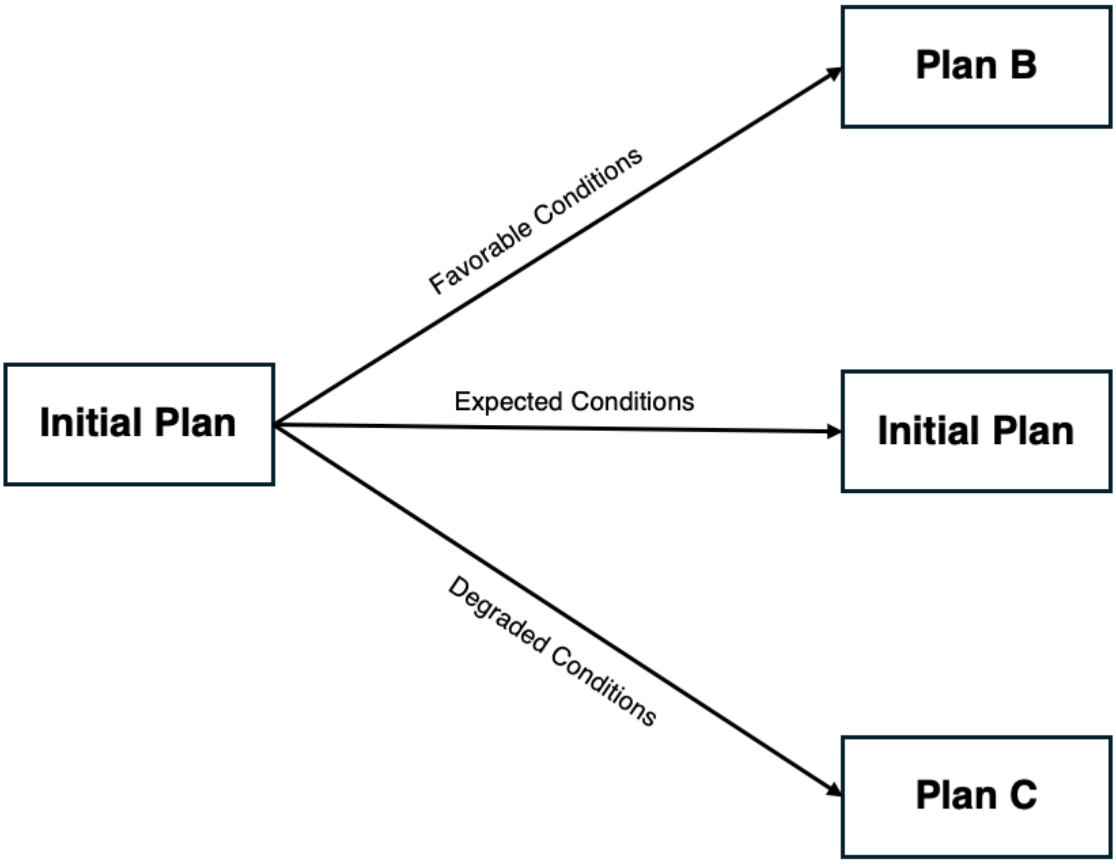


Figure 55: Example of a simple decision tree for the definition of Real-Options. Own figure.

6.3.3 Qualitative Index Rationale

For the definition of the End-of-Life strategy, we also have a requirement to return a score comprised between zero and one. Where 0 is the strategy with the least merit, and 1 the highest.

As defined in the conceptual model, the main objectives of the End-of-Life strategy are to minimise the required Delta velocity (Δv) and to minimise the risk of debris generation after the operations of the spacecraft. With the Real Options Analysis that we have integrated as a supplement in the process to account for the inevitable uncertainty, a third objective for flexibility is accounted. As defined in the literature (See Neufville [14]), to account for the flexibility of a system, we look at the Value-at-Risk of the system's merit instead of the expected merit (See figure 56, p.78).

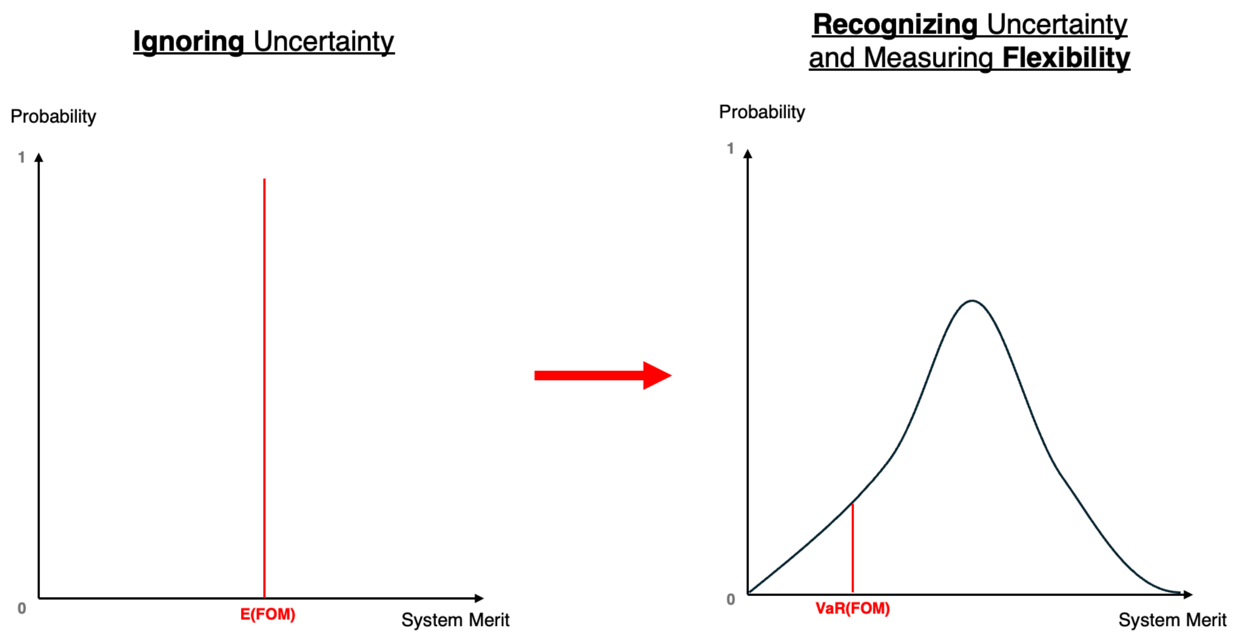


Figure 56: Recognising inevitable uncertainty and measuring flexibility of systems through the Value-at-Risk.

Quantitatively evaluating the stochastic properties of the different uncertainties requires too much resources at the current State-of-the-Art, hence accounting for the constraints of the concurrent engineering environment, we will perform a qualitative assessment. The rationale, derived from the previously defined objectives, is given by,

- **1:** Under degraded conditions, the End-of-Life strategy can be performed with a low Delta velocity (Δv), compliance with regulations is ensured, and the risk of debris generation can be considered low.
- **0.66:** Under degraded conditions, the End-of-Life strategy can be performed with a high Delta velocity (Δv) or compliance with regulations is not ensured, or the risk of debris generation is high.
- **0.33:** Under degraded conditions, the End-of-Life strategy can be performed with a high Delta velocity (Δv) and compliance with regulations is not ensured, and the risk of debris generation is high.
- **0:** Under degraded conditions, the End-of-Life strategy cannot be performed.

6.3.4 Research Gaps and Further Advancements

Similarly to the high-level life cycle assessment, we have clearly identified what would be needed to reliably integrate sustainability for the End-of-Life strategy definition. However some research gaps exist to integrate it in a Concurrent Design Facility, especially to make these procedures fast enough to be applicable. The following projects or research directions would help reduce these gaps and improve design processes:

- Research on the atmospheric impact of reentry and trade-off between demising strategies and non-demising strategies.
- Quantitative Real Options Analysis for End of Life Strategy, accounting for uncertainty in debris population. This analysis would return the propellant margin to load in the spacecraft to ensure that the End-of-Life is compliant with stakeholder expectations, in most cases.

6.3.5 Example of Concept of Operations for ENG-411

For the course ENG-411, a CONOPS for the End-of-Life strategy had to be created. The mission was placed in the L4 and L5 lagrangian points of the cislunar space. The main options for the end of life were given by:

- Heliocentric orbit
  - **Required Delta velocity (Δv):** HIGH
  - **Risk of debris generation:** LOW
- Graveyard orbit
  - **Required Delta velocity (Δv):** MEDIUM
  - **Risk of debris generation:** LOW
- Crash on the Moon surface
  - **Required Delta velocity (Δv):** LOW
  - **Risk of debris generation:** LOW
- Stay in place
  - **Required Delta velocity (Δv):** LOW
  - **Risk of debris generation:** HIGH

From these alternatives, the crash on the moon was clearly the dominant solution. It was also interesting to observe during the course the strong disagreement of some students regarding this solution, especially because of the uncertainty of debris generation due to impact velocity or the regulations regarding crashing on celestial bodies. These disagreements clearly pointed out the need for the integration of real-options in the design of the End-of-Life strategy to account for such uncertainties. The uncertainties that were identified for this case were defined by:

- Location of crash due to regulations
- Maximum allowable impact velocity
- Maximum time to perform End-of-Life strategy

To account for these uncertainties, we took an added margin on propellant of 10% (Value defined arbitrarily due to time constraints of the course), and the following decision tree shows the real-options that were integrated (See figure 57).

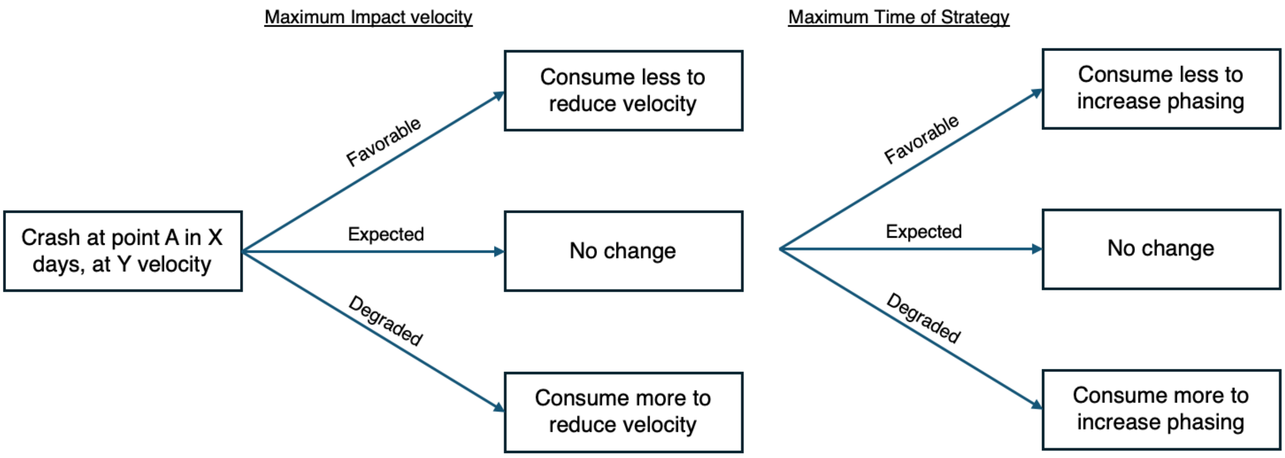


Figure 57: Partial view of the decision tree that is applied for the End-of-Life strategy of the course ENG-411.

The previous tree only shows a partial view of the flexibility brought by the strategy. To assess the merit of the strategy, we assess the merit on the branch where all conditions are degraded, but also where all is favorable. Using the definition of real-options, we are able to adapt to changing regulations, lower uncertainties regarding impact velocities, and changing stakeholder expectations. The overall strategy is delivered through a CONOPS (See figure 58, p.80).

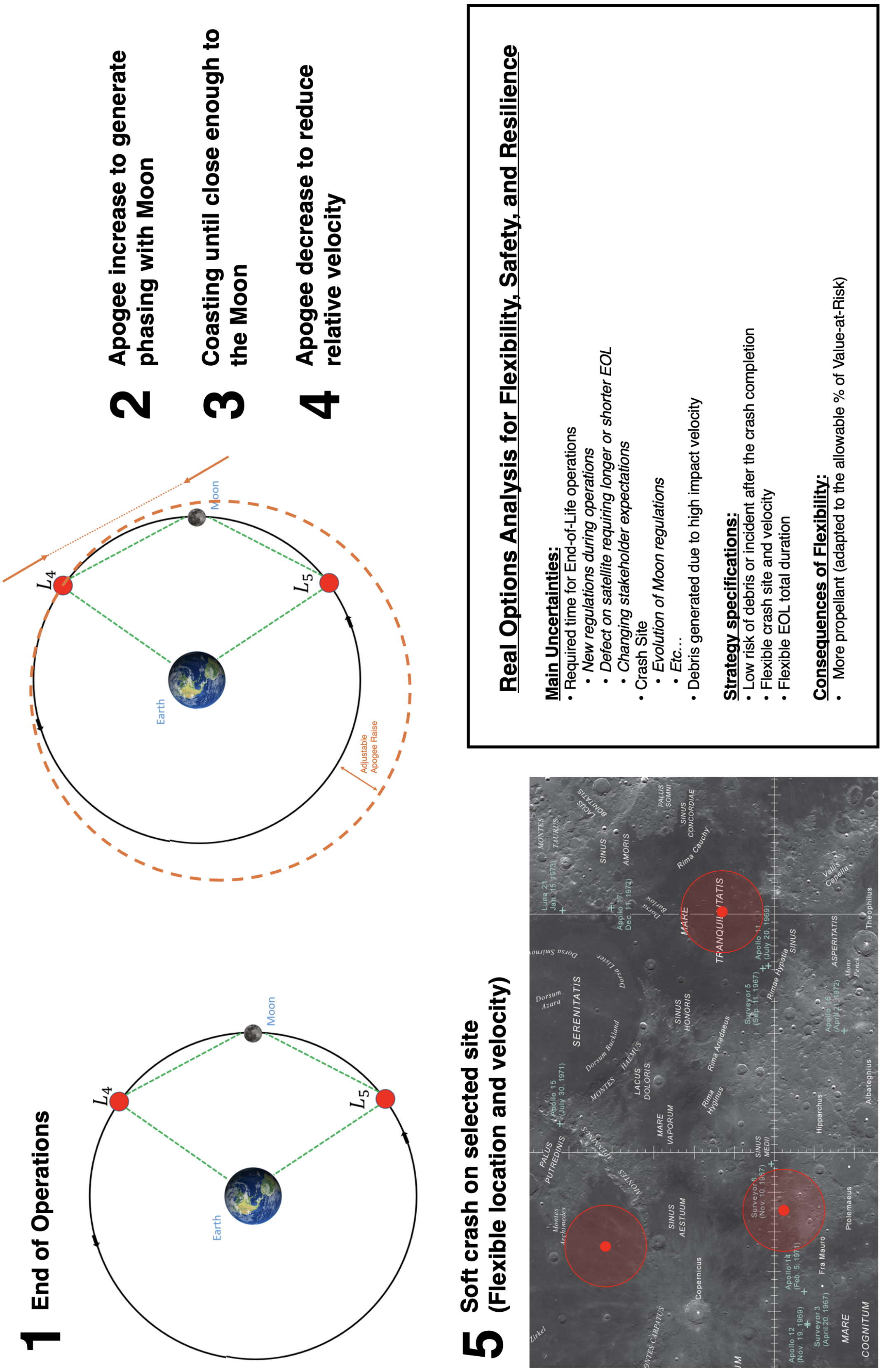


Figure 58: Concept of Operations for the End-of-Life strategy of the ENG-411 course. The Real Options Analysis was simplified due to the various constraints of the course. Own figure.

6.3.6 Requirements Verification

Requirements were defined for the End-of-Life strategy subsystem. As can be observed below, all requirements are verified and hence the subsystem can be integrated.

- **REQ_EOL_01:**
  - **Description:** The system shall provide a Concept of Operations for the End-of-Life strategy.
  - **Verification:** The figure 58 (page 80) is a Concept of Operations, which is an outcome of the case study for the system. Hence this requirement is verified.
- **REQ_EOL_02:**
  - **Description:** The system shall return a score comprised between 0 and 1, where one represents the strategy with the highest merit in terms of debris risk, and zero the lowest.
  - **Verification:** The rationale provided in subsubsection 6.3.3 allows to return a score between 0 and 1. Hence this requirement is verified.

6.4 Mission Sustainability Score

6.4.1 Conceptual Model

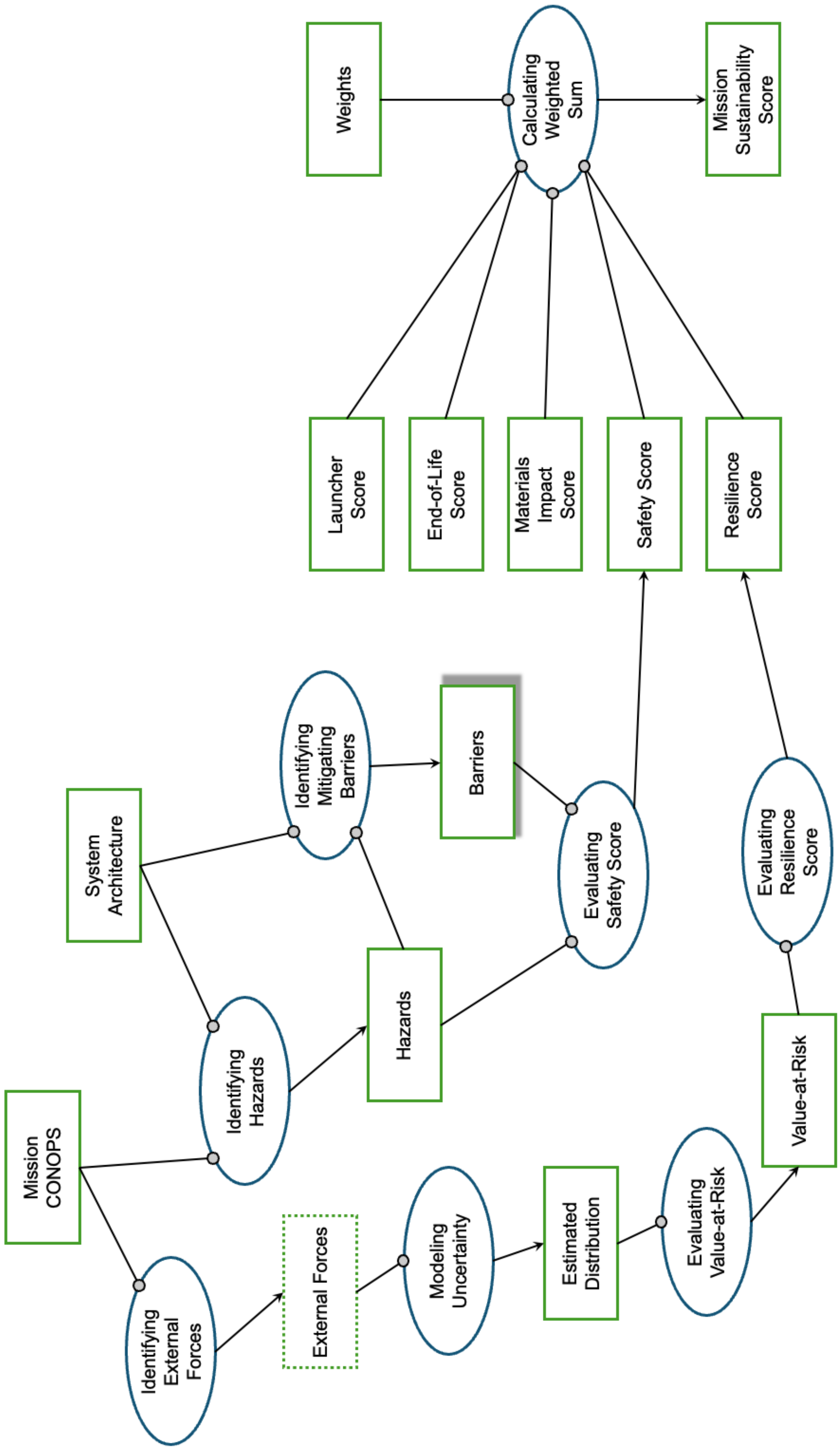


Figure 59: Object-Process Model of the Mission Sustainability Score calculation. Compliant with ISO 19450:2024 for OPM, see appendix B (page 97).

6.4.2 External Forces Analysis

In this external forces analysis, we intend to evaluate the resilience of the system. We define resilience as the capacity of a system to provide value under unexpected conditions. These conditions are defined by external forces, which themselves constitute the main sources of uncertainty for any system. Hence we want to characterise a case of degraded conditions that is possible and evaluate the merit of the system under these circumstances. The difference of provided value between the expected scenario and the degraded scenario will characterise how resilient the system is.

Step 1 - Identification

To characterise the environment of the system, we start by identifying the external forces of the system. These external forces are all the factors that may impact the function of the system but are out of the boundaries of the system.

Step 2 - Uncertainty Modeling

Now that we have identified the different factors that compose the environment of the system, we want to model them. This modeling will enable us to clearly define the degraded case. By nature, external forces are not in our control and their behavior is characterised by an inherent level of uncertainty. This level of uncertainty constrains the accuracy of the model that we are able to produce. By clearly identifying the level of uncertainty, we can define from the beginning the best model (See figure 60) that can be produced.

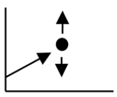
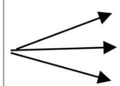
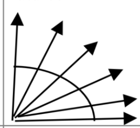
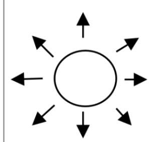
	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future 	Alternate futures (with probabilities) 	A few plausible futures 	Many plausible futures 	Unknown future 	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 60: Progressive levels of uncertainty. Figure from Marchau et al. [12].

There is also a trade-off that arises between the models accuracy and the time required to build them. For the sake of the project and the case study, we will eliminate level 1 and level 2 models to gain time and stress test the outcomes of the system more efficiently. For example we know that stochastic models (level 2 uncertainty) for debris impact can be generated, but it is too time intensive for us. Hence we will model all the different forces in the same way, as follows:

- **EXT_FORCE_XX:** XXX
  - Description: XXX
  - Normal:
    - Description: XXX
  - Degraded:
    - Description: XXX
  - Critical:
    - Description: XXX

Step 3 - System outcome evaluation for different conditions

Now that we have characterised the external forces of the system, we can provide a relevant description of degraded and critical cases for the system, and hence evaluate the outcomes of the system in these scenarios. If we were in a case of Model Based Systems Engineering, we could assess the outcomes quantitatively, but we are not. Therefore, and also for the sake of simplification, we will limit ourselves to a qualitative assessment and fill the following:

- Normal conditions:
  - System Outcome: XXX
- Degraded conditions:
  - System Outcome: XXX
- Critical conditions:
  - System Outcome: XXX

Finally, we can assign a score between 0 and 1 based on the following rationale, with the results of the previously defined system outcomes:

- **1:** The outcome in degraded conditions is the exact same as in normal conditions is the exact same as in normal conditions, hence the system is resilient.
- **0.66:** The outcome is close between normal and degraded conditions, and all functions remain compliant with the requirements.
- **0.33:** The outcome is significantly different and falls below requirements compliance, but the system survives.
- **0:** The system fails completely and does not survive.

6.4.3 System Analysis for Safety Assessment

We desire to assess the safety of the overall mission to integrate into the score. Safety is defined by the capacity of a system to protect from hazards. Hazards are defined in our case by all undesirable events that occur from within the system boundaries, like the failure of a subsystem. In this part we want to identify all the parts of the system that may fail or behave in way that was not intended. Then we want to analyse the behavior of the system that is caused by such an issue.

We also need to identify the barriers that are created in the system to counteract these hazards, and therefore assess if the system is safe. These barriers mostly take the form of redundancy when it comes to hardware but may also be planned modes transition in given circumstances. The state of the system after the mitigation must be assessed to ensure that it is an effective one and that it is sufficient to ensure the survival of the system.

Now that we have identified the different hazards that may arise, and that we have defined/identified mitigations for each of them, we are able to qualitatively assess the safety of the system. We can assign a score between 0 and 1 based on the following rationale, with the results of the previously defined system outcomes:

- **1:** All the hazards that are identified have a mitigation that allows the system to keep a desirable behavior.
- **0.66:** Most of the hazards that are identified have a mitigation that allows the system to keep a desirable behavior.
- **0.33:** Most of the hazards have mitigations but these mitigations do not maintain the system in a desirable state.
- **0:** The hazards are not mitigated.

6.4.4 Weighted Sum

We have the following inputs that are defined by the high level architecture:

- Materials impact score
- Resilience score
- Launch vehicle score
- Safety score
- End-of-life score

For the final score, a survey was conducted with engineers and managers from the industry (See appendix F, p.112 for the results). A goal of this survey was to determine the weights of the different objectives that we defined for a sustainable space system (See figure 27, p.35). The main outcome of this survey is that sustainability for the space environment is more important than for the earth environment, in the current state. The figure 68 shows the weights that were derived from the survey for the mission sustainability score.

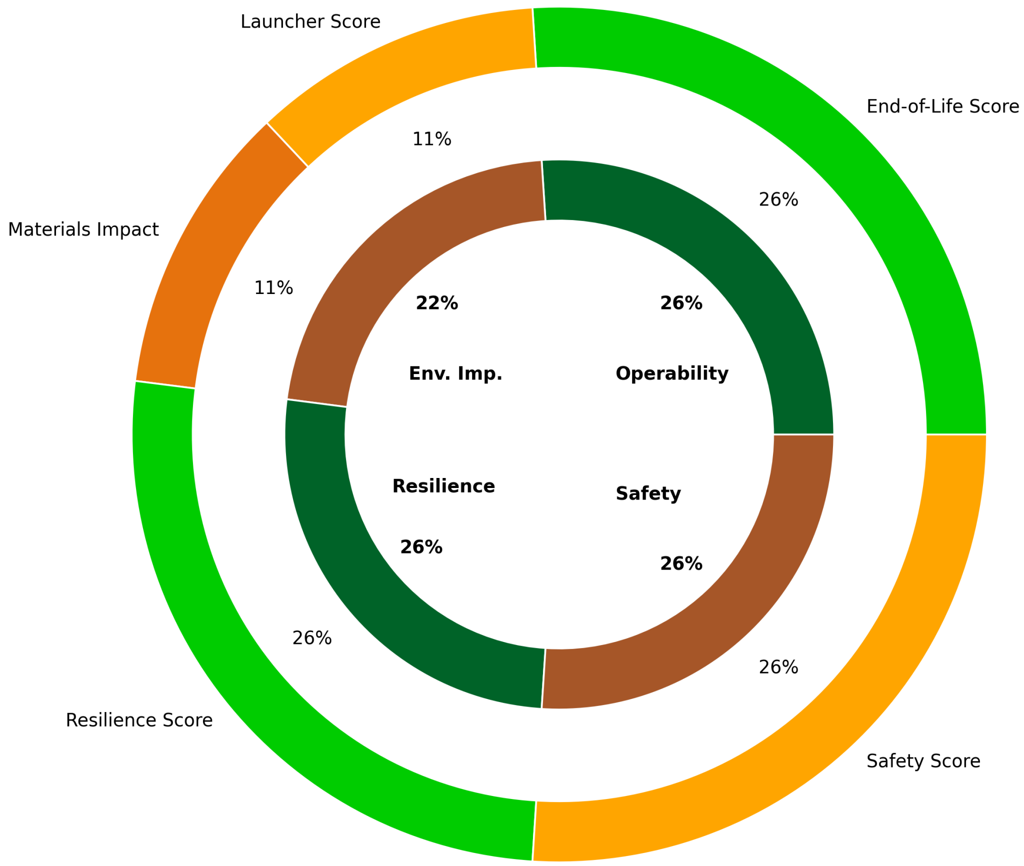


Figure 61: Weights allocation used for the weighted sum, derived from the ilities that define a sustainable space system, and the results of the industry survey. Own figure.

To obtain the final score, we simply compute the weighted sum of the different input scores. Since they are already all comprised between 0 and 1, and that the weights sum to unity (i.e. 1), we have a score that is compliant with the requirement.

6.4.5 Example of Scoring for the Course ENG-411

During the course ENG-411, we successfully integrated a sustainability role in the Concurrent Engineering process, although some research gaps were identified. These research gaps were replaced with unverified or simplified data, favorising the integration of the role to its accuracy. Also, due to some constraints of the course, like the fact that the different role are under the responsibility of students and not highly experienced engineers, some parts like the high level life cycle assessment were stressed and the results do not necessarily have the fidelity that was initially desired.

It is important to note that these scores are also defined as a case study and more advanced analyses would be required in a real mission design environment. The following serves as an example of application, and results are purposefully kept untouched after the end of the ENG-411 course for a clear perception of the outcomes.

High Level Life Cycle Assessment

Using the previously defined process for the high-level Life Cycle Assessment (See subsection 6.1), with unverified data to fill the research gap (Purpose of integration, see table 3, p.62), we obtain a score of **0.4** for the environmental impact of the satellite's design.

Launcher Selection

A requirement of the mission was to use a european launcher, which reduced the number of solutions considerably. Vega-C is dominated (See figure 50, p.72), hence discarded from the solutions set. We were left with Ariane 6, in either configuration. The total mass that needed to be sent was low enough to fit in a 62 configuration, and it was evaluated as the most sustainable choice as well in terms of atmospheric impact. Being the solution that is the best at the current State-of-the-Art in terms of atmospheric impact, the score of the Ariane 62 is **1**.

End-of-life Strategy

For the End-of-Life strategy, we chose the option with the lowest required Delta velocity (Δv), and integrated real-options to have a flexible strategy. Through this flexibility, compliance with regulations in ensured and debris generation due to the impact can be adapted. Hence the strategy complies with the rationale for a score of **1**.

External Forces Analysis

The external forces that are identified for the system are:

- **EXT_FORCE_01:** Debris
  - Description: This external force describes the debris population which may collide with the spacecrafts of the mission.
  - Normal:
    * Description: There is a low amount of debris in the cislunar space.
  - Degraded:
    * Description: There is a medium amount of debris in the cislunar space.
  - Critical:
    * Description: There is a high amount of debris in the cislunar space.

- **EXT_FORCE_02:** Solar Activity
  - Description: This external force describes the solar storms that may impact the spacecrafts of the mission.
  - Normal:
    - Description: Solar activity is low in the cislunar space.
  - Degraded:
    - Description: Solar activity is medium in the cislunar space.
  - Critical:
    - Description: Solar activity is high in the cislunar space.

And the Value-at-Risk of the system is assessed in the following list. We can conclude that even in degraded conditions, the system is delivering a desirable function, hence a score of **1** is assigned.

- Normal conditions:
  - System Outcome: The system functions as intended.
- Degraded conditions:
  - System Outcome: The low aspect ratio due to absence of solar arrays minimises the risk of collision and ensures functionality. Thermal shielding protects from solar storms.
- Critical conditions:
  - System Outcome: The previously described mitigations allow moderate impact on the satellite function but it may be forced to start it End-of-Life strategy operations earlier.

System Analysis for Safety Assessment

For the system analysis, the following hazards were considered as the most impactful on the spacecraft's function:

- Propulsion system failure
  - Identified barrier: Redundancy with 2 thrusters.
- Power system failure
  - Identified barrier: Redundancy with multiple batteries and independent solar cells.
- Communication system failure
  - Identified barrier: Redundancy with multiple antennas.

We see that all the hazards are mitigated and therefore we can assign a score of **1** for the safety of the system.

Weighted Sum

We did not have the results of the survey at the time of the last design session, hence we applied weights of our own choice*, and we obtained a result of **0.91** for the sustainability of the mission.

* *(Launcher: 15%, Materials Impact: 15%, End-of-Life: 30%, Resilience: 20%, Safety: 20%)*

6.4.6 Requirements Verification

Requirements were defined for the mission sustainability score subsystem. As can be observed below, all requirements are verified and hence the subsystem can be integrated.

- **REQ_EXT_FORCES_01:**
  - **Description:** The system shall return a value ranging between zero and one, where one represents an equal value under normal or degraded conditions, and zero represents a failure of the system under degraded conditions.
  - **Verification:** The rationale provided in subsubsection 6.4.2 allows to return a score between zero and one for the resilience. Hence this requirement is verified.
- **REQ_SAFETY_01:**
  - **Description:** The system shall return a value ranging between zero and one, where one represents a totally safe system where all hazards are mitigated, and zero represents a very unsafe system that puts the overall function in jeopardy.
  - **Verification:** The rationale provided in subsubsection 6.4.3 allows to return a score between zero and one for the safety. Hence this requirement is verified.
- **REQ_SCORE_01:**
  - **Description:** The system shall return a value ranging between zero and one, where one represents the most sustainable system that can be designed at the current state-of-the-art and zero is the threshold from which the system is considered not sustainable at all.
  - **Verification:** The weights derived from an industry survey (See figure 68, p.117) allow to perform a weighted sum of scores that are all ranging between zero and one. Hence this requirement is verified.

7 System Verification: ENG-411 Concurrent Engineering of Space Missions

7.1 Iterative Design Process

The goal is to design a system to integrate a sustainability role in the concurrent design facility. In the context of this project, the system is directly tested and verified through the concurrent engineering course at EPFL (ENG-411). As can be observed on the figure 62, the course has a timeline that - relative to the project - is quite challenging and unusual. A normal course of actions would be to first design the system in details and then test it to iteratively improve it. Here we need an operational concept very early on to rapidly iterate over the design, and then reflect on the lessons that can be learned from these tests. It is challenging because it requires to rapidly change the design between sessions, to keep track of everything that needs improvement and to keep track of the evolution of the system to ensure compliance with the requirements that were defined.

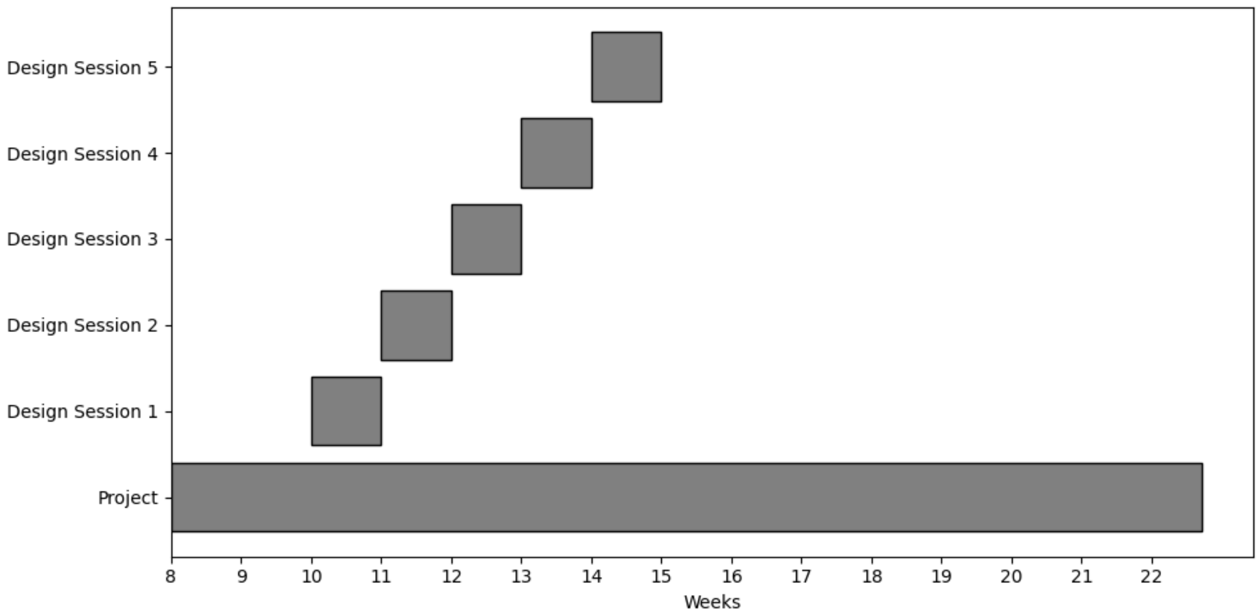


Figure 62: Gantt chart showing the timeline of the course ENG-411 relative to the one of this project. Weeks of 2025. Own figure.

To effectively integrate the feedback from each design session into the system, a template for the documentation is created (See appendix D, p.105) and updated between sessions. This document is intended to operate the system as intended during the course, and comprehensively evaluate the Outcomes of Interest at each session. The goal is also to ensure the compliance with the requirements, identify the weakest points and hence apply the most relevant corrections to the system. The overall design process aims at starting with a broad range of solutions, that are progressively eliminated to reduce the complexity of the system of increase its merit up to the point of being compliant with the requirements.

7.2 Risk Analysis

An initial risk analysis was prepared, and iteratively updated through the design sessions (See appendix D, p.105). These risks were divided in two categories, with uncertainties coming from external forces which are all the interfaces that are required for the system to function. The second category is the hazards, which aims at planning responses for failures of elements from the system itself, and avoiding undesired behavior due to propagation of these failures.

7.2.1 External Forces for Robustness and Resilience

The definition of the external forces is critical in defining the conditions to which the system is subject. These conditions have an "expected value", but their behavior can vary. This "variance" induces a risk of not falling under expected conditions, and hence we want to define a probable scenario of deterioration and the worst case scenario. For all of these scenarios, a plan shall be prepared to have a robust and resilient strategy. This step is especially important in the context of the CDF because all the interfaces are defined by human interaction, which are uncertain by nature. That is the reason why it is recommended to integrate safety in systems that are comprised of human components (like operators, see figure 12, p.21).

7.2.2 Hazards for Safety

We define here the hazards as being the issues that occur directly from inside the system. These may be due to unexpected dynamics or any design subtility that was underestimated. We want to try to identify these hazards early on to create barriers that will prevent undesired outcomes. This is the point where we integrate safety in the system. All the processes of the sustainability role are performed by an operator (the engineer) and it is therefore important to plan for varying human behavior. In future steps, safety can also be increased by limiting the operations of the engineer and automating processes.

7.3 Evolution of Outcomes of Interest

All along the design sessions, the Outcomes of Interest were tracked in order to effectively identify weaknesses and target the most important changes to make. Most of the changes occured in the first design sessions. These changes were not only due to the feedback of the sessions, but also because the system had a very low initial readiness. Actual changes due to direct feedback from the sessions occured in later iterations where actual data was collectible from other subsystems. More sessions would be valuable to stress test the system and improve it further.

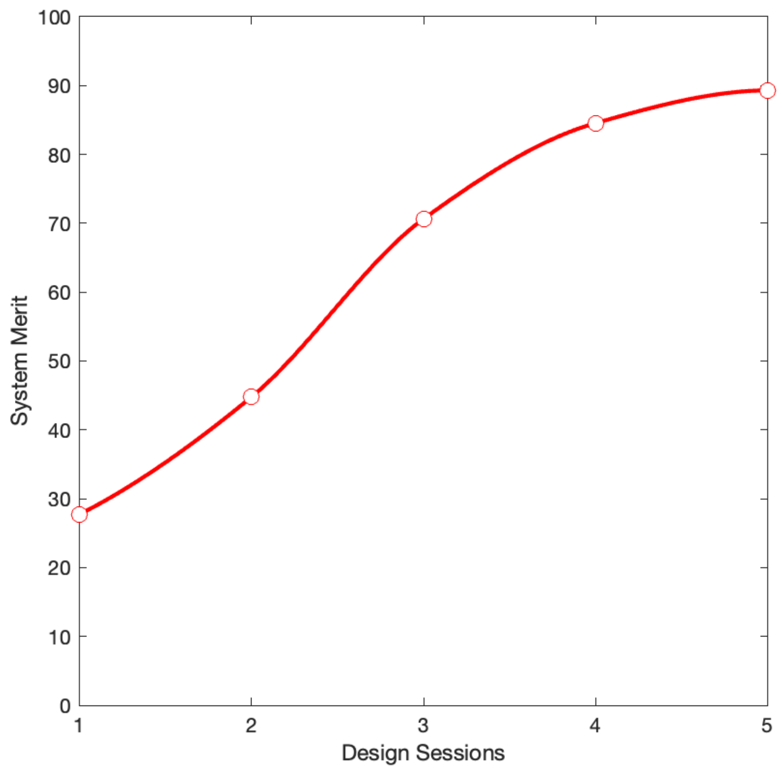


Figure 63: Evolution of the merit of the system through the design sessions. Merit defined as the weighted sum of the Outcomes of Interest, with the weights derived from the stakeholder expectations (See figure 33, p.47).

7.4 Evolution of External Forces

We have previously performed a risk analysis, and a part of this analysis focused on the external forces. We defined three cases from normal to critical. These forces were tracked along the design sessions (See table 6), to assess the accuracy of the initial assumptions and to analyse if the system could benefit from improved conditions.

It is important to note that these forces were tracked based on criteria that would be applicable in an industrial environment. Due to the fact that the system was tested in a academic environment, the result are naturally low. Also, the role of the customer was different from a real industrial case. Indeed, actual industrial projects usually exhibit requirements ambiguity and dynamics that affect expectations. In our case, these factors were not "simulated".

External Force		Design sessions				
ID	**Name**	**#1**	**#2**	**#3**	**#4**	**#5**
EXT_FORCE_01	COMET	Critical	Critical	Degraded	Degraded	Degraded
EXT_FORCE_02	System Engineer	Critical	Degraded	Degraded	Degraded	Degraded
EXT_FORCE_03	Structure Engineer	Critical	Critical	Critical	Critical	Critical
EXT_FORCE_04	Propulsion Engineer	Critical	Critical	Degraded	Normal	Normal
EXT_FORCE_05	Power Engineer	Critical	Critical	Critical	Critical	Degraded
EXT_FORCE_06	Customer	Normal	Normal	Normal	Normal	Normal
EXT_FORCE_07	Activity Browser	Critical	Critical	Degraded	Degraded	Degraded

Table 6: Evolution of the external forces across the design sessions

We can observe that due to the fact that the case study was performed in the context of a university course where many students had little to no experience in space systems engineering and concurrent design, many interfaces were found as being in degraded or even critical states. The answer that were planned for these conditions seemed to be appropriate but the overall sustainability of the mission was impacted.

We can also observe that the softwares were both degraded, and therefore their merit was overestimated before the start of the sessions. For the case of Activity Browser, it was even totally replaced during the sessions for AI-generated data. This allowed to identify clearly where the research gaps existed between current LCA practices and the concurrent engineering process.

Finally, the software that served as the central tool for concurrent design (i.e. COMET) revealed to be constraining in terms of communications capabilities. The main issue that was encountered and not initially expected is that it cannot support basic engineering tools like the Concept of Operation. In the end, most data exchanges occured through oral communication and bypassed COMET.

7.5 Overall Results and Requirements Verification

Overall it was possible to integrate the system in the concurrent engineering process, and a positive impact was observed. As can be observed below, all the requirements are verified.

- **REQ_01:** System Readiness
  - **Description:** The system shall have a final readiness level of 100%, enabling Off-The-Shelf integration in the concurrent engineering process for the design of space missions.
  - **Verification:** With the system documentation provided by the appendix D (page 105), an integration is directly possible with clear input requirements. Hence this requirement is verified.
- **REQ_02:** System Flexibility via Safety Measures
  - **Description:** All the identified hazards shall have an associated mitigation.
  - **Verification:** A full set of mitigations is provided with the documentation (See appendix D, p.105), therefore the system is verified.
- **REQ_03:** System Modularity
  - **Description:** The system's modules shall be specified using a Newman Eigenvectors method applied on the DSM of the system architecture.
  - **Verification:** The figure 40 (page 57) shows that this requirement is verified.
- **REQ_04:** Documentation Comprehensiveness
  - **Description:** The final documentation comprehensiveness shall be 100%. A full documentation of the system is provided, with complete formatting. A full feedback form is filled after the desing session to keep track of the events and failures the arised in operation.
  - **Verification:** The appendix D (page 105) constitutes the documentation that verifies this requirement.
- **REQ_05:** Innovation
  - **Description:** The final system shall at least be at a State-of-the-Art level.
  - **Verification:** Sustainability was succesfully integrated in the Concurrent Engineering process and multiple research gaps were identified, showing that the system evolves further than the State-of-the-Art or at least at its edge.
- **REQ_06:** System Comprehensiveness - Environmental Impact
  - **Description:** The environmental impact shall be fully covered and a positive impact can be observed.
  - **Verification:** A high-level "LCA" is integrated and fed back to the different subsystems so that they can account for them, and the launch vehicle selection is actively made towards a sustainability objective. Hence this requirement is verified.
- **REQ_07:** System Comprehensiveness - Operability
  - **Description:** The long-term operability shall be fully covered and a positive impact can be observed.
  - **Verification:** The End-of-Life strategy is actively selected for debris generation minimisation, and an increase in strategy flexibility ensures a probabilistically advantageous outcome. Therefore this requirement is verified.
- **REQ_08:** System Comprehensiveness - Resilience
  - **Description:** Resilience shall be covered.
  - **Verification:** A resilience assessment is performed, without direct and explicit role to improve it. However this still verifies the requirement.
- **REQ_09:** System Comprehensiveness - Safety
  - **Description:** Safety shall be covered.
  - **Verification:** A safety assessment is performed, without direct and explicit role to improve it. However this still verifies the requirement.

8 Conclusion

The purpose of this project was to design and test a system to integrate a sustainability role in the concurrent engineering process, specifically applied to the design of space missions. This role was oriented towards four axes that represent characteristics of a sustainable space systems: *Environmental efficiency, long-term operability, safety, and resilience*. These four objectives were all served by different processes, from launcher selection to high-level Life Cycle Assessment. All these processes were then fed into a single sustainability score for the mission that was then provided to systems engineers.

In terms of integration in the concurrent engineering process, the project was successful and the system verified all the requirements, hence ensuring compliance with stakeholder expectations. On the side of the content of the role, multiple research gaps were identified and the feasibility of future advancements was assessed.

To fill the gaps that were identified, and improve the design processes in the field of sustainability in space systems engineering, the following list of research topics is defined:

- Creation of a tool for mission concept trade-off accounting for sustainability (e.g. figure 29, p.37).
- Definition of a standard LCA procedure (for this specific application) for results that are coherent, reproducible, and reliable.
- LCA projects relying on the previously defined standard procedure, all serving the purpose of filling the gaps in the database and focusing on the required energy for the production of technologies $\left(\frac{kWh}{kg}\right)$.
- Projects for the integration of environmental impact criteria in the supplier selection process, in a direction that facilitates policymaking.
- Exploration of partnerships with Launch Vehicle operators (e.g. Arianespace) to integrate atmospheric impact measurement systems on launchers and collect data in different layers of the atmosphere.
- Analysis of collected data for atmospheric impact of launches in different layers of the atmosphere.
- Research of the atmospheric impact of reentry and trade-off between demising strategies and non-demising strategies.
- Quantitative Real Options Analysis for flexible End-of-Life strategy, accounting for uncertainty in debris population. This analysis would return the propellant margin to load in the spacecraft to ensure that the End-of-Life is compliant with stakeholder expectations, in most cases. The goal is to mitigate risks, but also to enable to take opportunities in favorable scenarios (e.g. extend lifetime).
- Integration of DSM based safety assessment in concurrent engineering, collaborating closely with systems engineers. The goal is to have a more rigorous approach to safety and a more quantitative method for the identification of hazards.

For the subject of space sustainability, this project is placed at the highest level of space engineering activities, mission design. At the first step of a long chain of design processes, an integration of sustainability paves the way for the definition of meaningful requirements at lower levels and the design of more eco-efficient space systems.

Sustainability can now start to be progressively integrated in the Concurrent Engineering process and used directly in the industry. With systems engineering as the foundation of the role, it can easily be adapted from space mission design to other CDF activities, like technology roadmapping (See figure 26, p.34).

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A Abstract of EUCASS Paper

Space sustainability in systems engineering and design processes - Industry overview and case study at EPFL

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Key words: Space Sustainability, Systems Engineering, Life Cycle Assessment, screening, early design, future space systems, Concurrent Engineering

Abstract

The increasing cadence of launches, satellite production, and spacecraft atmospheric re-entries prompts the space industry and regulators to better consider the growing environmental impacts of space missions on Earth and on orbital resources. It is known that the largest leverage for impacts reduction is during the early design phases of a new system, which is incentivizing the industry to consider (space) sustainability more closely during the design process. Indeed, it is increasingly being recognized as a critical component of systems engineering for space mission design.

Some actions are already undertaken in industry, but are - so far - too isolated and with limited results. The long-term objective of research around space sustainability is to extend the current design-to-time, design-to-objective and design-to-cost philosophies, by including design-to-environmental-impacts. Indeed, industries have to prepare now to anticipate growing scrutiny from the general public and space agencies, as well as increasing regulatory pressure from national entities and international ones like the European Union. This can only be reached with a workforce that is educated about the challenges of space sustainability, and has the necessary skill set. Although not yet existing everywhere, some educational programs have been developed for active professionals as well as for students who will soon graduate and take up positions in industries.

This paper draws on existing literature and known projects to review current practices and challenges in integrating sustainability in the early design process of space systems. Interviews have been conducted with engineers, practitioners, and managers in the space sector about how they implement sustainability criteria into their design and decision making processes. It was investigated if and what type of guidelines or handbooks they use, as well as whether simplified Life Cycle Assessment (LCA) is applied". Moreover, interview questions delved into their integration of environmental criteria within design methods such as Multidisciplinary Design Analysis and Optimization (MDAO), and systems engineering approaches like Model-Based Systems Engineering (MBSE). A case study performed in the Concurrent Design Facility (CDF) during a class at EPFL is presented, highlighting practical challenges and potential strategies for embedding sustainability into collaborative design environments. The paper also emphasizes the critical need for education in space sustainability, in order to prepare the next generation of leaders and to raise awareness amongst the current decision makers in the space sector. Finally, the paper proposes recommendations for the best course of action to improve the synergies between space sustainability and systems engineering.

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B Main ISO 19450-compliant OPM Symbols

The content of this appendix is from Dori [5] and shows a summarised version of the ISO 19450 standard.

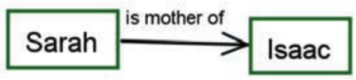
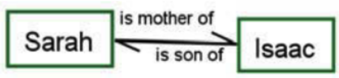
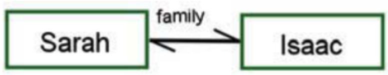
Things: stateful objects and processes

thing property	value (notation)	thing		
		object	**stateful object**	**process**
essence	Informatical (flat)	Recipe	Recipe outdated updated	Counting
	Physical (shaded)	Hammer	Hammer broken fixed	Mining
affiliation	Systemic (solid)	Balance	Drill faulty operational	Producing
	Environmental (dashed)	Record	Recipe outdated updated	Exporting

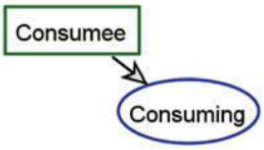
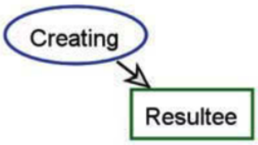
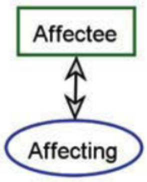
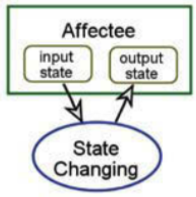
Fundamental structural links

modality	aggregation-participation	exhibition-characterization	generalization-specialization	classification-instantiation
Graphics – Object-Process Diagram (OPD)	Whole Part	Exhibitor Attribute	General Specialization	Class Instance
Textual – Object-Process Language (OPL)	**Whole** consists of **Part.**	**Exhibitor** exhibits **Attribute.**	**Specialization** is a **General.**	**Instance** is an instance of **Class.**

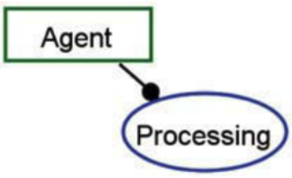
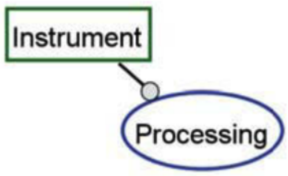
Tagged structural links

unidirectional tagged link	bidirectional tagged link	Reciprocal tagged link
 **Sarah is mother of Isaac.**	 **Sarah is mother of Isaac.** **Isaac is son of Sarah.**	 **Sarah** and **Isaac** are **family.**

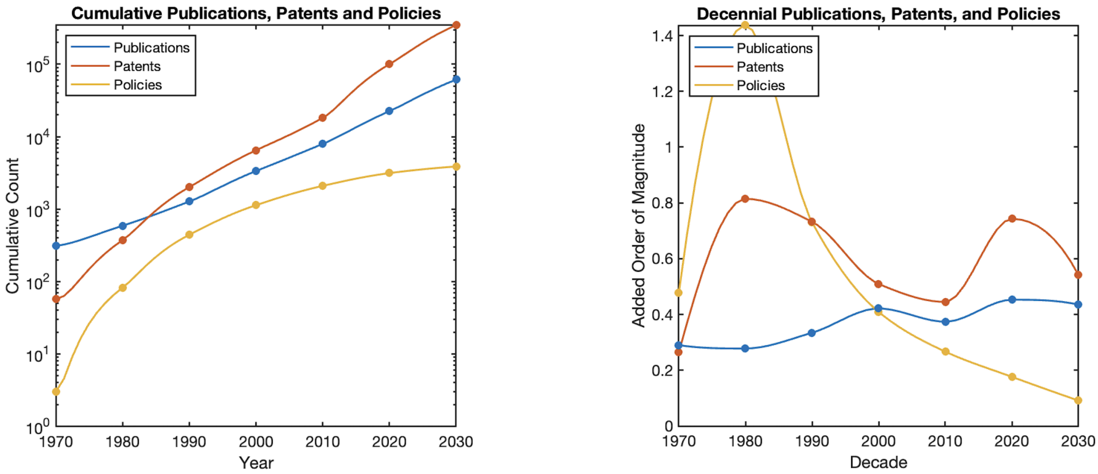
Procedural transforming links

consumption link	result link	effect link	in-out link pair
 **Consuming** consumes **Consumee.**	 **Creating** yields **Resultee.**	 **Affecting** affects **Affectee.**	 **State Changing** changes **Affectee** from **input state** to **output state.**

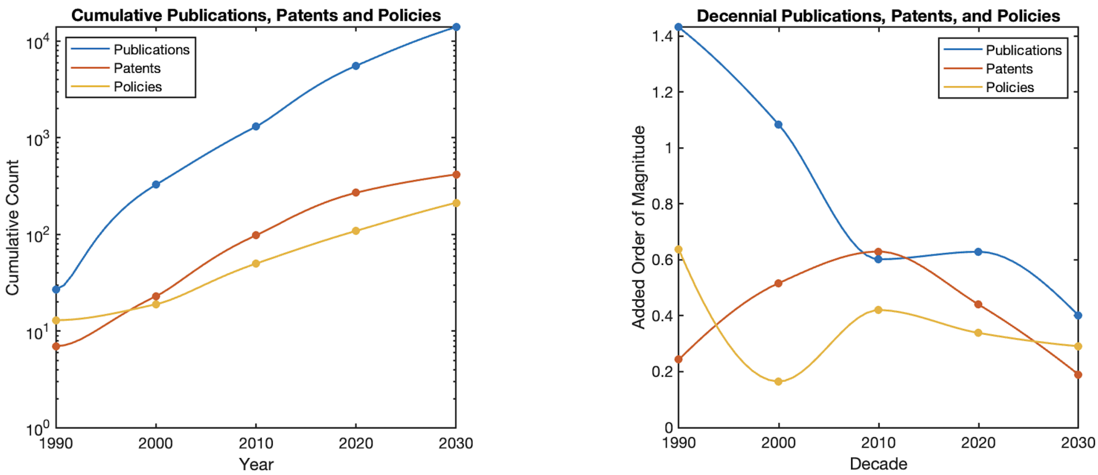
Procedural enabling links

agent link	instrument link
 **Agent** handles **Processing.**	 **Processing** requires **Instrument.**

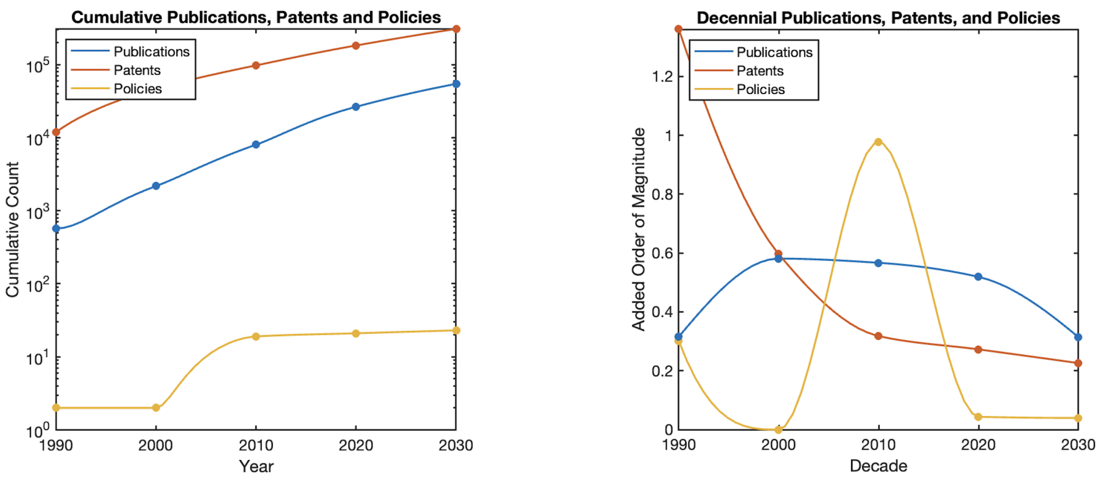
C Comparative Analysis of Ilities in Publications, Patents, and Policies



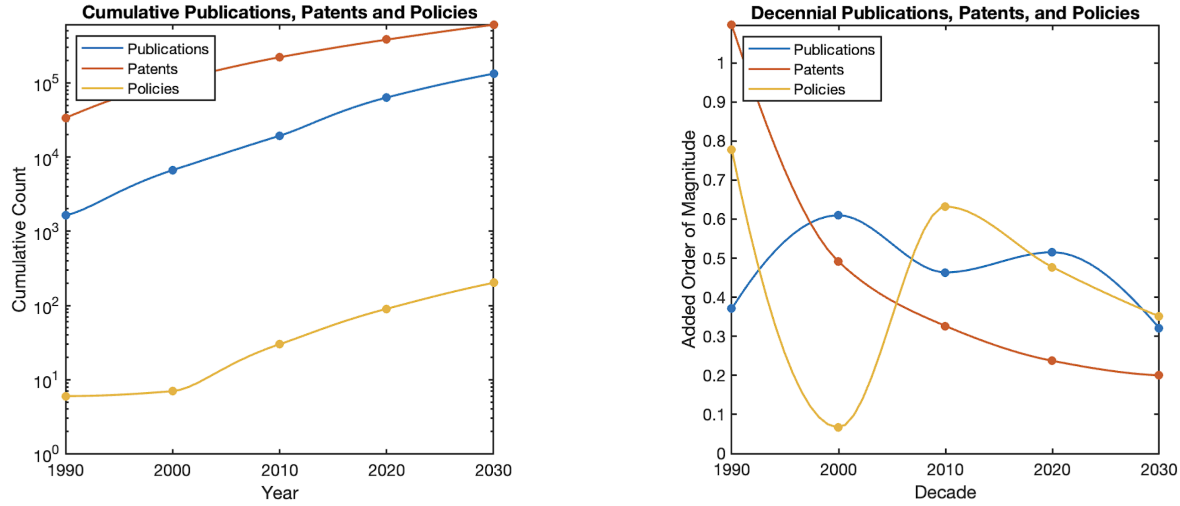
Comparative analysis of publications, patents, and policies relating adaptability.



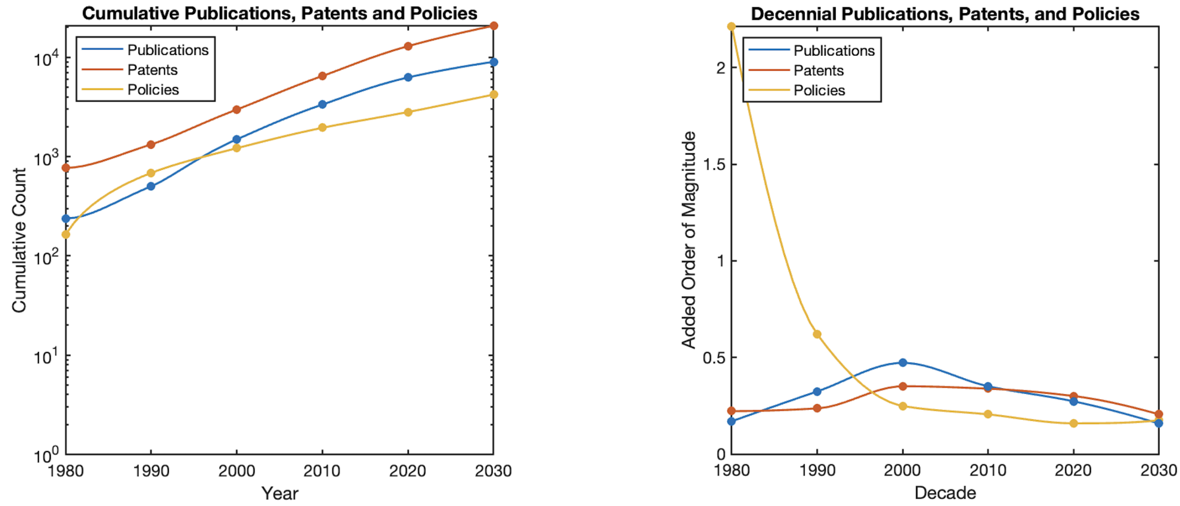
Comparative analysis of publications, patents, and policies relating affordability.



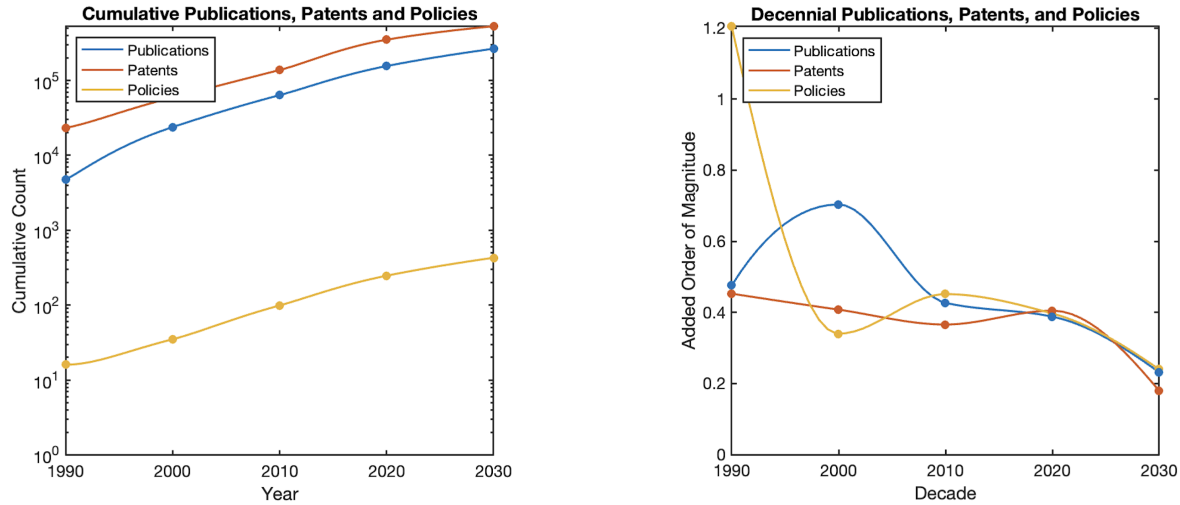
Comparative analysis of publications, patents, and policies relating usability.



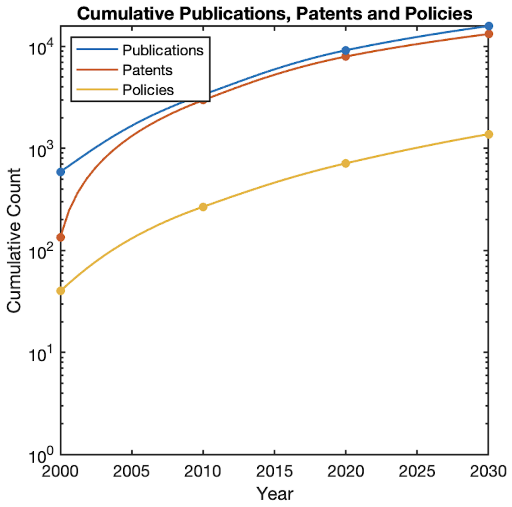
Comparative analysis of publications, patents, and policies relating durability.

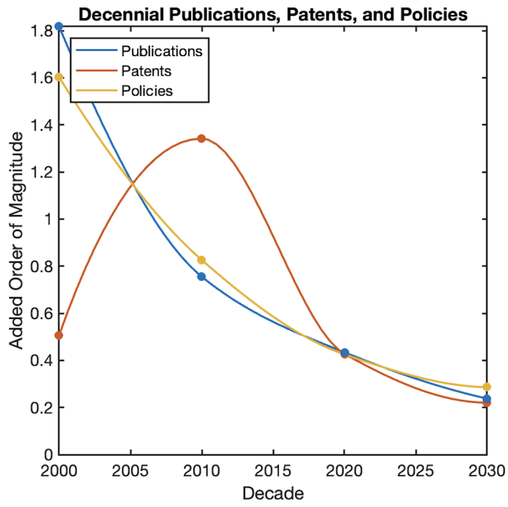


Comparative analysis of publications, patents, and policies relating extensibility.

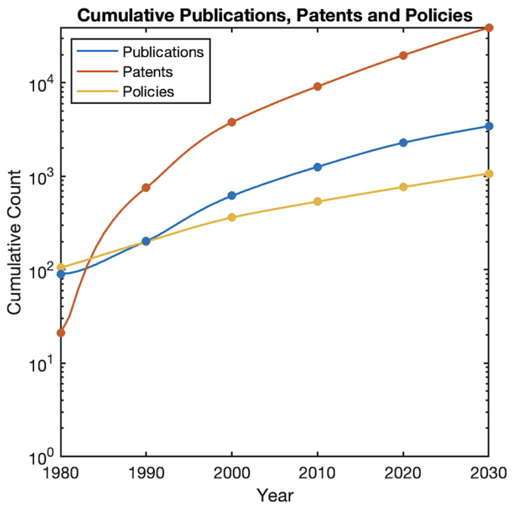


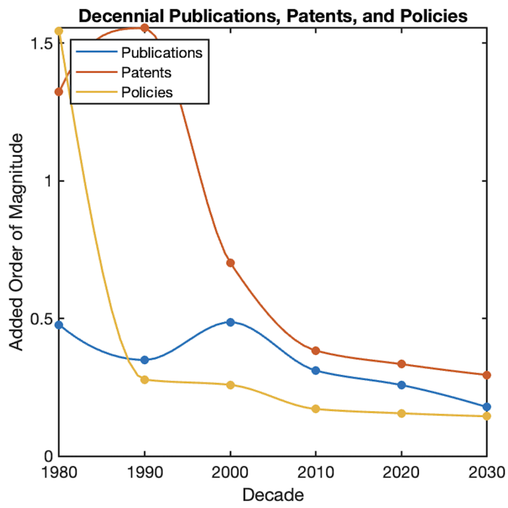
Comparative analysis of publications, patents, and policies relating flexibility.



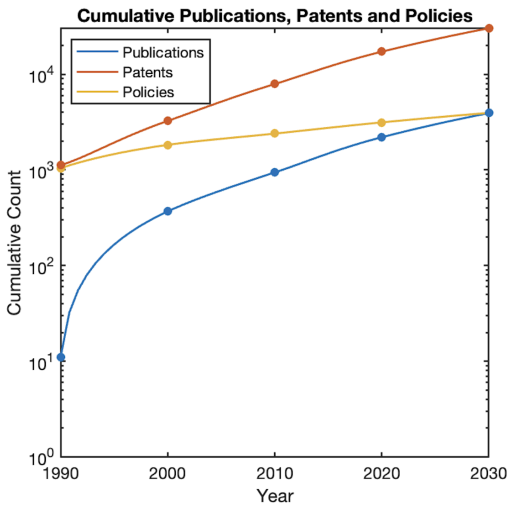


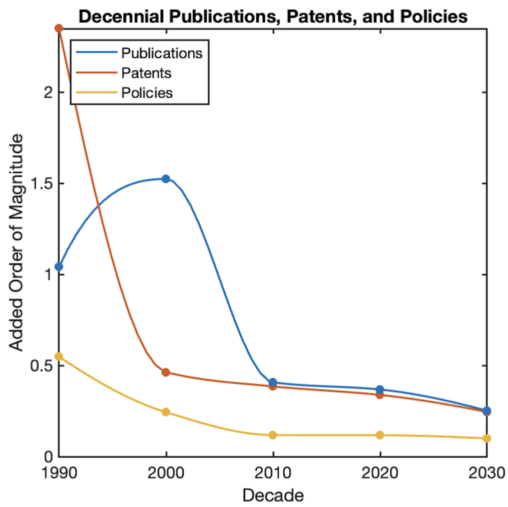
Comparative analysis of publications, patents, and policies relating interoperability.



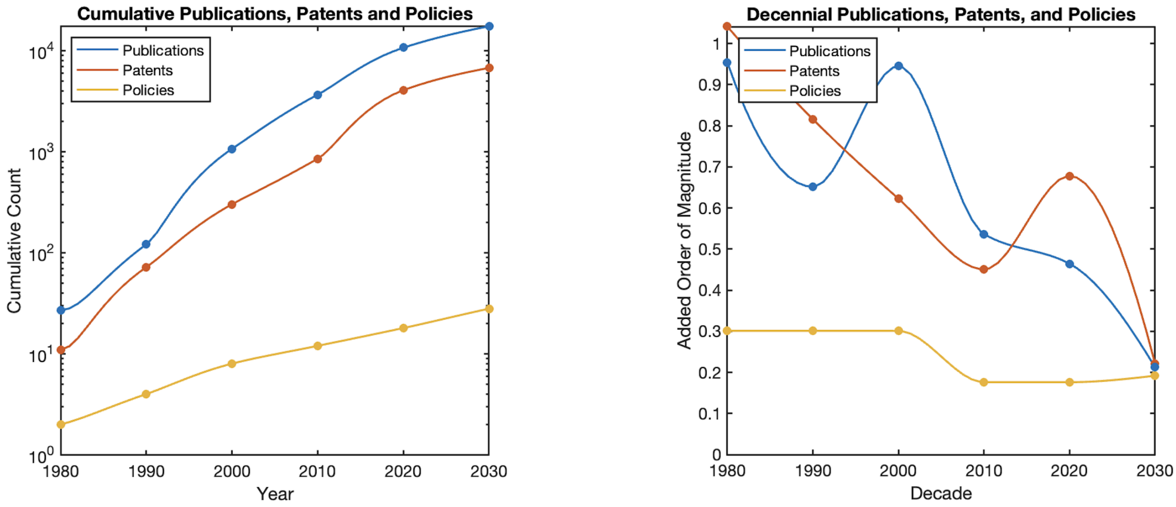


Comparative analysis of publications, patents, and policies relating maintainability.

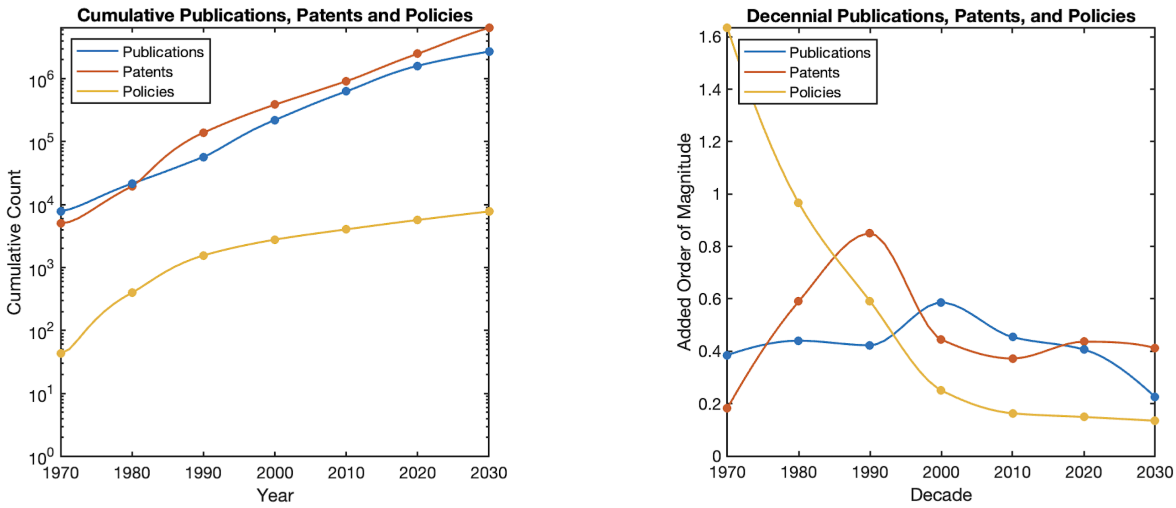




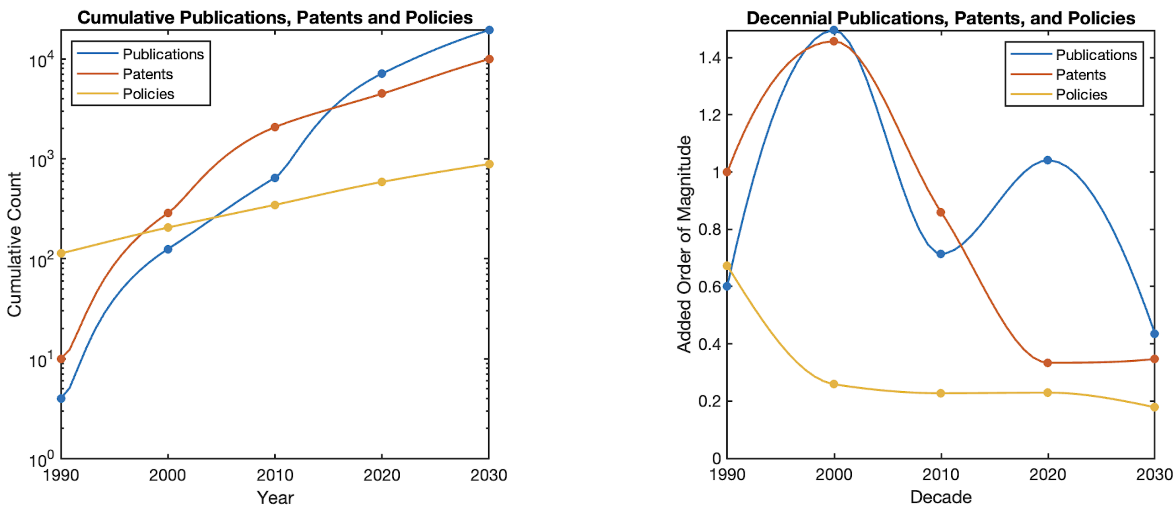
Comparative analysis of publications, patents, and policies relating manufacturability.



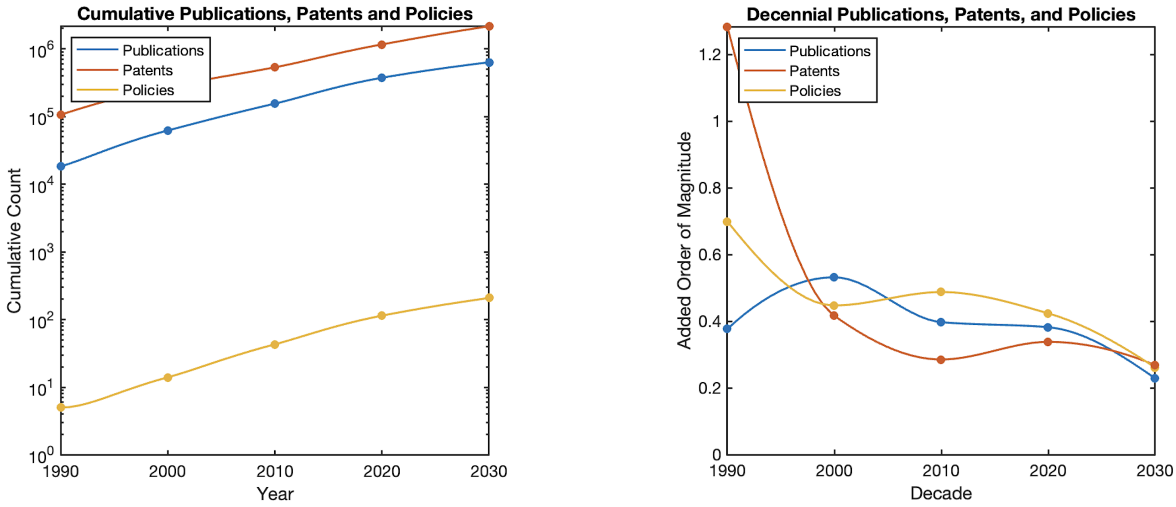
Comparative analysis of publications, patents, and policies relating modularity.



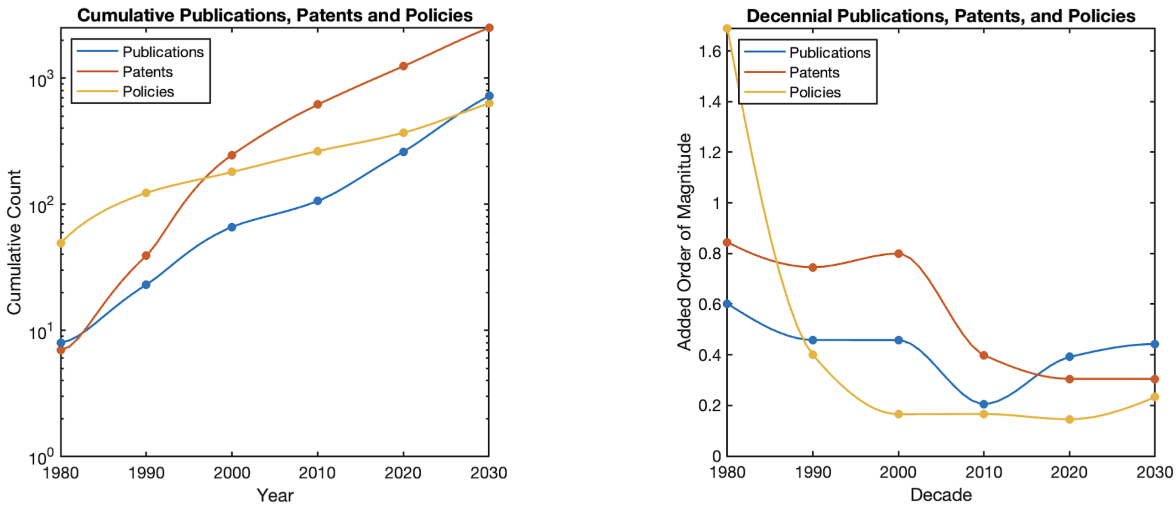
Comparative analysis of publications, patents, and policies relating quality.



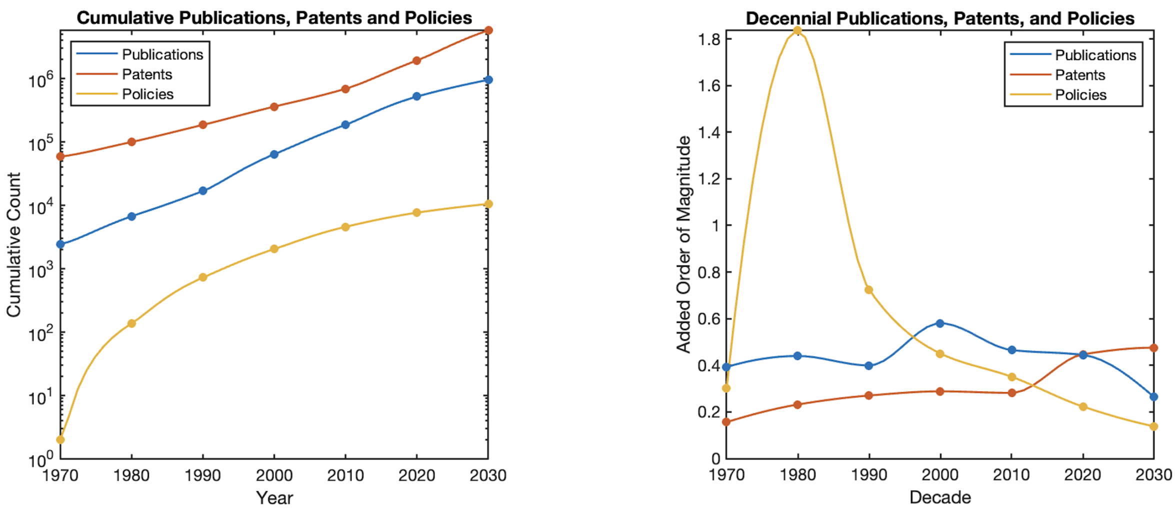
Comparative analysis of publications, patents, and policies relating recyclability.



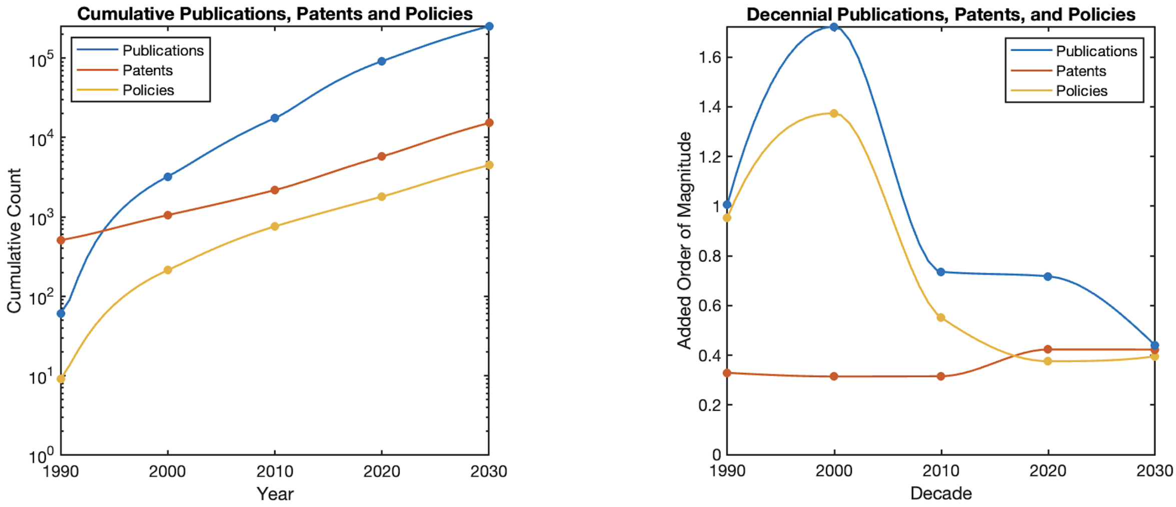
Comparative analysis of publications, patents, and policies relating reliability.



Comparative analysis of publications, patents, and policies relating repairability.



Comparative analysis of publications, patents, and policies relating safety.



Comparative analysis of publications, patents, and policies relating sustainability.

D Sustainability in CDF: Operations Handbook

This appendix serves the purpose of showing the structure of the document that was used during the design sessions of the course ENG-411. To avoid redundant information in this report, most parts describing the system itself directly send to the relevant sections of the report.

1 Conceptual Model

The conceptual model of the system can be found on figure 37 (page 54).

2 System Architecture

The modularised system architecture and relevant analysis can be found in subsection 5.4 (page 56).

3 Processes

3.1 High-level Life-Cycle Assessment

The steps of the high-level life-cycle assessment are described in the subsubsection 6.1.5 (page 66).

3.2 Launcher Selection

The figure 50 (page 72) serves as reference for the launcher selection process.

3.3 End-of-Life Strategy

The steps of the End-of-Life strategy are described in the subsection 6.3 (page 74).

3.4 External Forces Analysis for Resilience Assessment

The steps of the high-level life-cycle assessment are described in the subsubsection 6.4.2 (page 83).

3.5 System Analysis for Safety Assessment

The steps of the high-level life-cycle assessment are described in the subsubsection 6.4.3 (page 84).

3.6 Mission Sustainability Score

The steps of the high-level life-cycle assessment are described in the subsubsection 6.4.4 (page 85).

4 Risk Analysis

4.1 External Forces

The definition of the external forces is critical in defining the conditions to which the system is subject. These conditions have an "expected value", but their behavior can vary. This "variance" induces a risk of not falling under expected conditions, and hence we want to define a probable scenario of deterioration and one worst case scenario. For all of these scenarios, a plan shall be prepared to have a robust and resilient strategy.

- **EXT_FORCE_01:** COMET
  - Description: COMET is the software that enables to manage the interfaces between the different subsystems. It is used by ESA for their concurrent engineering endeavors. It is a critical external force because it is where the main system output goes.
  - Normal:
    - Description: In the expected case, COMET works normally without any apparent issues. We can seemlessly add the parameters that are relevant to our system, and retrieve values from other subsystems.
    - Strategy: No particular action, operation of the system as shown in the conceptual model.
  - Degraded:
    - Description: COMET comes with anomalies, the needed values cannot all be retrieved, or an unacceptable amount of time is needed before getting them. There are also issues to integrate our own model and values.
    - Strategy: Reduce the data entries to the minimum and operate some calculations on external software.
  - Critical:
    - Description: COMET is not operational at all.
    - Strategy: Perform calculations on external device. Communicate information to others directly.
- **EXT_FORCE_02:** System Engineer
  - Description: System Engineers constitute a source of inputs parameters for the system.
  - Normal:
    - Description: Delivery of needed parameters early on.
    - Strategy: Perform calculations as intended.
  - Degraded:
    - Description: Late delivery of needed parameters.
    - Strategy: Setup the model with mock up values, while keeping an easily changeable as possible.
  - Critical:
    - Description: No delivery of needed parameters.
    - Strategy: Perform informed assumptions on possible values, with 3 values corresonding to: expected value, plus or minus one standard deviation.
- **EXT_FORCE_03:** Structure Engineer
  - Description: Structure Engineers constitute a source of inputs parameters for the system.
  - Normal:
    - Description: Delivery of needed parameters early on.
    - Strategy: Perform calculations as intended.
  - Degraded:
    - Description: Late delivery of needed parameters.
    - Strategy: Setup the model with mock up values, while keeping an easily changeable as possible.
  - Critical:
    - Description: No delivery of needed parameters.
    - Strategy: Perform informed assumptions on possible values, with 3 values corresonding to: expected value, plus or minus one standard deviation.

- **EXT_FORCE_04:** Propulsion Engineer
  - Description: Propulsion Engineers constitute a source of inputs parameters for the system.
  - Normal:
    - Description: Delivery of needed parameters early on.
    - Strategy: Perform calculations as intended.
  - Degraded:
    - Description: Late delivery of needed parameters.
    - Strategy: Setup the model with mock up values, while keeping an easily changeable as possible.
  - Critical:
    - Description: No delivery of needed parameters.
    - Strategy: Perform informed assumptions on possible values, with 3 values corresonding to: expected value, plus or minus one standard deviation.
- **EXT_FORCE_05:** Power Engineer
  - Description: Power Engineers constitute a source of inputs parameters for the system.
  - Normal:
    - Description: Delivery of needed parameters early on.
    - Strategy: Perform calculations as intended.
  - Degraded:
    - Description: Late delivery of needed parameters.
    - Strategy: Setup the model with mock up values, while keeping an easily changeable as possible.
  - Critical:
    - Description: No delivery of needed parameters.
    - Strategy: Perform informed assumptions on possible values, with 3 values corresonding to: expected value, plus or minus one standard deviation.
- **EXT_FORCE_06:** Customer
  - Description: The customers define the expectations of the mission and drive the CONOPS. They also impose a cost constraint that enters in the trade-off analysis of the launcher selection.
  - Normal:
    - Description: Clear requirements from the beginning.
    - Strategy: Perform calculations as intended.
  - Degraded:
    - Description: Ambiguous requirements.
    - Strategy: Study alternatives and propose a choice.
  - Critical:
    - Description: Very ambiguous requirements.
    - Strategy: Make a choice that is as robust as possible, focusing on the performance and cost, to ensure the functional integrity.
- **EXT_FORCE_07:** Activity Browser
  - Description: It is a required software to perform the high level LCA.
  - Normal:
    - Description: The system works as intended.
    - Strategy: Perform calculations as planned.
  - Degraded:
    - Description: Issues with the software with limited information.
    - Strategy: Make some assumptions and search for data directly online.
  - Critical:
    - Description: Activity browser is not functional.
    - Strategy: Use online data and/or make assumptions.

4.2 Hazards

We define here the hazards as being the issues that occur directly from inside the system. These may be due to unexpected dynamics or any design subtility that was underestimated. We want to try to identify these hazards early on to create barriers that will prevent undesired outcomes.

- **HAZARD_01:** External Forces Analysis Failure
  - Description: The analysis might fail.
  - Estimated impact: Low
  - Estimated probability: Medium
  - Integrated barrier: If happens: remove from the weighted sum and adjust the weights in consequence.
- **HAZARD_02:**System Analysis Failure
  - Description: The analysis might fail.
  - Estimated impact: Low
  - Estimated probability: Medium
  - Integrated barrier: If happens: remove from the weighted sum and adjust the weights in consequence.
- **HAZARD_03:** Trade-off Analysis Failure
  - Description: The analysis might fail.
  - Estimated impact: High
  - Estimated probability: Low
  - Integrated barrier: If happens: Choose the least expensive launcher for the required dimensions and mass.
- **HAZARD_04:** Real-Options Analysis Failure
  - Description: The analysis might fail.
  - Estimated impact: Medium
  - Estimated probability: Low
  - Integrated barrier: If happens: No actions linked to the End-of-Life, remain "as-is".
- **HAZARD_05:** High Level LCA Failure
  - Description: The LCA might fail and return erronated values.
  - Estimated impact: High
  - Estimated probability: Medium
  - Integrated barrier: If happens: Do not provide feedback to Structure, Power, and Propulsion. Enter the average value of possible range for the materials impact (0.5).
- **HAZARD_06:** Weights error
  - Description: A weighted sum is performed to compute an overall sustainability score. The weights might have been derived from misevaluated customer expectations and therefore might lead to errors.
  - Estimated impact: Medium
  - Estimated probability: High
  - Integrated barrier: Recurring communication with customer at the beginning of sessions and end of sessions.

5 Post-Operations Evaluation

This section must be filled after operation to identify points of failure and improvements for next iteration.

5.1 Conditions of Expected External Forces

- **EXT_FORCE_XX:**

  ....

5.2 Unexpected External Forces

....

5.3 Unidentified or Underestimated Hazards

....

5.4 Evaluation of System Readiness

....

5.5 Evaluation of System Flexibility

....

5.6 Evaluation of System Modularity

....

5.7 Evaluation of System Innovation

....

5.8 Evaluation of System Comprehensiveness

5.8.1 Integration of Environmental Impact

....

5.8.2 Integration of Long-term Operability

....

5.8.3 Integration of Resilience

....

5.8.4 Integration of Safety

....

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E Spreadsheet for Launcher Selection Trade-off Analysis

Name	Propellant 1	Normalised impact 1	Mass 1 (tons)	Propellant 2	Normalised impact 2	Mass 2 (tons)	Cost (M$)	Launch Mass to LEO (kg)	$/kg to LEO	Normalised Affordability	Sustainability	Normalised Sustainability
Ariane 62	Solid	0	284	Hydro/Lox	1	180	$ 108.00	10350	$ 10,434.78	75%	39%	55%
Starship Real	Metha/Lox	0.5	4600	-	0	0	$ 100.00	40000	$ 2,500.00	94%	50%	71%
Starship Musk	Metha/Lox	0.5	4600	-	0	0	$ 20.00	250000	$ 80.00	100%	50%	71%
Electron	Kero/Lox	0	14.5	-	0	0	$ 7.50	300	$ 25,000.00	41%	0%	0%
New Glenn	Metha/Lox	0.5	1000	Hydro/Lox	1	120	$ 68.00	45000	$ 1,511.11	97%	55%	79%
Soyuz	Kero/Lox	0	200	-	0	0	$ 55.00	8200	$ 6,707.32	84%	0%	0%
Long March 5	Kero/Lox	0	572	Hydro/Lox	1	165	$ 70.00	25000	$ 2,800.00	94%	22%	32%
Falcon 9	Kero/Lox	0	510	-	0	0	$ 67.00	22800	$ 2,938.60	93%	0%	0%
Delta IV Heavy	Solid	0	490	Hydro/Lox	1	255	$ 350.00	28790	$ 12,157.00	71%	34%	49%
Vega C	Solid	0	88	Solid	0	23	$ 45.00	2500	$ 18,000.00	57%	0%	0%
Space Launch System	Solid	0	1000	Hydro/Lox	1	2300	$ 4,000.00	95000	$ 42,105.26	0%	70%	100%
Falcon Heavy	Kero/Lox	0	1330	-	0	0	$ 120.00	63800	$ 1,880.88	96%	0%	0%
Ariane 64	Solid	0	560	Hydro/Lox	1	180	$ 124.00	21500	$ 5,767.44	86%	24%	35%
Ariane 5 ECA	Solid	0	480	Hydro/Lox	1	170	$ 180.00	21000	$ 8,571.43	80%	26%	37%
Vulcan	Solid	0	200	Metha/Lox	0.5	265	$ 125.00	27200	$ 4,595.59	89%	28%	41%
Atlas V ULA	Kero/Lox	0	284	Solid	0	220	$ 153.00	19000	$ 8,052.63	81%	0%	0%
Ariane 4	hydrazine	0	200	hydrazine	0	0	$ 160.00	7600	$ 21,052.63	50%	0%	0%

F Industry Survey Results

This appendix shows the results of part of the industry survey that is relevant to this project. For this survey, a total of 12 answers were collected.

1. How important would you evaluate the expectations of your stakeholders for more sustainable future missions? (1: not important, 5: very important)
   - *Average Rating: **3.27***
2. And specifically your customers? (1: not important, 5: very important)
   - *Average Rating: **3.55***
3. How much importance do you give to the environmental impact of future missions (on Earth)? (1: low important, 5: high importance)
   - *Average Rating: **3.91***
4. How much importance do you give to the long-term operability of the space environment? (1: low importance, 5: very high importance)
   - *Average Rating: **4.64***
5. How much importance do you give to the resilience and safety of future missions? (1: low importance, 5: very high importance)
   - *Average Rating: **4.64***
6. Would you benefit from integrating sustainability in rapid decision making at the high level? How?
   - *Main Outcome: Yes, most of the results are yielded from high level decisions.*
7. Do you feel that integrating sustainability in high level decision making is too uncertain or complicated to be accountable in the current state? Why?
   - *Main Outcome: Highly uncertain, currently not accounted for design, need for better defined rules and principles.*
8. Have you already been part of a concurrent design session / study?
   - *55% Yes ; 45% No*
9. If yes, did it include some considerations about space sustainability? And how?
   - *Main Outcome: The only Yes relates about debris mitigation requirements, the rest is No.*
10. Do you think that, combined with effective tools, a simplified LCA with a short data collection effort, to support choices of technology, could be performed already during an early-phase concurrent design study? If not, what is currently missing for that?
    - *Main Outcome: Yes. One thinks it would differ from a traditional LCA. One has concerns about the validity of results.*

Qualitative analysis of survey's outcome

The results of this survey are mainly used in this project to define the weights of the mission sustainability score. It is important to note that these weights serve as a reference, but should be adapted with a stakeholder analysis tailored to each project. Moreover, the low number of answers to the survey does not allow to say that the results are representative of reality. Even with a higher response rate, we should make sure that the participants come from diversified backgrounds to avoid biases.

To verify a result, a high number of responses shall be collected (>100) from different backgrounds (i.e. military, research, industry, ...) and only then, statistical analysis could be performed (based on distributions of results) to provide insights on stakeholder expectations.

G EUCASS Paper Contribution - Sustainability in the CDF

Concurrent engineering consists in grouping experts from different relevant domains in one "room" to concurrently design a mission or system. The experts supposedly carry the knowledge of the State-of-the-Art in their relevant fields and directly face constraints from other parties to reach a compromise that is the most suited for the goals of the mission. To this date, active efforts to integrate sustainability as a role in the CDF were made [21] [3], but further advancements are required to enable a concrete application as part of an actual space mission design. This section aims at integrating it and defining how sustainability can transition from an assessment purpose to design, and how it interacts with other roles. A test conducted at EPFL's concurrent design facility over the course of a 7-week timespan, and the different elements were refined and improved based on the lessons learned from these design sessions.

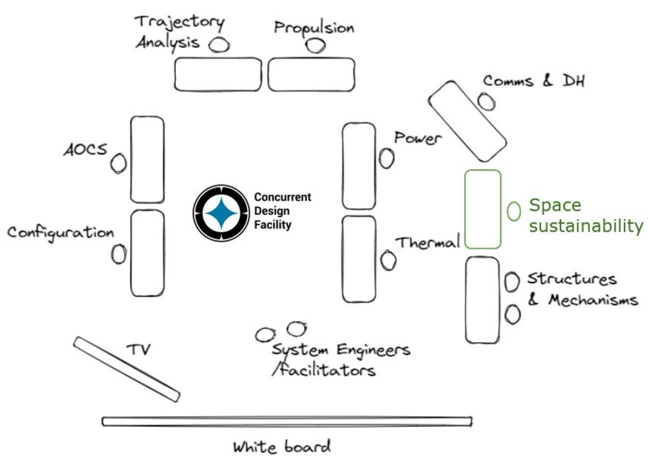

Figure 64: Set up of the EPFL CDF, with the space sustainability domain of expertise.

G.1 Axes of focus

Typical engineering processes are centered around functionality and do not take into account other factors, or at least not explicitely. Although it may be acceptable at a very low system level where feedback is rapidly obtained and changes easily propagated, it is a different matter for complex engineering systems with thousands of components. Indeed, long design and life durations as well as the very large amount of components and interfaces make the initial phases of the design "freeze" many choices early on. Once made, these decisions - such as the architecture - are nearly impossible to modify.

From this, the topic of lifecycle properties - also known as *ilities* - has been a growing research topic in engineering systems, and especially on methods to implement them in early design phases, such as system architecture. Accounting for ilities enables better awareness regarding the merit of different concepts and paves the way for trade-offs between architectures alternatives. Functionality cannot be the only accounted factor when selecting a system architecture because many challenges arise which are not directly correlated with the function of the system. According to Rhodes et al. [11], ilities can be seen as a response to these challenges, which are identified as: life cycle, complexity, human behavior, uncertainty, and dynamics. The figure 65 shows the principal ilities identified as a relevant response for each challenge.

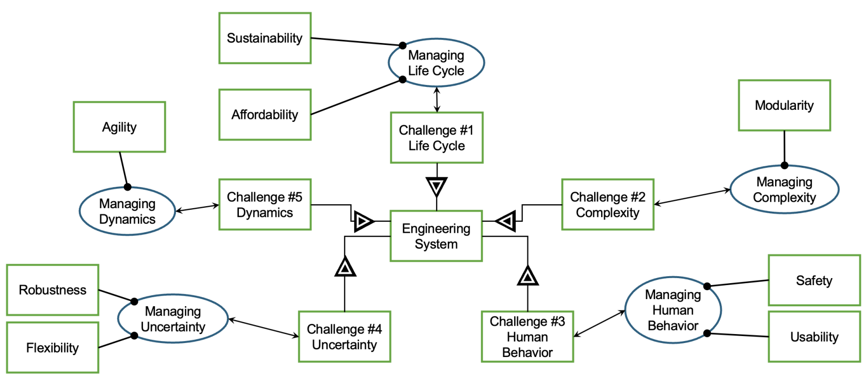

Figure 65: Object-Process Model of the response that ilities provide to the challenges of engineering system, the model is not complete but provides the most used ilities for each challenge. Inspired from Rhodes et al. [11].

In 2015, the United Nations (UN) defined the Sustainable Development Goals (SDG). These goals provide an explicit foundation regarding the objectives that should be targeted. They can be used to define a basis for a quantitative measure for sustainability. For example, in the work of Maier et al. [11], a metric of eco-efficiency (See equation 9) is produced with the SDGs, with some goals defined as "Levers for transformation". We can hence observe that science and technology play an important role in improving the situation, with clear incentives on affordability, clean energies (Low environmental impact), innovation, and circular economy.

$$\text{Eco-efficiency} = \frac{\text{Human wellbeing}}{\text{Environmental impact}} \tag{9}$$

We can create a link between the space sector, equation 9, and figure 65, by correlating the "Human well-being" with usability and safety. And in the sense of space systems, usability can be translated into operability to be better suited, where it can immediately be linked with the well-known problem of debris. We can also add the factor of resilience, which is compliant with the concept of a lasting system, and correlated with sustainability according to De Weck [19]. Hence, we can define an adapted version of equation 9, tailored for space systems (See equation 10).

$$\text{Space Systems Sustainability} = \frac{\text{Operability} \cdot \text{Safety} \cdot \text{Resilience}}{\text{Environmental Impact}} \tag{10}$$

G.2 High-Level Design Processes for Sustainability in the CDF

The role of sustainability in concurrent engineering follows the direction dictated by the previously defined objectives (See equation 10, p.114). To this end, four main processes ensure a comprehensive approach to the design of the mission: Launcher selection, End-of-Life strategy, high-level Life Cycle Assessment, and a mission sustainability score (itself integrating resilience and safety assessments).

G.2.1 Launcher Selection

The atmospheric impact of the launcher on the atmosphere is a topic that is quite unknown. Some tools attempt to assess quantitatively these effects, but they require too much information to be used and to be relevant at our level. We know from Sirieys et al. [18] that the most impactful parameter for the atmospheric impact of a launcher is its propellant. We also know that the main negative impacts of each propellant occur through three different phenomena. These phenomena are ozone depletion and radiative forcing in the Stratosphere, as well as cloud formation in the Mesosphere. The figure 66 provides the foundation for the selection of a launcher in the CDF, with an integrated qualitative sustainability rating based on whether each propellant impacts those phenomena, and on their mass proportions.

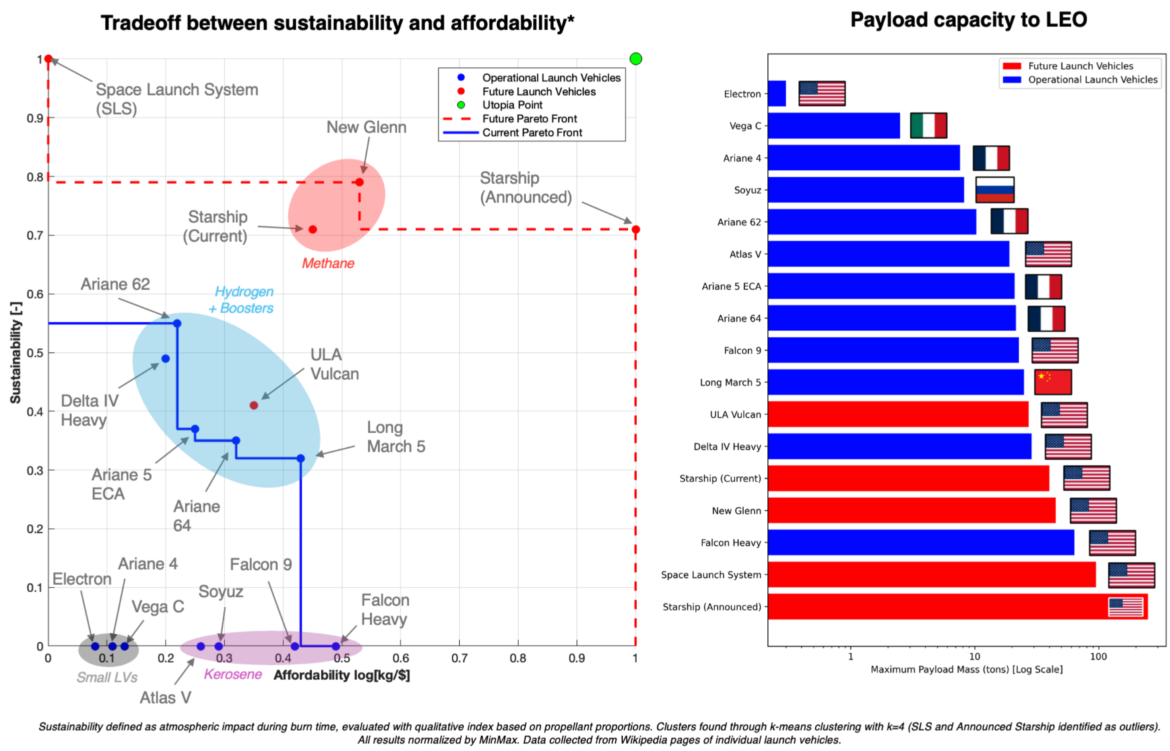

Figure 66: Decision support for launch vehicle selection. Sustainability index based on negative atmospheric impacts of propellants described by Sirieys et al. [18].

G.2.2 End-of-Life Strategy

The traditional method for selecting the End-of-Life strategy is to simply perform a trade-off between the different alternatives, select one, and compute the required Delta velocity (Δv). This method becomes less and less robust with time because some uncertainties are more impactful. For instance, increasing debris population or future regulations are more and more important for the mission design. These uncertainties cannot be ignored if the long-term operability of the space environment needs to be ensured. Recognising these uncertainties is especially crucial in the selection of the End-of-Life strategy because it is planned for the end of the mission, usually being after at least 5 years of operations, without accounting the time between mission planning and commissioning.

Real-Options Analysis (ROA) [14] offers a solution to this matter by introducing flexibility in systems to make them more robust to inevitable uncertainty. The ultimate goal of such an analysis is reduce risks, but also to take profit of opportunities. Due to the constraints of the CDF, this analysis is limited to being qualitative but sets the foundation to recognising uncertainties, and planning options for potential case. These options then allow to refine the computations of the propellant margins for instance. The merit of this strategy is improved by the addition of the ROA, and is then qualitatively evaluated, based on a predefined rationale.

G.2.3 High-Level Life Cycle Assessment

LCA is a method used to evaluate the environmental impact of a system from the extraction of materials to the disposal. It is mostly used to evaluate systems that are already designed and manufactured, as a reference for future improvements. In our case, we want to determine if it is feasible to integrate this method as a design tool, especially in very early design of space missions.

To evaluate the feasibility of such a task, we need to identify the unknown parameters at the stage of the CDF, and assess the sensitivity of the outcomes to these parameters. In the CDF, we are performing trade-offs for the selection of technologies, hence the suppliers and the detailed components of each technology is unknown. The figure 67 shows the parts of the carbon footprint, specifically for aluminum production, that are dependent on the direct emissions of the production processes and the indirect emissions due to their energy consumption. We can immediately observe the very high impact of this second parameter. Therefore, having it as an unknown is a major issue, and we can directly draw the conclusion that it is unfeasible to reliably assess the carbon footprint at such a high-level.

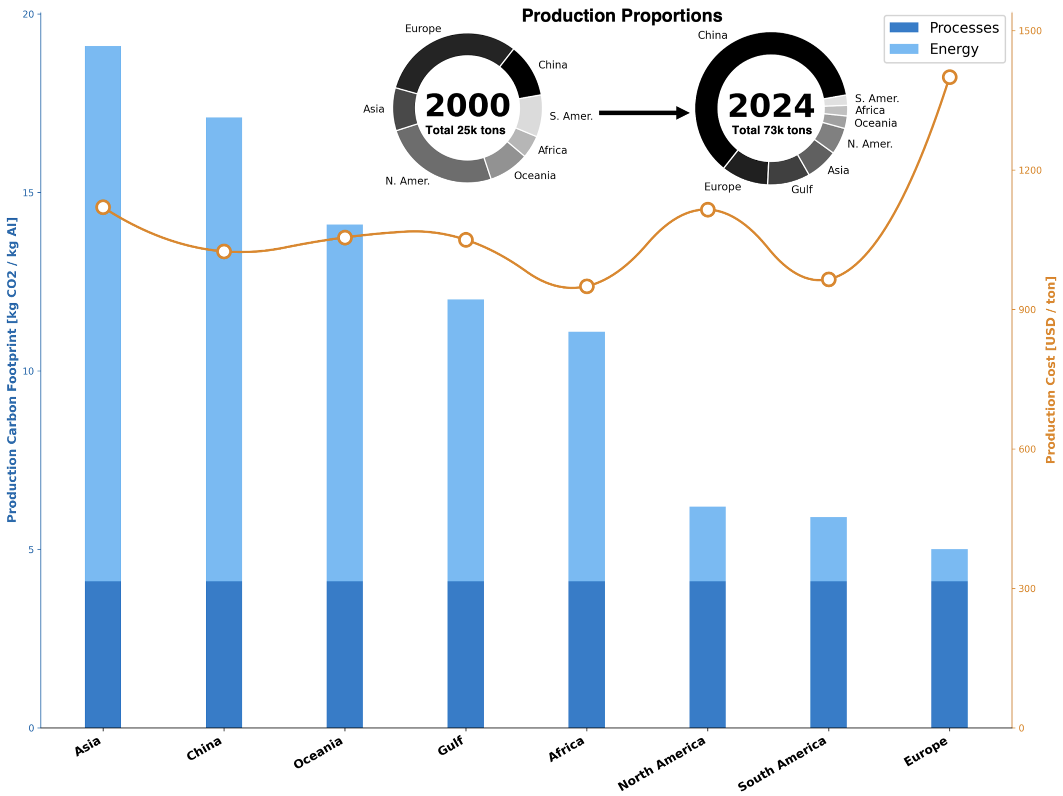

Figure 67: Carbon footprint and production cost of aluminum, by region and on average. Data for carbon footprint from Saevarsdottir et al. [17], data for production cost partly from Thunder Said Energy [6], and proportions data drom International Aluminium [2].

We can also observe that the carbon footprint due to the process itself is constant across locations, showing a standardisation of the process. We can conclude that the variation is due to the impact of the energy source and that the required energy for production is stable across locations. Moreover, for the second unknown parameter, the components being defined by the architecture has to be stable for a technology, given that it is a mature one. In the case of space systems, we integrate mature technologies. Therefore, we determined that the carbon footprint is unfeasible to evaluate in the CDF (See olive factor in equation 11), but by removing the uncertainty source (namely the supplier's environmental impact, see red factor in equation 11), we obtain a stable metric, which is defined by the required energy to produce a technology (See blue factor in equation 11).

$$\left[\frac{kg.CO_2.eq}{kg}\right]_{\text{Production}} = \left[\frac{kg.CO_2.eq}{kWh} \cdot \frac{kWh}{kg}\right]_{\text{Energy}} + \left[\frac{kg.CO_2.eq}{kg}\right]_{\substack{\text{Processes}\\\text{(constant)}}} \tag{11}$$

For an integration in the CDF, the metric of the required energy for production is used as reference for the environmental impact of a technology, and traditional trade-off analysis methods can be applied. It can be accounted in the exact same way as cost and performance are, and provided to relevant subsystems.

G.2.4 Mission Sustainability Score

We now want to compute a sustainability score that accounts for all the aspects of the mission and is provided to systems engineers to enable the integration of sustainability in mission level trade-offs. We have previously defined a score for the sustainability of the launcher, the LCA also returns a score from the required energy for production (relative to other technology alternatives, normalised), and the End-of-Life strategy is accompanied by a rationale that enables a scoring of the outcome. To integrate resilience and safety (See equation 10, p.114), we will add scores based on two additional assessments. Both of these assessment result in qualitative scoring, based on predefined rationale. We can therefore integrate all of these previous processes in the overall score.

The first analysis aims at assessing the resilience of the mission, through an external forces analysis. We define resilience as the capacity of a system to provide value under unexpected conditions. These conditions are defined by external forces, which themselves constitute the main sources of uncertainty for any system. Hence, we want to characterise a case of degraded conditions that is possible and evaluate the merit of the system under these circumstances. The difference of provided value between the expected scenario and the degraded scenario will characterise how resilient the system is.

The second analysis aims at assessing the safety of the mission. Safety is defined by the capacity of a system to protect from hazards. Hazards are defined in our case by all undesirable events that occur from within the system boundaries, like the failure of a subsystem. We want to identify all the parts that may fail or behave in a way that was not intended. Then we want to analyse the behavior of the system that is caused by such an issue, especially how failure propagates.

For the final score, a survey was conducted with engineers and managers from the industry (see appendix A *of the paper*). A goal of this survey was to determine the weights of the different objectives (See figure 68, p.117). To compute this score, we simply apply a weighted sum of the different input scores. All of these scores are required to be normalised and comprised between 0 and 1, so that we get a percentage of sustainability for the mission as an outcome.

G.3 Integration in the Concurrent Engineering Process

The content of the process that are integrated in the role of a sustainability expert is important, but the most crucial aspect of concurrent engineering is communication, and therefore the interfaces with others. This part will elaborate on the integration within the concurrent engineering process, and specify the interfaces both for inputs and outputs.

G.3.1 Interfaces with Other Roles

The figure 69 (page 118) defines the conceptual model of the role and emphasises four interfaces, namely the Systems engineers, Structure engineers, Power engineers, and Propulsion engineers.

G.3.2 Integration Test at EPFL

The previously defined system was experimented at EPFL in the course "Concurrent Engineering of Space Missions", where its integration was successful. The interfaces with other experts were clear and respected. Another important aspect that was noted is that the role did not only have an assessment role, but exhibited an active impact on the mission and clearly oriented the different choices. To see more about the results of the feasibility study in the course, check the study report[1]. This system could now be tested in larger scale concurrent design sessions and refined for more rigorous applications, with a proven architecture.

[1] `https://cdf.epfl.ch/ce_studies/2025_ENG-411`, consulted 28.05.2025.

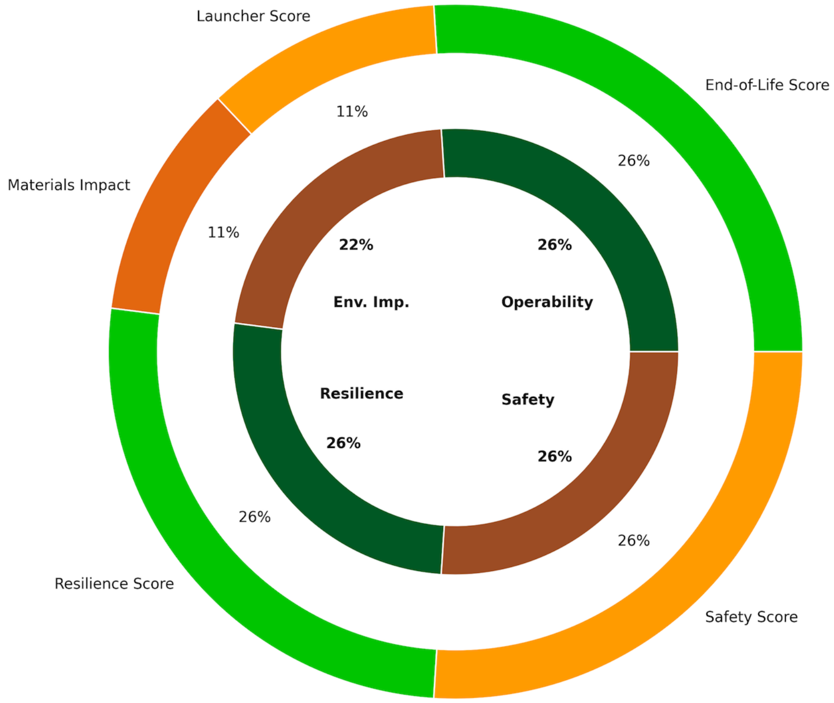

Figure 68: Weights allocation used for the weighted sum, derived from the ilities that define a sustainable space system (See equation 10, p.114), and results of the industry survey.

G.4 Identified Research Gaps and Conclusions

In terms of integration in the concurrent engineering process, the role that was specified was a success and a positive impact was noticeable. On the side of the pure content of the role, multiple research gaps were identified during the specification of the processes. These gaps are not only specific to concurrent engineering, but belong to any case of sustainability in space systems engineering. Indeed, processes such as a traditional LCA were found unfeasible, and research directions are proposed for future projects:

- LCA projects for the definition of a database for the selection of technologies, based on the required energy for the production of different technologies ($\frac{kWh}{kg}$).
- Definition of policies or guidelines for the integration of sustainability in the supplier selection process (in addition to cost).
- Projects in collaboration with launch vehicle operators to measure the atmospheric impact of launches in the different layers of the atmosphere.
- Projects to evaluate the atmospheric impact of reentry and trade-off between demising and non-demising strategies.

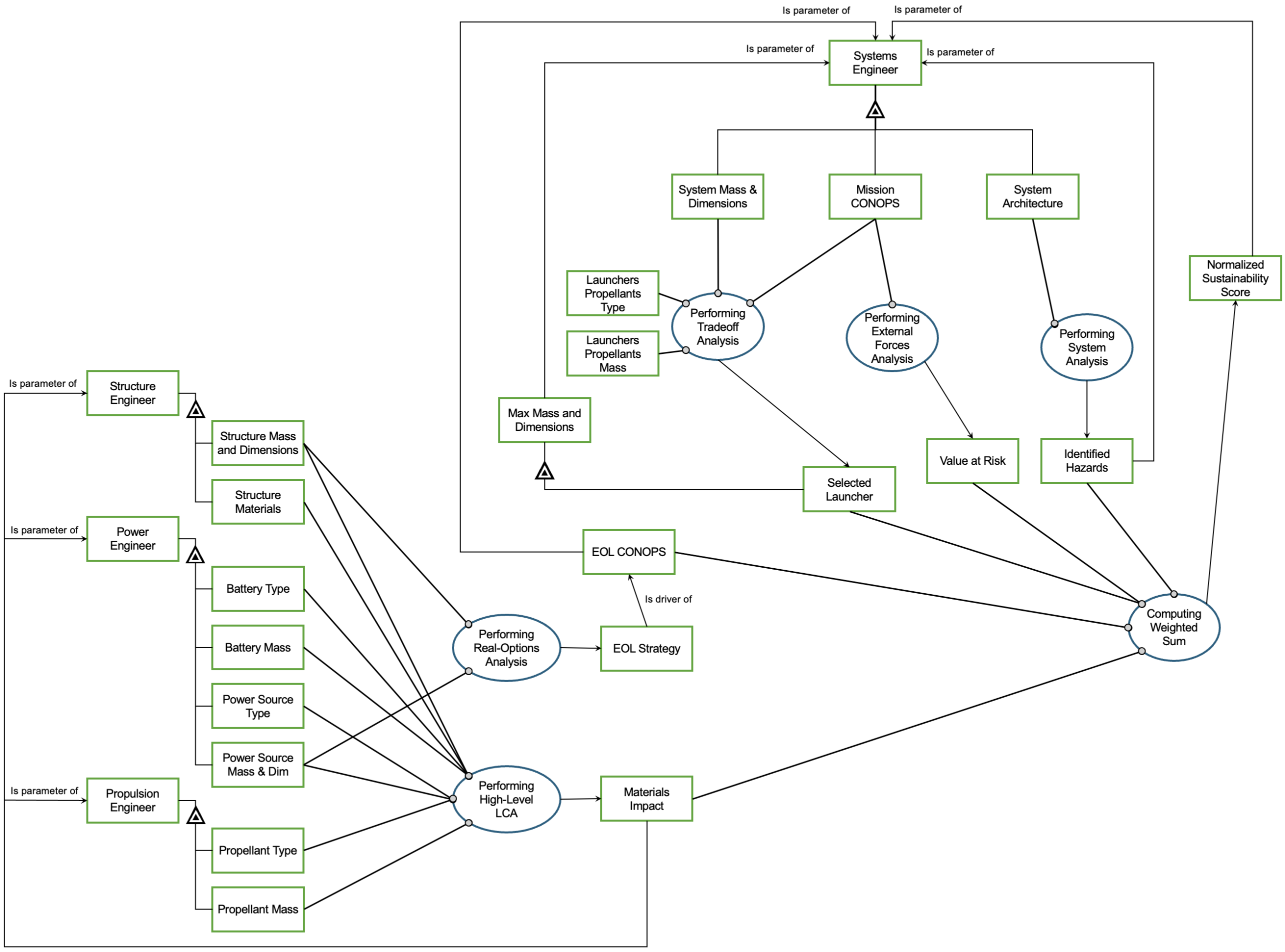

Figure 69: Object Process Model of the role of a sustainability expert within a CDF environment.

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