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DEPARTMENT OF MECHANICHAL ENGINEERING AND AERONAUTICS [AERONAUTICAL ENGINEERING DEPARTMENT]
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Diploma Thesis

Value–driven decision-making process for application to an aeronautical case study

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Diploma thesis submitted to the Department of Mechanical Engineering and Aeronautics of the University of Patras

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Abstract

The latching mechanism of a Lower Deck Cargo Door (LDCD) of an aircraft is considered one of the most crucial and important systems that compose the overall structure of a cargo door. The main function of such a mechanism is to keep the LDCD in a closed and locked position throughout the flight and in an open and locked position when required.

The identification of a latching mechanism, among others, as the optimum alternative requires the implementation of a well-structured decision-making process, balancing multiple attributes. Particularly, in the current thesis, a comparative analysis is carried out among three already developed latching mechanisms: Hook Spool Latching Mechanism (HSLM), Bar Latch Mechanism (BLM) and C-Latch Mechanism (CLM). Each architectural design is evaluated by seven different Key Performance Indicators (KPIs) which are derived from four specific domains: Sustainability Domain, Reliability Domain, Performance Domain and Supply Chain Domain. By applying the Multi Attribute Utility Theory (MAUT), trade-off analyses and decision-making are performed.

By implementing the outlined methodology for the estimation of the considered KPIs, it is observed that the first architectural design (HSLM) is the most reliable and sustainable. The CLM stands out for the lowest mass whereas, the BLM demonstrates the best supply chain performance. Furthermore, according to the reference case study (equal weights and linear utility functions have been assigned to all KPIs), some of the resulting alternatives are being identified as the optimum solutions (6 in total), as they combine relatively high value and low overall cost. Nevertheless, when some of the indicators are prioritised, those optimum solutions may be changed as is demonstrated in other examined case studies. This underlines the importance of contextual decision-making, where trade-offs must be carefully evaluated based on the demands and constraints of the particular research.

Generally, the identification and evaluation of judicious trade-offs among various attributes assist in improving the overall reliability and effectiveness of the latching system. The present framework has been developed for a latching system of a cargo door, however with some modifications, it can easily be adopted by other aeronautical or non-aeronautical systems.

Keywords:
Latching mechanism, MAUT, Sustainability, Trade-Off Analyses, Decision-Making

Διαδικασία λήψης αποφάσεων με γνώμονα την αξία για ένα αεροναυπηγικό σύστημα

Παναγιώτης Παντέλας

Περίληψη

Οι μηχανισμοί μανδάλωσης μιας πόρτας φορτίου του κατώτερου καταστρώματος ενός αεροσκάφους, θεωρούνται πλέον ένα από τα πιο κρίσιμα και σημαντικά συστήματα τα οποία συνθέτουν τη συνολική δομή μιας πόρτας φορτίου. Η κύρια λειτουργία ενός τέτοιου συστήματος είναι είτε να διατηρεί την πόρτα σε κλειστή και ασφαλισμένη θέση καθ’ όλη τη διάρκεια της πτήσης, είτε σε ανοικτή και ασφαλισμένη θέση όταν απαιτείται.

Ο εντοπισμός ενός μηχανισμού μανδάλωσης ως τη βέλτιστη εναλλακτική λύση απαιτεί την εφαρμογή μιας καλά δομημένης διαδικασίας λήψης αποφάσεων, η οποία εξισορροπεί πολλαπλά χαρακτηριστικά. Στην παρούσα διπλωματική εργασία, πραγματοποιείται συγκριτική ανάλυση μεταξύ τριών ήδη ανεπτυγμένων μηχανισμών μανδάλωσης: Μηχανισμός Μανδάλωσης Καρουλιού–Γάντζου (ΜΜΚΓ), Μηχανισμός Μανδάλωσης Ράβδου (ΜΜΡ) και Μηχανισμός Μανδάλωσης C (C-MM). Κάθε μια αρχιτεκτονική αξιολογείται με βάση εφτά διαφορετικούς δείκτες απόδοσης οι οποίοι προέρχονται από τέσσερεις διαφορετικούς τομείς: Τομέας Βιωσιμότητας, Τομέας Αξιοπιστίας, Τομέας Αποδοτικότητας και Τομέας Εφοδιαστικής Αλυσίδας. Κάνοντας χρήση της θεωρίας χρησιμότητας πολλαπλών χαρακτηριστικών (ΘΧΠΧ), πραγματοποιούνται αναλύση αντισταθμίσεων και λήψης αποφάσεων.

Με βάση την περιγραφείσα μεθοδολογία για την εκτίμηση των εξεταζόμενων δεικτών απόδοσης, παρατηρείται ότι ο ΜΜΚΓ είναι η πιο βιώσιμη και αξιόπιστη αρχιτεκτονική. Ο μηχανισμός C-MM ξεχωρίζει για το μειωμένο βάρος του ενώ, ο τρίτος μηχανισμός παρουσιάζει την καλύτερη απόδοση στον τομέα της Εφοδιαστικής Αλυσίδας. Επιπλέον, με βάση το σενάριο αναφοράς (ίσοι συντελεστές βαρύτητας και γραμμικές συναρτήσεις χρησιμότητας αναθέτονται σε όλους τους δείκτες απόδοσης), ορισμένες από τις εναλλακτικές λύσεις που προκύπτουν αναγνωρίζονται ως οι βέλτιστες λύσεις (6 στο συνολο), καθώς συνδυάζουν σχετικά υψηλή αξία και χαμηλό συνολικό κόστος. Ωστόσο, όταν δοθεί μεγαλύτερη βαρύτητα σε ορισμένους από τους εξεταζόμενους δείκτες, οι εν λόγω βέλτιστες λύσεις μπορεί να αλλάξουν, όπως καταδεικνύεται από την εξεταση άλλων σεναρίων. Αυτό, υπογραμμίζει τη σημαντικότητα των αντισταθμίσεων, όπου πρέπει να αξιολογούνται προσεκτικά με βάση τις απαιτήσεις και τους περιορισμούς της εκάστοτε έρευνας ή εφαρμογής.

Γενικά, η αξιολόγηση συμβιβασμών μεταξύ διαφόρων χαρακτηριστικών βοηθούν στη βελτίωση της συνολικής αξιοπιστίας και αποδοτικότητας του συστήματος μανδάλωσης. Το παρόν πλαίσιο έχει αναπτυχθεί για ένα μηχανισμό μανδάλωσης. Παρόλα αυτά με μερικές τροποποιήσεις μπορεί να εφαρμοσθεί και για άλλα αεροναυπηγικά ή μη - αεροναυπηγικά συστήματα.

Λέξεις Κλειδιά:

Μηχανισμός μανδάλωσης, ΘΧΠΧ, Βιωσιμότητα, Ανάλυση συμβιβασμών, Λήψης αποφάσεων

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Acronyms and Abbreviations

Acronym	***Description***
LDCD	Lower Deck Cargo Door
KPIs	*Key Performance Indicators*
MAUT	Multi Attribute Utility Theory
HSLM	*Hook Spool Latching Mechanism*
BLM	*Bar Latch Mechanism*
CLM	*C-Latch Mechanism*
LCA	*Life Cycle Assessment*
HS	*Holistic Sustainability*
SAF	Sustainable Aviation Fuels
GHGs	Greenhouse Gas Emissions
EC	Energy Consumption
WG	Waste Generation
RD	Resource Depletion
LM	Latching Mechanism
PP	Production Phase
UP	Use Phase
EoLP	End of Life Phase
LCPs	Life Cycle Phases
FMECA	Failure Modes Effects and Criticality Analysis
FMEA	Failure Modes Effects Analysis
FEA	Finite Element Analysis
ESI_{LM}	Environmental Sustainability Index of a Latching Mechanism
TCs	Technical Components
Al	Aluminium
Ti	Titanium
St	Steel
A/C	Aircraft
ESI_{TCtot}	Total Environmental Sustainability Index of a Technical Component
FMs	Failure Modes
CA	Criticality Analysis
S_{FM}	Severity of each failure mode
O_{FM}	Occurrence of each failure mode
D_{FM}	Detectability of each Failure Mode
RPN_{FM}	Risk Priority Number of each Failure Mode
$Mass_{LM}$	Total Mass of the Latching Mechanism
SC	Supply Chain
OEM	Original Equipment Manufacturer
HU	Handle Unit
CS	Case Study

Contents

Prologue

This thesis has been carried out during the academic year 2024-2025 and it has been undertaken in collaboration between the University of Patras and the German Aerospace Centre (DLR - Deutsches Zentrum für Luft- und Raumfahrt). It aims to provide additional knowledge on a chosen topic as a student of the Department of Mechanical and Aeronautical Engineering of the University of Patras. Main purpose of this thesis is to perform a multi-criteria decision-making process for a latching system, by investigating some Key Performance Indicators. PyCharm, VALORISE and Microsoft Excel software have been mainly used to support the entire analysis.

The thesis has been performed under the supervision of Mr. Angelos Filippatos, Assistant Professor of the Department of Mechanical and Aeronautical Engineering, University of Patras and member of Machine Design Laboratory, Mr Dionysios Markatos, PhD Research Associate of the Department of Mechanical and Aeronautical Engineering, University of Patras, Mrs. Giuseppa Donelli, PhD Research Scientist of the German Aerospace Centre (DLR) and Mr. Carlos Cabaleiro de la Hoz, M.Sc. Research Scientist of the German Aerospace Centre (DLR).

Here, I would like to express my gratitude to all the people mentioned previously for their supervision and guidance during the entire process. Additionally, formal appreciates are given to University of Patras, German Aerospace Centre (DLR) and an industrial partner of DLR for providing computational programs, various software as well as data in order to be able to delve the topic of the thesis.

1. Introduction

Aerospace engineering is an inter-disciplinary field integrating principles from aerodynamics, material science, propulsion and control systems. Nowadays, modern aeronautical systems aim to balance efficiency, environmental sustainability, reliability and cost-effectiveness. Thus, decision-making in the broader aeronautical domain, where precision, safety and efficiency are recognised as essential aspects, holds a fundamental role in guiding the selection of the optimum solutions among competing objectives. In many cases, the selection of the ideal alternative is of vital importance for the improvement of the overall performance and effectiveness of the system of interest. To this end, and to demonstrate the applicability of decision-making in this field, an aeronautical system is investigated in the current thesis with primary aim of drawing robust and logical conclusions based on the outlined methodology.

The system under investigation, a latching mechanism for an outward-opening Lower Deck Cargo Door (LDCD) of an aircraft, is evaluated by multiple criteria to ensure that it meets a number of key objectives set by the stakeholders. More specifically, the present thesis focuses on the analysis of three different and predefined latching mechanism architectures, each one representing a different approach to the overall system design (functions, technical components, etc.). Figure 1-1 depicts a main deck cargo door of an A320-neo aircraft type, in which some of the key components of the mechanism under examination can be spotted. In particular, the latching spools which are attached to the fuselage of the aircraft, as well as the latching hooks which are integrated in door's structure, are visible.

Figure 1-1 Main deck cargo door of an Airbus A320-neo aircraft [1]

The current thesis, mainly aims to perform a well-structured multi-criteria decision-making approach for the selection of the most suitable architecture, assessing them in four core domains by using seven Key Performance Indicators (KPIs) in total.

To achieve this, systematic methodologies are developed for the assessment of each considered KPI, ensuring the consistency and reliability of their overall assessment. In addition, for the aggregation of the seven different KPIs of each architecture into a single value, the Multi-Attribute Utility Theory (MAUT) is applied, allowing the comparative analysis of each architecture among different scenarios under examination. Often, conventional evaluation methodologies struggle to integrate multiple criteria under a single framework, leading to subjective rather than objective conclusions. Therefore, MAUT is implemented, which is a quantitative decision-making tool that allows the consistent aggregation of several KPIs into a single value. Eventually, trade-off analyses are carried out by varying the weighting factors or the utility functions initially assigned to each KPI.

Improvements of how various decisions are taken in the aeronautical field enhances the selection of the most efficient system, while ensuring higher performance and better reliability. The present study provides an organised decision-making framework to the stakeholders (e.g. researchers, industrial companies, etc.), taking into account many and various aspects among different domains. Furthermore, the followed methodology is flexible, easy to use and adaptable to applications beyond this specific field.

This diploma thesis is framed by six main chapters which are then divided into shorter sections. In the present chapter (Chapter 1), the main topic of the research, its key objectives and significance are introduced. Chapter 2 presents a comprehensive literature review, where the relevant theories are analysed, while Chapter 3 outlines the developed methodologies. In continuation, Chapter 4 focuses on the methodology implementation whereas, Chapter 5 presents the research results, highlighting the most important findings. Finally, Chapter 6 summarises the whole thesis, focusing on its key aspects, as future research guidelines are suggested.

2. Literature Review

This Chapter presents a comprehensive review of the existing literature pertinent to the research topic, by systematically analysing key theoretical frameworks, empirical findings, methodological approaches and techniques. Moreover, it evaluates scholarly contributions of the different methodologies, identifying in parallel gaps in literature that warrant further investigation. Broadly, the literature review establishes the academic foundation of the various studies, situating it within the broader scholarly discourse while, substantiates the importance of the research. Furthermore, a well organised literature review ensures that the research is grounded in established academic principles while contributing to the advancement of knowledge in the field.

In the upcoming sections of this chapter, all examined aspects are outlined in order to establish a structured framework. The first section delves into the fundamentals of the systems of interest (i.e., latching mechanisms of an aircraft door), examining their characteristics and operational constraints. Across the second section, the definition of all the Key Performance Indicators (KPIs) selected for evaluating the system of interest (latching mechanism) are presented. In the third section, an introduction and explanation of the Multi Attribute Utility Theory (MAUT) is given, highlighting its principles and advantages in aerospace domain as decision-making tool. Finally, the current Chapter concludes with a summary of the identified science gaps and the formulation of the research questions, framing and guiding the study.

2.1. Latching System Architectures

With the development of the aeronautical industry, many different mechanisms for latching the lower deck cargo doors have been developed. The main function of such a mechanism, is to keep the LDCD in a closed and locked position throughout the entire flight (take-off, cruise, landing) and in an open and locked position when required (e.g. loading/unloading the cargo). In this thesis, the focus rests on three distinct latching mechanism architectures that have been developed for an outward opening cargo door [2]. More specifically, these mechanisms are called: Hook Spool Latching Mechanism (HSLM), Bar Latch Mechanism (BLM) and C-Latch Mechanism (CLM). All of them are widely used in modern passenger aircrafts. For instance, HSLM and BLM are used in A320, A350 and A380 aircraft types, whereas CLM is commonly used in B747, B777 and B787. Under the following subsections, the three mentioned architectural configurations are described in detail.

2.1.1 Airbus Hook Spool Latching Principle

The first architectural design that is described, refers to a latching mechanism for an outward-opening aircraft cargo door. This concept is called: Airbus Hook Spool Latching Principle and is widely used in freight, cargo as well as passenger aircrafts. This patent has been registered by Arthur Kupfernagel [2], [3].

One of the key features of this mechanism is that, a hook is attached to the aircraft cargo door. This hook is capable of being rotated by means of an actuator, so that it can be passed over the corresponding spool which is fixed to the fuselage of the aircraft while the door is being opened. At each door more than one of these hook latching units are installed. Figure 2-1 demonstrates the Airbus Hook Spool Latching Principle in two different states that the mechanism can be in. On the left, the mechanism is being in the unlatched state and on the right in the latched [2].

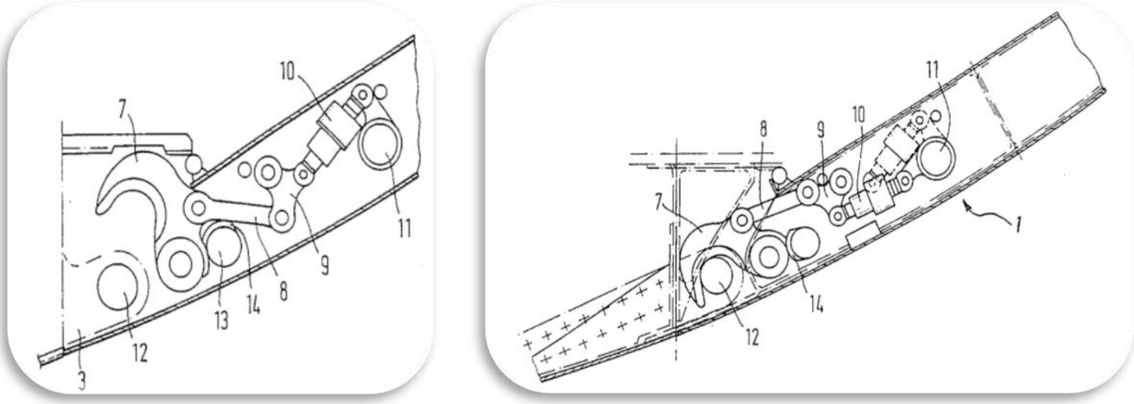


Figure 2-1 Airbus Hook-Spool Latching Principle, Left: Unlatched state, Right: Latched state [3]

With the mechanism in the latched position, there is a mechanical contact between the hook and the spool (components **7** and **12** in Figure 2-1 accordingly). In combination with the structural elongation caused by the differential pressure during flight, a tangential force is generated in the direction towards the outer skin of the door. However, to open the door, the hook must be first rotated to the unlatched position. The door is now free to rotate about the piano hinge axis at the upper end of the door. The mechanism may be driven by means of a manually or hydraulically operated device acting on a latch shaft (component **11** in Figure 2-1), which in turn, through coupling members, causes a number of latch hooks to be activated [2], [3].

2.1.2 Airbus Bar Latch Principle

The second architectural design that is being introduced below is called: Airbus Latch Bar Principle. Similar to the first architectural design presented in section 2.1.1, it has been developed for an outward–opening cargo door. The specific patent has been invented by Roland Risch in 2008 [4]. A transitive latch bar is the main characteristic of this configuration. Two different cross–sections of this bar are demonstrated in Figure 2-2. With the number **84** is denoted the large cross-section whereas, with **89** the small cross-section. Of the two cross–sections, the larger is used to latch the cargo door. For opening, the latch bar shall be moved transitionally to a position such that the smaller cross–section can pass through the latching stamps fixed to aircraft fuselage. The latch stamp is designated with the number **80**. A lever mechanism is used to move the latch bar translationally, which it also includes an over-centre latch securing function.

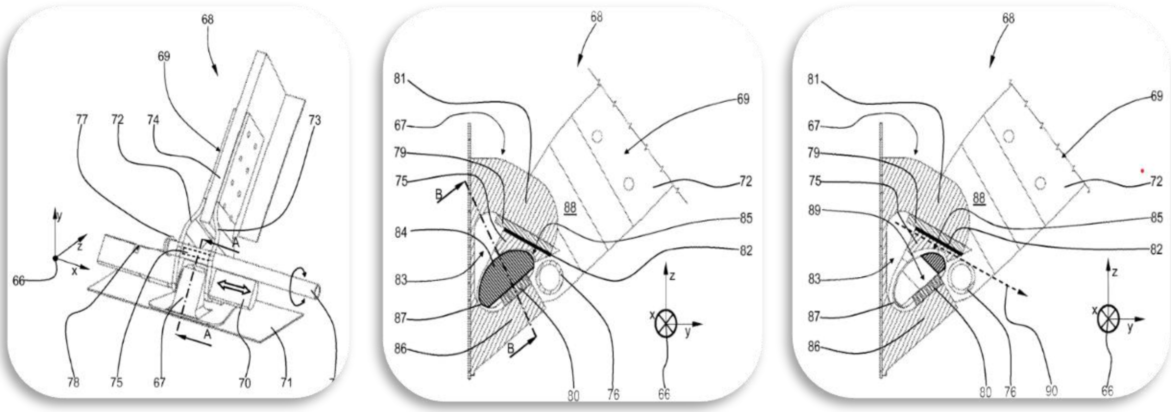


Figure 2-2 Bar Latch Principle, Left: Mechanism's perspective view, Middle: Latched state, Right: Unlatched state [4]

The left side of Figure 2-2, shows a perspective view of the Airbus Bar Latch Principle, in the middle and right sides is presented the door in a closed and latched position and in a closed and unlatched position, respectively. Both of these figures are presented in a sectional view, extending along the A-A line as illustrated on the left figure.

In the fully closed and latched position, mechanical contact is established between the latch bar and the latch stamp, ensuring a secure engagement that prevents unintended disengagement during the flight under various conditions. This interface is designed to withstand significant aerodynamic forces and pressure differentials, ensuring the cargo door remains firmly locked throughout the aircraft's operational envelope. Furthermore, the latch bar system incorporates redundant locking mechanisms and interlocking features that prevent accidental release due to structural flexing or vibrations. In the direction of the door opening, as indicated by the dotted arrow on the right side of Figure 2-2, the small cross–section of the latch bar can be moved above the latch stamp, allowing a controlled displacement that facilitates smooth operation.

This movement is designed to ensure minimal resistance during door actuation, reducing mechanical stress and wear on the latch components while maintaining precise alignment with the locking system.

2.1.3 Boeing C-Latch Principle

The Boeing C-Latch Principle is an innovative cargo door latching mechanism developed by the Boeing Company in 1955. It has been published under the name "Blow-Out Safe Aircraft Doors" [5]. This architectural design employs a C–shaped latch designed to securely latch an outward–opening cargo door, ensuring reliability and structural integrity during flight operations. The mentioned component (C-shaped latch) is illustrated with the number **2** in Figure 2-3. Additionally, this principle has been developed with the start of production of the Boeing 70X series of aircraft, where cargo transportation demands necessitated advancement in door security and operational efficiency. The C-latch mechanism has been first implemented in an outward-opening main deck cargo door of the 707-freighter aircraft [2].

Figure 2-3 presents two illustrations from the published article. On the left side of the figure, the cargo door is slightly opened and therefore the mechanism is in the unlatched state. In addition, the mechanism's door-closed but unlatched position is depicted using chain-dotted lines. On the right side of the mentioned figure, the cargo door is in the closed position and the latching mechanism is in the latched state.

The Boeing Company has applied this principle to all the following commercial aircraft [6]:

- ❖ Boeing 747, Boeing 767, Boeing 757, Boeing 777, Boeing 787 Dreamliner

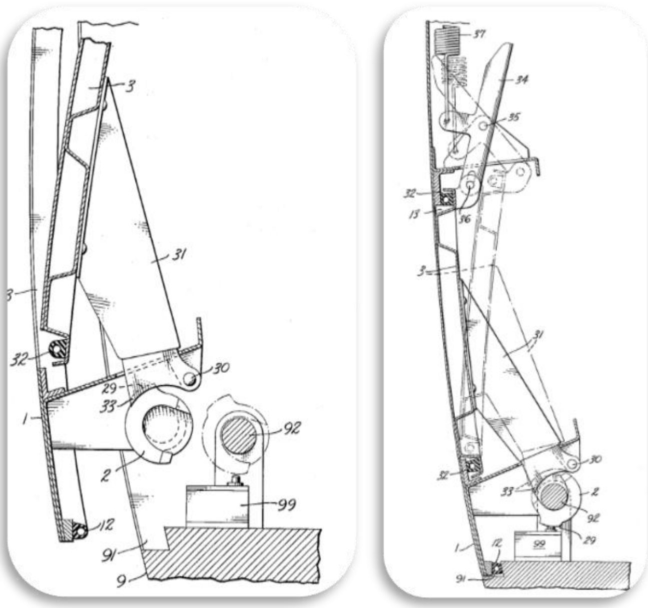
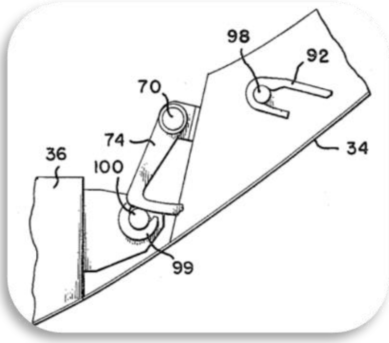
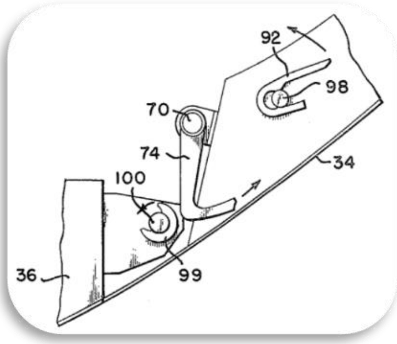


Figure 2-3 C-Latch Patent Overview [5]

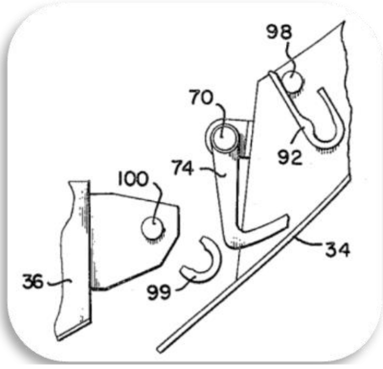
After Boeing performed the first flights of the 757 and 767, which were in 1982 and 1981 respectively, an updated version of the C–Latch Principle has been released. The revised version was invented by Opsahl Barnes [7]. Figure 2-4 shows the updated version of the C–Latch Principle by means of four different illustrations, which are the four distinct states that the cargo door and the mechanism can be in.



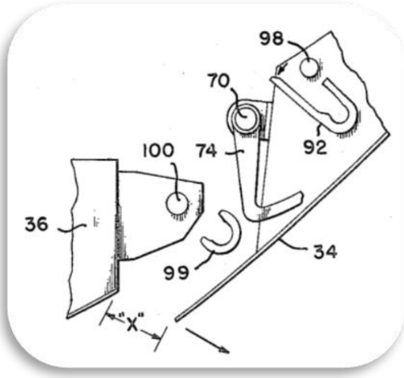
Door closed, latched and locked



Door closed, unlatched and unlocked



Door not pulled in, unlatched



Door open, unlatched, unlocked

Figure 2-4 Boeing C-Latch Principle in four distinct states [7]

In the upper left part of Figure 2-4, the cargo door in in the closed position and the latching mechanism is in latched and locked configuration. The sided bolt fixed to the fuselage is in mechanical contact with the cargo door sided C-latch and thus it is ensured that the cargo door remains firmly locked throughout the entire flight. Apart from the mechanical contact between these two technical components, the C-latch is prevented from rotating by a locking lever as demonstrated in the related figure. The bolt, C-latch and locking lever are denoted by the numbers **100, 99** and **74** respectively.

2.2. Selection of KPIs Assessment Methodologies

KPIs are measurable values that assist in monitoring and evaluating the progress or the performance of a particular objective, domain or system. In order to evaluate the system of interest in a proper way, the selection of the correct KPIs is of high importance. Frequently the selection is driven by industrial standards, empirical validation or even for alignment with certain research objectives.

This section examines the KPIs that used in order to assess the system of interest of the current analysis, i.e., a latching mechanism. In particular, seven KPIs are introduced and investigated, which are derived across four distinct domains: Sustainability Domain, Reliability Domain, Performance Domain and Supply Chain Domain. Each of the domains is represented by one or more characteristic indicators (KPIs). The associated indicators of each domain are reported below. It is underlined that the KPIs related with the Sustainability, Reliability and Mass Domains depend solely on the technical characteristics of each considered architectural design (HSLM, BLM, CLM). On the other hand, the indicators representing the Supply Chain Domain, depend on the architecture's technical characteristics as well as on the considered production and assembly scenario.

- Sustainability Domain: Environmental Sustainability KPI
- Reliability Domain: Reliability KPI
- Performance Domain: Mass KPI
- Supply Chain Domain: $Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$ KPIs

2.2.1 Sustainability Domain

Sustainability has emerged as a fundamental principle of modern engineering, affecting industries worldwide. In general, Sustainability outlines the attempt to minimise environmental impact resulting from a system while maintaining its operational performance. In aerospace field, Sustainability plays a crucial role in guiding technological innovation, regulatory frameworks and corporate strategies. In view of the industry's high energy consumption and dependence on non–renewable resources, achieving sustainability requires a multi-faceted approach that integrates green propulsion systems, lightweight materials and more energy–efficient designs. Regulatory organisations such as ICAO and EASA are actively shaping sustainability policies, pushing for reduced emissions and more sustainable practices [8].

In aerospace domain, Sustainability refers to the ability of systems, processes and materials to minimise their environmental impact while maintaining their efficiency and effectiveness. Its primary purpose is to reduce the ecological footprint of aerospace operations and to comply with global environmental regulations [8]. Sustainability is mainly evaluated through KPIs [9], such as carbon footprint, fuel efficiency, energy consumption, waste generation, noise pollution and recyclability. Every single mentioned indicator is quantified using specific metrics However various aspects coming from the society, economic, circular economy and performance domains, can accounted to evaluate the holistic sustainability of a system [15].

The evaluation of the overall Sustainability of a system can be performed by using various methodologies. Many of them are available in the literature. However, for the purposes of the current analysis only three of them are reported as, they are widely known and implemented.

- **Life Cycle Assessment Approach**
- **Holistic Sustainability Approach**
- **Three-Pillar Approach**

Life Cycle Assessment (LCA) is a widely applied methodology that monitors the environmental footprint of materials and processes from the very early phase of raw materials extraction through to disposal [8]. Holistic Sustainability (HS) integrates aspects form society, economy, environment, performance and circular economy into a unified framework, which underlines the necessity of the connectivity of all those pillars. On the other side, Three-Pillar approach involves aspects only from society, environment and economy so it is assumed as a sub-category of the HS.

Each of the mentioned approaches has its advantages and disadvantages. Regarding the LCA, it provides a very well-structured methodology for assessing the environmental impact of a system throughout its entire life cycle. In addition, it is highly adaptable, allowing the possibility of comparisons among alternatives. However, aspects from the other pillars (Performance, Society, Economy, Circular Economy) are usually overlooked, while high-quality data are needed to obtain reliable results [10], [11]. Figure 2-5 illustrates the main phases of the LCA methodology.

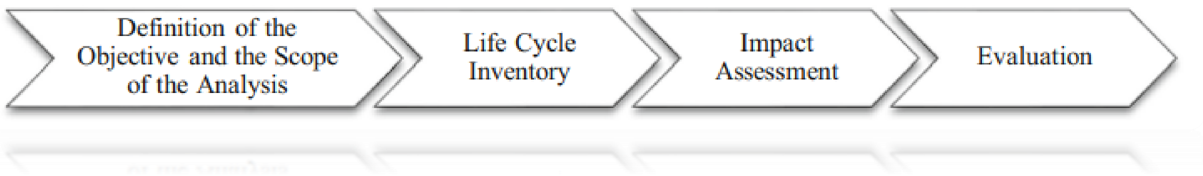


Figure 2-5 Phases of a life cycle assessment according to ISO 14040/14044 [8]

The Three-Pillar approach is not dealing only with the environmental impact of a system across its entire life cycle as LCA does. This particular method incorporates aspects from the society and economy sectors. It is a methodology that offers a balanced framework among these three pillars (Environment, Society and Economy) and is widely accepted in corporate strategies and policy-making. However, except the mentioned advantages it has its weaknesses as well. Too often the attempt to balance and integrate the three pillars into a single framework results in trade-off analyses rather than holistic sustainable-solutions. Furthermore, the fact that the environment, society and economy are broad concepts and there is no structured method for their precise evaluation, achieving accurate and realistic results becomes difficult [12], [13], [14]. Base on Figure 2-6 which illustrate the Three-Pillar method, the region of sustainable design is the one where intersected by all three pillars (Indicated by an arrow).

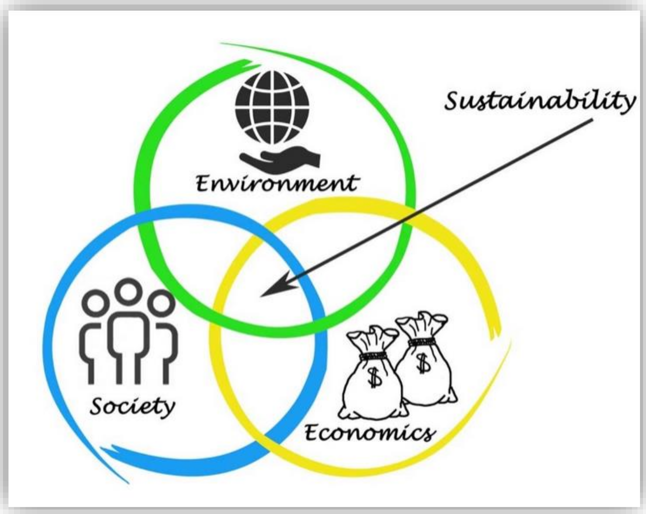


Figure 2-6 Demonstration of Three-Pillar approach [14]

On the other side, the HS methodology incorporates five different pillars. Three of them are common to those introduced under the previous methodology, whereas the performance and circularity pillars are integrated as well. This methodology ensures the alignment of sustainability efforts across different sectors while promoting resilient and adaptive strategies rather than isolated trade-offs among the pillars. Moreover, the fact that five fundamental pillars are involved to evaluate a system, means that the obtained results are of a holistic nature [15], [16]. Despite all mentioned benefits, the engagement of five different pillars under the same framework makes it challenging to implement the methodology. Additionally, in order to be able to be applied in decision-making field, it is necessary to develop specialised and well-established frameworks. Furthermore, there are no standardised metrics for the assessment of the various pillars, leading to confusion [11]. In Figure 2-7 a descriptive schema of this particular methodology is demonstrated. In the middle of the drawing, the system of interest is depicted, while each corner of the pentagon represents a specific pillar.

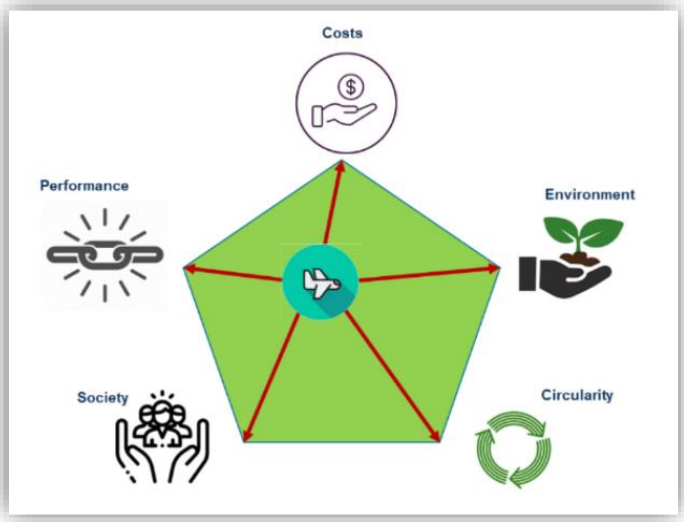


Figure 2-7 Overall schema of the holistic sustainability methodology [15]

In contrast of the major advancements in sustainability measurement of a system, several challenges and limitations still persist. Some of those difficulties are reported below:

- **Complexity of emission tracking**
- **High cost of sustainable technologies**
- **Difficulties in structures recycling**
- **Variation in regulatory standards**
- **Lack of standardised sustainability KPIs**

Various studies indicate that the lack of standardised framework makes it difficult to compare sustainability efforts among stakeholders and manufacturers [8]. Furthermore, the transition to Sustainable Aviation Fuels (SAF) and electric propulsion faces technological and economic barriers. Currently, aerospace industry is undergoing a significant transformation toward sustainability, driven by advancements in SAF, hydrogen–powered aircraft, Artificial Intelligence driven flight optimisation and electric propulsion. SAF adoption is escalating, by companies as United Airlines and Neste leading production efforts in America, while hydrogen propulsion projects such as Airbus ZEROe and ZeroAvia's HyFlyer II offer promising zero–

emission alternatives [17]. Artificial intelligence is optimising flight routes to enhance fuel efficiency [18]. Electric and hybrid–electric aircraft from Eviation and Heart Aerospace are shaping the future of the regional aviation, while innovations like blended wing bode design by NASA improve aerodynamics and fuel efficiency [17], [19]. These trends demonstrate the industry's commitment to achieving zero-net emissions by 2050 [20], aligning with global sustainability targets and regulatory demands.

Based on the purposes of the current analysis, out of the methods discussed previously, the LCA and Three-Pillar methodologies are collaborating for the evaluation of the overall sustainability of each considered latching mechanism. LCA methodology enables a quantitative analysis aimed at limiting the environmental impact of a system, as it is of primary importance. In addition, it is flexible and can be adjusted quite easily to the system of interest of this analysis. On the other hand, Three-Pillar approach offers the possibility to understand the primary principles of sustainability in order to select representative metrics for the system of interest. However, none of them are explicitly implemented as specified by the ISO regulations (for the LCA method) or related scientific articles (for the three-pillar method), but with some minor modifications.

The implemented methodology consists of **four** main stages. In the first stage, the selected metrics framing the analysis are explained and documented, but in parallel, all the data needed for the proper estimation of each of them are provided as well. Briefly, four metrics are considered in this analysis which are the **Greenhouse Gas Emissions (GHGs), Energy Consumption (EC), Waste Generation (WG)** and **Resource Depletion (RD)**. According to the LCA method, all these metrics must be estimated throughout the entire life cycle of the investigated system of interest, i.e., a latching mechanism. To this end, the entire life cycle of the mechanism is separated into three distinct life cycle phases (LCPs): **Production Phase (PP), Use Phase (UP)** and **End of Life Phase (EoLP)**. During the second stage, the environmental sustainability index (ESI) of each particular technical component that compose each architectural design, is estimated. Right after, in the third stage, **weighting factors** are assigned to each of the considered metrics. The third stage is of high importance due to the fact, different combinations of weighting factors can lead to different results. Lastly, the **overall environmental sustainability index** (ESI_{LM}) is estimated for each architectural design. More details on the followed methodology are provided in section 3.1.

2.2.2 Reliability Domain

Reliability refers to the ability of a system or a technical component to perform its intended function consistently over time without failure. It is a very important KPI that is directly associated with the safety, maintenance costs and effectiveness of the entire system, establishing it as a fundamental metric in aircraft design. High reliability is associated with reduced downtime, reduced maintenance expenses and satisfactory mission success rates [21].

Usually, the reliability of a system is evaluated using analytical methods which help to identify potential failure modes, assess risk levels and optimise maintenance strategies. These methodologies collectively ensure that reliability assessments of a system are valid and effective. Additionally, their primary objective is to improve the overall performance of a system, reduce downtime and minimise maintenance costs. Some of the most applicable methodologies are reported and briefly explained below:

- **Failure Mode and Effects Analysis (FMEA):** Identifies failure modes and evaluates their impact on system performance [22].
- **Failure Modes, Effects, and Criticality Analysis (FMECA):** Extends FMEA by ranking failure modes based on severity and criticality, ensuring high-risk issues receive priority [23].
- **Fault Tree Analysis (FTA):** Uses logical diagrams to assess failure probabilities and identify root causes in complex aerospace systems [24].
- **Reliability-Centred Maintenance (RCM):** Optimizes maintenance strategies to enhance reliability and minimize unexpected failures [25].
- **Mean Time Between Failures (MTBF):** Measures the average operational time between system failures, providing insights into component longevity [26].
- **Mean Time to Repair (MTTR):** Evaluates the average time required to restore functionality after a failure, supporting predictive maintenance planning [27].

However, the application of these methodologies is often accompanied by some limitations which depend on many parameters. Some of them are mentioned and justified below:

- **Data availability and accuracy:** Reliability assessments rely on historical failure data [30]
- **Complex system architectures:** Difficulties in modelling failure probabilities [31], [32]

- **Harsh operational environment:** Extreme temperatures, vibrations, and pressure variations complicate accurate reliability predictions [28]
- **Stringent regulatory requirements:** Demand high reliability standards [28], [32]
- **Balance cost-effectiveness with reliability improvements:** Reliability often requires advanced materials and predictive maintenance strategies [28], [32]

Addressing these challenges and limitations requires continuous advancements in predictive analysis and artificial intelligence diagnostics. Several studies highlight that optimisation of reliability through preventive maintenance, fault detection algorithms and usage of advanced materials enhances aircrafts' performance. In addition, research has been carried out analysing the challenges and innovations in aeronautical reliability, with an emphasis on the impact of the extreme weather conditions and complex system architectures on system performance. Attention is also given to how predictive maintenance and artificial intelligence–based diagnostics improve reliability in modern aerospace applications [28]. Other study explores the so-called digital reliability indicators [29]. In that research, particular attention is given to how data–driven approaches improve system monitoring and failure prediction. In many applications, reliability indicators guide aircraft maintenance programmes, various component testing and system design optimisation. Predictive maintenance models are enhanced by data derived from those indicators, ensuring early detection of potential failures [28].

For the purposes of the thesis, among the presented methodologies, FMECA method is chosen for the reliability estimation of each architectural design. Generally, this methodology is advantageous in some points compared to the other reported methodologies. One of its main features is the very well-defined and clear structure that it has. Additionally, in this method the criticality analysis is incorporated which enhances decision-making. Moreover, it enables the identification of potential failure modes, the assessment of their immediate effects and the determination of their criticality. Finally, FMECA offers the ability of using both qualitative and quantitative approaches to assess the severity, occurrence and detectability of the different failure modes. Further details of how the FMECA methodology has been implemented in the current thesis as well as the related data, are given in section 3.2.

2.2.3 Performance Domain

Mass is recognised as a fundamental KPI in the field of aeronautical engineering since, it directly influences the overall performance of the aircraft, fuel efficiency and payload capability. Mass KPI optimisation is a vital issue for reducing operational costs, improving sustainability and enhance flight dynamics. Mass reduction strategies, as for example the usage of lightweight composite materials, contribute to optimise the aerodynamics and reduce fuel consumption. Moreover, a research on aerospace manufacturing, emphasises the role of mass in structural integrity and safety, ensuring that mass reduction–optimisation does not compromise the durability of the structure [33].

Several experimental and computational methodologies have been developed for the measurement of this particular KPI. More specifically, mass in aeronautics is usually measured using accurate weighting systems, computational models as well as experimental validation techniques. All these methodologies ensure precision during the design phase and performance optimisation. In nowadays in order to estimate the Mass KPI, a widely known and implemented methodology is the so-called Finite Element Analysis (FEA), which can predict the mass distribution over the structure with high accuracy. In Figure 2-8 the FEA method has been applied for an aircraft and the resulting finite element model is demonstrated. Moreover, FEA helps to optimise weight reduction strategies by simulating the structural behaviour under several conditions [34]. An additional advantage of FEA it that it allows engineers to evaluate the effect of different materials and geometries on the overall mass of the structure. LCA is also used for the evaluation of the environmental impact of mass–related decisions in aerospace field. Through this method the sustainability of materials and manufacturing processes can be assessed, ensuring that mass optimisation is aligned with environmental targets.

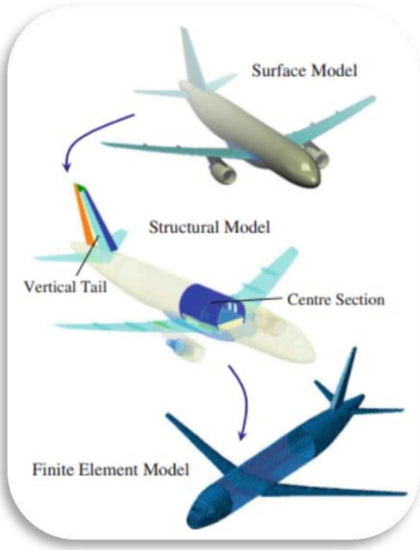


Figure 2-8 Illustration of a Finite Element Model [34]

One of the major challenges in mass optimisation is the trade-off between the weight reduction and structural integrity. Fuel efficiency is improved by the implementation of lighter materials but may compromise the durability and structural integrity of the structure [32]. Furthermore, manufacturing constraints raise difficulties as advanced lightweight materials require specialised production techniques and methods, resulting in increased cost and complexity [36]. In addition, standardisation across all aeronautic fields remains a challenge, since different aircraft configurations complicate and limit the universal implementation of mass KPIs [38]. Due to that fact, holistic digitalisation KPI framework for the aerospace industry, emphasising mass as a crucial factor in optimising production processes has been proposed by Krol and other experts [35]. That research highlights that digitalisation enhances mass monitoring, leading to better resource management, waste reduction and improved operational effectiveness. Mass measurement techniques in aerostructures are examined in a similar study, pointing their importance in production and reduction of the overall costs [36]. Additionally, formal reports recognise the mass as a basic KPI, as it ensures operational efficiency and structural reliability [37].

In the present thesis, no specific methodology is chosen for the evaluation of the mass KPI. The mass of each of the technical components that compose each examined latching architecture is already available from previous study [2]. According to that study, the manufacturing material density of a technical component, is available, while in parallel the volume of each technical component has been estimated by using a Computer Aided Design (CAD) tool. Thus, by multiplying the calculated volume of each component by the relevant production material density, the total masses of all the components have been estimated.

2.2.4 Supply Chain Domain

Broadly, supply chain KPIs are used to assess the efficiency, cost–effectiveness and reliability of manufacturing and logistics. Some common supply chain KPIs are the lead time, manufacturing time, return rate, defect rate, cost per part, transportation cost, reliability of the supplier, quality of the supplier etc. All these KPIs help numerous organisations and enterprises to optimise critical aspects associated with the Supply Chain Domain. By monitoring the supply chain KPIs, it is ensured that production is rationalised, delays are reduced and resources are better allocated. In addition, there is significant increasement of the suppliers' performance, production efficiency but in the same time reduction of the overall production and transportation risk [39], [40].

Often the evaluation of these KPIs is complex, as various parameters by all the involved fields must be taken into consideration, in order to obtain realistic results. For this purpose, it is necessary to use analytical frameworks and basic industry benchmarks. Combining the two above-mentioned principles, the reliability and robustness of operational efficiency is mainly ensured. Appropriate and specialised methodologies, which are representative for the purpose of each research, are applied for the evaluation of each selected metric.

The primary objective of the numerous supply chain–related research projects is the optimisation of all those different KPIs. In a study that has been carried out, the various strategies for selecting suppliers have been examined, while the importance of formal and informal inspections on random components to ensure the required quality and reliability have been highlighted [40]. Similar research, outlines the several challenges caused by global supply chain disruptions and geopolitical risks, underlining the necessity of advanced strategies development to manage such issues. Furthermore, it is pointed out that through such KPIs it is possible to evaluate the supplier's performance and develop risk mitigation techniques [39]. However, despite the potential improvements and innovations regarding the measurement of the Supply Chain associated KPIs, still there are several issues that must be addressed. By tackling them, the efficiency and resilience of the overall supply chain performance can be increased. Some of the main challenges which are outlined below, make it difficult to evaluate and optimise the supply chain KPIs:

- **Development of risk management techniques:** Supplier dependency and unpredictable disruptions in the supply chain require adaptive strategies [40].
- **Cost fluctuations:** Resource pricing variability and geopolitical factors create financial unpredictability [40].
- **Limitation of defects:** Due to the need of transporting products from the production site to the suppliers, the quality of them may be affected [40].
- **Supplier reliability and quality issues:** Variability in supplier performance can lead to delays in production timelines [40].

In the current analysis, this domain plays a significant role since, as previously mentioned in section 2.2, it depends on both the technical characteristics of the examined latching mechanism and production scenario under consideration. Thus, with the selected indicators (which are introduced below), the aim is to characterise both of these aspects. According to that and based on an already developed method [78], four distinct KPIs are selected to describe this specific domain. These indicators are cost, time, risk, and quality. In order to evaluate the reported KPIs, the same procedure has been followed as outlined in [78]. Some minor modifications have been done for the current analysis. More specifically, the overall supply chain cost, time and risk are evaluated by accounting the contribution of two different terms (instead of three as in the mentioned methodology), the fixed term and transportation term. On the other hand, the overall supply chain quality is assessed exclusively by the fixed term. For the assessment of the fixed cost, time, risk and quality, multiple aspects which are associated with the geographical location of each considered enterprise have been accounted. The transportation cost, time and risk terms are evaluated based on the route that must be followed in order to transport the technical components from the production sites to the assembly sites. More details about the considered enterprises, the estimation methodology of the fixed terms as well as the applied transportation mode are mentioned in section 3.4.

2.3. Multi Attribute Utility Theory for Decision-Making

Under the previous section, the seven different KPIs considered for this analysis have been introduced. As mentioned, those indicators derive from different domains. Through this section, the way in which these indicators are aggregated in order to allow decision-making and conclusions to be drawn, is presented. To this end, among others, Multi–Attribute Utility Theory (MAUT) is selected and described which is a widely used decision-making framework designed to evaluate alternatives surrounding by multiple and often conflicting criteria.

MAUT, operates in the broader context of Multi–Criteria Decision-Making (MCDM) theory [41]. It assists decision-makers to quantify their preferences and assign utility values to various alternative decisions. The utility function, which assigns numerical values to various attributes based on their relative importance, holds a key position in MAUT, allowing decision-makers to objectively evaluate alternatives. In order to ensure a structured approach, MAUT incorporates a weighting system where decision-makers or organisations, determine the importance of each attribute to accurately reflect on their priorities. As attributes may vary in scale (i.e. different unit of measurement), the normalisation of their utilities is necessary and crucial to make them comparable. By doing so, it is assured that each attribute is fairly assessed in the context of the overall decision–making process. [42], [43].

2.3.1 Historical Background

The theory (MAUT) has been formally introduced by Ralph L. Keeney and Howard Raiffa in their important book titled "Decision with multiple Objectives: Preferences and Value Trade-offs" in 1976 [44]. Their research has established the foundation for structured decision–making in scenarios where multiple opposing criteria have to be considered. Over the years, MAUT is widely applied in fields such as engineering, business management, public policy and many other fields, offering a systematic approach to evaluate alternatives [45]. One of their (Ralph L. Keeney and Howard Raiffa) key contributions was the introduction of trade–offs, allowing decision makers to balance competing objectives by assigning utility values to different attributes. That concept has had a significant impact on multi–criteria optimisation models, which are now being incorporated into modern analytical systems and artificial intelligence to enhance strategic decision–making [46].

2.3.2 Mathematical Framework

The two primary models utilized in MAUT are additive and multiplicative utility functions, which determine how individual attribute utilities contribute to the total utility of an alternative [44].

In the additive model, total utility is derived from the sum of the weighted utilities of each attribute, which makes it appropriate when attributes are independent. This model is popular for its simplicity and computational efficiency. It works by summing the weighted utilities values of individual attributes, making it an intuitive approach for decision-makers concerned with independent criteria [44]. Furthermore, it is advantageous in scenarios where trade–offs remain constant, allowing a simple comparison of alternatives based on their overall utility values [45]. However, its assumption that attributes do not interrelate can be a limitation when evaluating complex scenarios involving interdependencies between criteria [47] and thus, this model may not be fully capturing the complex interactions that exist between attributes.

In contrast, the multiplicative model accounts the interactions among the considered attributes, allowing for more complex exchanges by multiplying utility terms. Rather than summing the utilities of attributes, this model multiplies them, ensuring that changes in one criterion can affect overall utility more dynamically [47]. Such a characteristic makes it particularly valuable in risk assessment, environmental management and engineering. On the other hand, the multiplicative model introduces greater computational complexity and requires careful normalisation of the utilities values in order to avoid disproportionate weighting [45]. In addition, its non–linear nature may make the utility values more difficult to be interpreted compared to additive model, requiring more advanced analytical tools for its effective implementation.

Figure 2-9 illustrates the general procedure to be followed for the proper implementation of the MAUT. As presented, this procedure consists of four distinct levels. At the first level, all the requirements, objectives, measures and alternatives related to the specific application are identified. Regarding the second level, data are collected for each of the identified alternatives at the first level. Then the relative importance of each alternative in relation to all the others is detrmined and an utility function is formulated as well. Right after, at the fourth level, the sum of all the weighted alternatives is obtained. That aggregate result is the so-called value. As a final step, a sensitivity analysis and comparison of results is carried out. Thus it is possible to select the optimum solution characterised by the highest value.

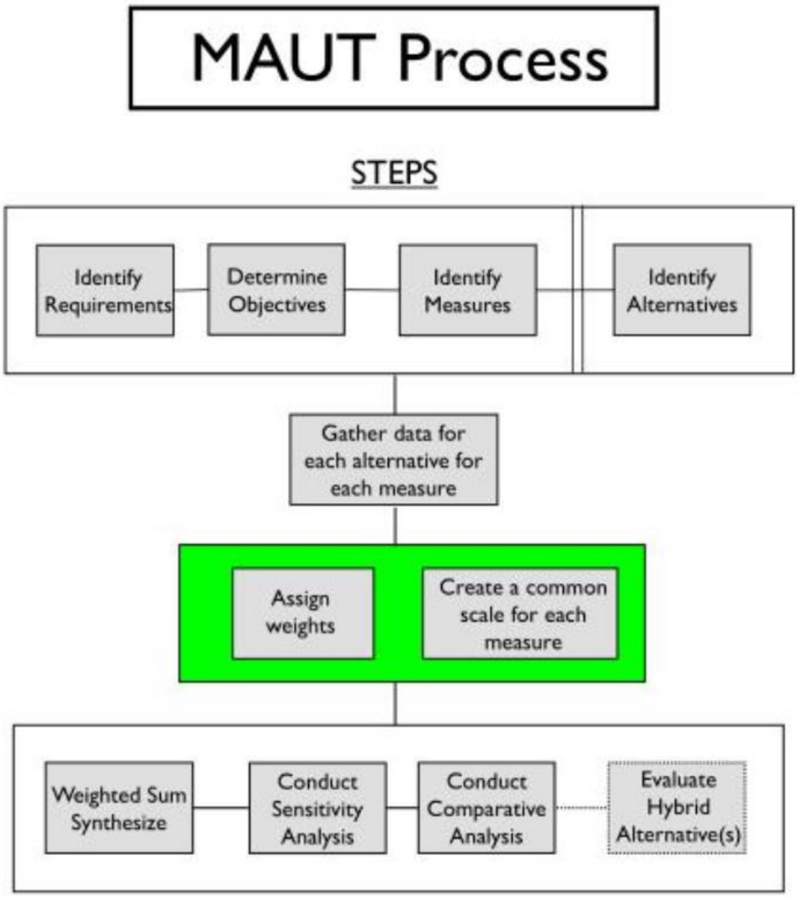


Figure 2-9 Demonstration of the various steps that must be implemented during the application of the MAUT

2.3.3 Applications MAUT in Aerospace Domain

MAUT has become a fundamental tool in aerospace engineering, allowing decision-makers to evaluate complex trade–offs among multiple criteria. One of its prime applications is in the aircraft design optimisation, where engineers assess competing factors such as fuel efficiency, structural integrity and environmental impact to determine the most viable configurations. In addition, it is being used in satellite mission design, helping organisations prioritize various requirements associated with the space–based systems. Figure 2-10 shows a notional plot from the reported application, which illustrates the acceptance and rejection region, the utility value of each architectural alternative and the effective frontier [49]. Further, MAUT has a crucial role in space exploration, guiding decision-making processes on robotic mission architectures by balancing science objectives, risk factors and budget constraints. In military aviation, it is utilized for design–cost assessments, ensuring optimal trade–offs among economic aspects and operational effectiveness [50].

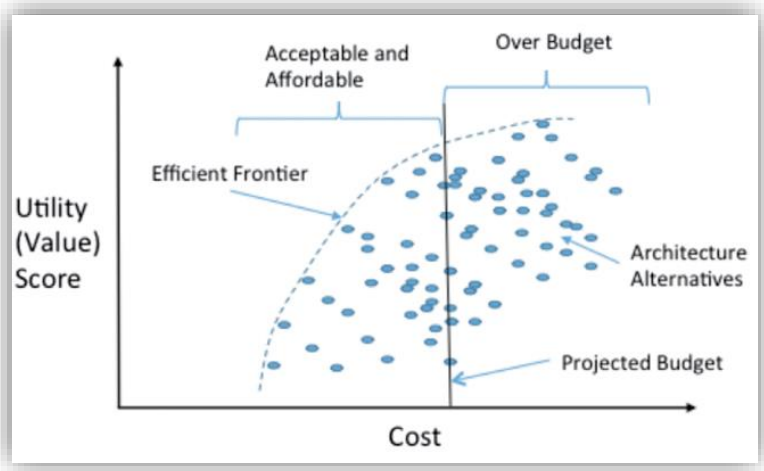


Figure 2-10 Notional effective frontier plot (Utility Vs Cost) [49]

This theory (MAUT) stand out among other decision-making models used in aerospace due to its ability to handle multiple conflicting objectives while incorporating uncertainty. Unlike the Analytic Hierarchy Process (AHP), which is based on pairwise comparisons and is suitable for qualitative evaluations, MAUT provides a more quantitative approach, ensuring accurate trade–off judgements [51]. Additionally, while Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives based on proximity to an ideal solution, MAUT offers greater flexibility in prioritizing preferences, thus becoming more suitable for complex aerospace decisions involving safety, cost and performance trade–offs [52].

2.4. Science Gaps & Research Questions

This section underlines the main scientific gaps related to the topic under examination. The research questions and the objectives of this thesis are also stated.

The first scientific gap identified in the literature, relates to the total number of KPIs that are used by a research to perform decision making. Several studies in the aerospace engineering field focus on and investigate mainly two fundamental factors: mass and cost, and the trade-offs between them. Usually, priority is given to them due to the fact that, reduction of the overall weight or minimising the production costs of the structure are of high importance in this particular field. However, a more comprehensive approach is required that considers aspects from different domains such as sustainability and reliability of the system under consideration. By integrating aspects from these domains into trade-off studies, the overall decision-making process is clearly more balanced, providing the opportunity for more objective results. To this end, one of the main targets of this thesis is to aggregate KPIs among four different domains to perform trade-offs and then decision-making.

The next scientific gap, concerns the connectivity of the supply chain domain with various other engineering domains and how to evaluate it. Numerous scientific articles explain explicitly the indicators to be considered for the efficiency assessment of the supply chain, but in general there is no a standardised methodology focusing on this particular issue. In addition, a limited number of studies provide guidance on how supply chain domain is linked to the manufacturing and design domain, leading to a concurrent design. However, no methodologies have been identified that link the supply chain domain to the sustainability, reliability and performance domains, which have been of great interest nowadays. Thus, the aim is to cover this gab by using already developed methodologies that discuss concurrent design and concatenation of domains under a generalised framework as well as the methodologies described in this thesis.

Concerning MAUT, the primary gap observed in the literature is its relatively limited applications in the aerospace field. Despite its widespread use in various fields such as finance and operational research, it still remains restricted in the aerospace field. This is partly explained by the fact that among aerospace systems, complex attributes' dependencies and various constraints are developed. Nevertheless, MAUT is evident as a very valuable tool for decision-making which offers a structured approach to quantify trade-offs in complex systems. Based on that, among other value model techniques previously mentioned, MAUT is used in the current study, highlighting its significance and usefulness in aeronautical applications.

At this point of the thesis, the primary research question is framed as:

How can a multi-criteria decision-making process among four different domains can be achieved and the best alternative for a latching system be identified?

The primary research question can be broad and for that reason is supported by three specific questions:

- How can a trade-off among different latching systems be performed and the best solution be identified?
- How can sustainability and reliability KPIs be evaluated for a latching system?
- How can a different production and assembly scenario be investigated and assessed?

In the following chapters of the thesis, the answer of these questions is addressed.

3. Methodology Formulation

The methodology forms the backbone of every research, guiding the entire process from data collection, to the analysis and the interpretation. In this chapter, main aim is to provide a detailed explanation of the procedures and techniques deployed in order to evaluate the various KPIs, ensuring the validity and the reliability of the findings. To this end, the developed methodology for the assessment of each one of the seven different KPIs (see section 2.2) is explained and documented in detail.

In total, seven different KPIs are investigated. Four of them describe the performance of the Supply Chain Domain, one describes the overall Environmental Sustainability of the mechanism, another the overall Reliability and finally one which is related to the Mass of the mechanism. Through the different methodologies outlined below, the primary objective is to estimate all these indicators for each one of the interested architectural designs. More details are given in the following sections. Figure 3-1 presents the overall methodology followed for the evaluation of each KPI, as well as the aggregation of them into a single value by using the MAUT.

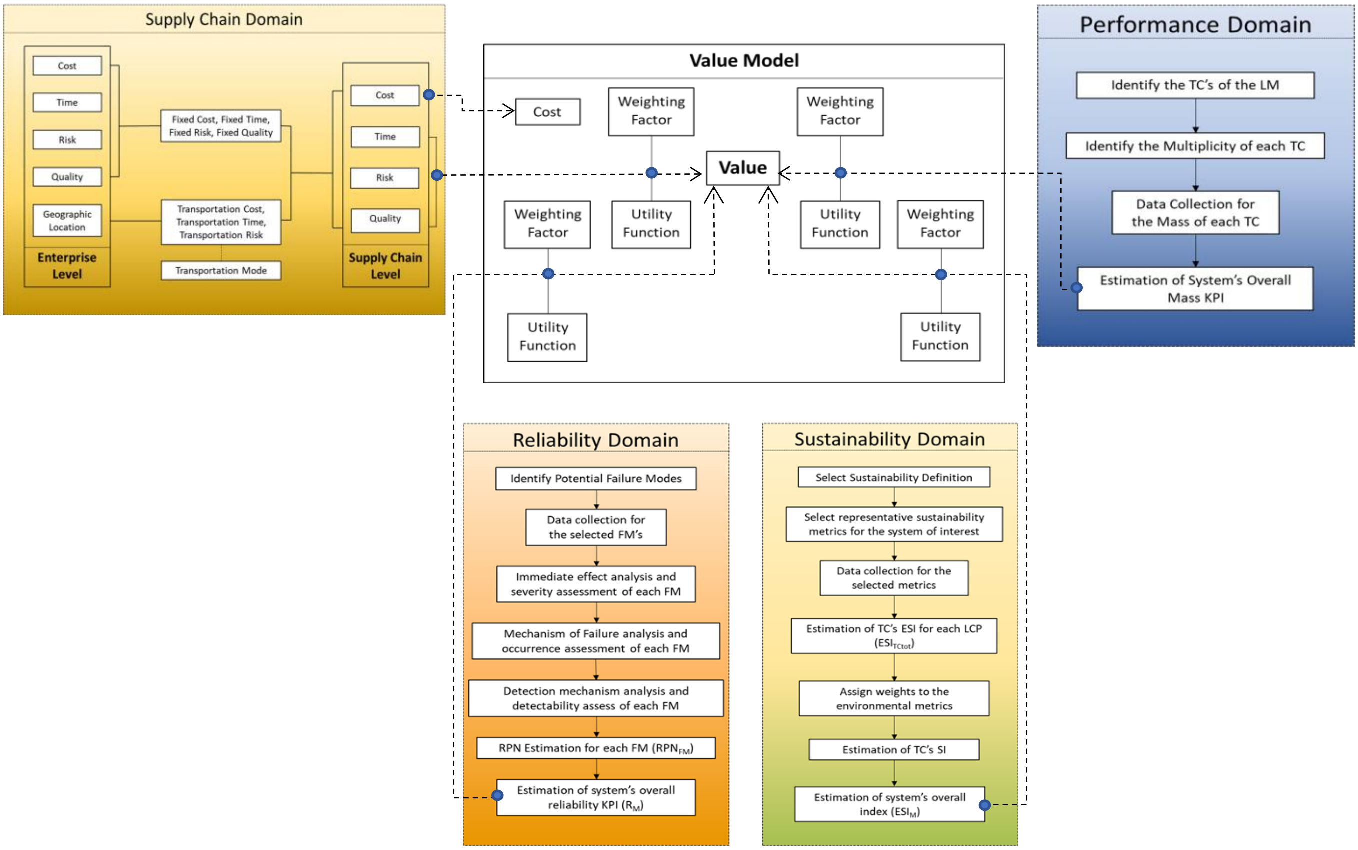


Figure 3-1 Graphical representation of the overall methodology followed in the current analysis in order to estimate the various KPIs and later on the aggregation of them into a single value

3.1. Sustainability Domain

As has been stated in section 2.2.1, the sustainability of one system can be estimated by many and different approaches. In the current analysis, the Three-Pillar Sustainability definition has been used in order to understand the main principles of the Sustainability, whereas the LCA methodology is being followed for the evaluation of the Sustainability KPI of each latching mechanism (see section 2.2.1). The three most known Three-Pillar approaches that are being implemented in the new era to define the sustainability of a system are listed below [53], [54]:

1. **Triple Bottom Line Definition**
2. **Strong Sustainability Definition**
3. **Weak Sustainability Definition**

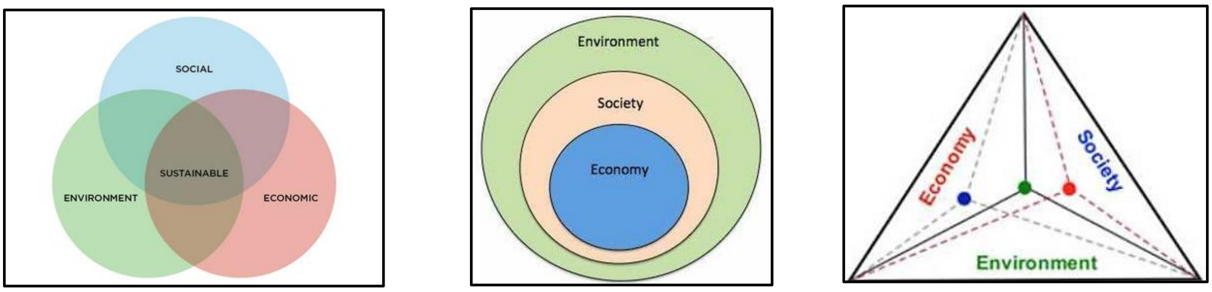


Figure 3-2 Various sustainability definitions: 1) Triple bottom line, 2) Strong sustainability definition, 3) Weak sustainability definition [53]

As can be seen in Figure 3-2, each one of the mentioned definitions, consists from three main pillars which are presented below [53]:

1. **Environmental Pillar**
2. **Society Pillar**
3. **Economy Pillar**

For the purposes of the analysis, only some metrics associated with the environmental pillar are considered in order to evaluate the overall Sustainability Index of the latching mechanisms. To this end, it is renamed as overall Environmental Sustainability Index (ESI_{LM}). This assumption derives from the fact that the environment provides natural resources and ecosystem services necessary for economic and social development [55]. Economic development depends on both social and environmental pillars, whereas both economic and social processes influence environmental conditions [53]. In addition, the environmental pillar recognized as a fundamental aspect for the sustainability analysis. Based on that, the other two pillars (Society, Economy) are not accounted in the current analysis.

A metric, is an operational representation of an attribute of a system. All the sustainability metrics have a degree of uncertainty that arises from the collection and analysis of the various data. Only the most important and representative metrics must be selected in order to evaluate the sustainability index of a system. Thus, based on the system of interest and the main purposes of the particular analysis the chosen metrics may be varied. Index is the outcome of the aggregation of two or more metrics into one single value [53], [56].

For this particular application case, four key environmental metrics have been selected in order to evaluate the overall Environmental Sustainability Index of the latching mechanisms (ESI_{LM}), which are reported below:

1. **Greenhouse Gas Emissions (GHG)**
2. **Energy Consumption (EC)**
3. **Waste Generation (WG)**
4. **Resource Depletion (RD)**

The Greenhouse Gas Emissions (GHG) metric is crucial for the overall sustainability estimation, as it quantifies the environmental impact of a system and guides their reduction strategies. Regarding the second metric (EC), is also essential for sustainability estimation of a system, as it directly related with the GHG. It highlights the need to use renewable energy sources since conventional energy production methods emit carbon dioxide as well. Moreover, Waste Generation (WG) metric is a key metric, as it evaluates environmental impact and encourages reduction and recycling efforts. The last considered metric is related with the Resource Depletion (RD). It is critical for sustainability estimation, as it monitors the consumption of natural resources and encourages sustainable management practices.

The Environmental Sustainability Index of each latching mechanism is estimated for its entire life cycle. A life cycle of a mechanism encompasses all stages from raw material extraction for the production of the various technical components, the operational phase, until the disposal of the entire mechanism. Based on the LCA methodology there are three main and distinct Life Cycle Phases (LCPs), which are presented below:

1. **Production Phase (PP)**
2. **Use Phase (UP)**
3. **End of Life Phase (EoLP)**

Each phase has distinct goals and impacts, contributing uniquely to the components' overall life cycle. PP involves all the different procedures and stages from the extraction of raw materials to the shaping and machining of the various technical components that compose a mechanism. Regarding the UP, the final technical component or mechanism, performs its indented function. The EoLP of a technical component or a mechanism involves proper disposal, recycling, or repurposing procedures in order to minimize environmental impact. All the four mentioned metrics are evaluated during all three phases being considered for this analysis. The total contribution of each of the metrics to the overall index of each LM (ESI_{LM}) is estimated as sum of these three phases (PP, UP, EoLP). In Figure 3-3 is illustrated an overview of the applied methodology for the estimation of the ESI_{LM}.

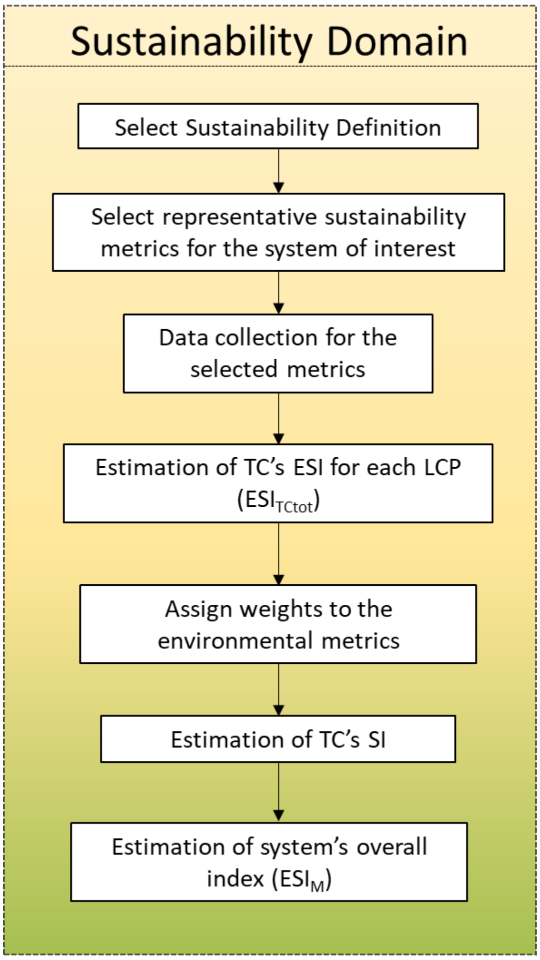


Figure 3-3 Overall process for the sustainability KPI estimation of each architectural design

At this point, it is necessary to identify the materials that the technical components (TCs) that consist of the LMs are made of. Across the technical components of each architecture, four different materials are detected in the provided document [2] which are listed below:

1. **Titanium (Ti)**
2. **Steel (St)**
3. **Aluminium (Al)**
4. **Thermoplastic (Tp)**

Upon discussion with the experts, all the TCs made of Tp are ignored for the purposes of the present analysis. This assumption is based on the fact that very few TCs are made of that material and are also common to all three architectural designs.

3.1.1 Environmental Metrics Data – All Life Cycle Phases

This section summarises all the necessary and relevant data needed in order to be able to estimate the considered metrics of this analysis. Comprehensive and accurate information are provided for every distinct life cycle phase (production, use, and end-of-life) to ensure a thorough and reliable evaluation. Data are available for the emission factors of each process, the energy intensity of each process, waste generation rates, and resource depletion rates. Additionally, general parameters are provided to ensure a thorough and precise analysis.

3.1.1.1 Greenhouse Gas Emissions Environmental Metric

All the factors which are related with GHG estimation during the different LCPs, are summarized in the current section. As the various technical components of each architectural design are produced by Titanium, Steel or Aluminium, the involved production processes and thus the emission factors of them vary based on the material that the technical component is made of. To this end, for titanium TCs the 6 (six) most important and main processes are included [57], [58], for steel TCs seven (7) key formatting procedures have been taken into consideration [59], [60] whereas, for aluminium TCs four (4) fundamental processes are accounted [61]. All the different processes and their related emission factor are reported in Table 3-1.

The LM is integrated into the LDCD of an aircraft. For this reason, the emission factors for the estimation of the GHG during the UP are based on the entire aircraft's performance and lifetime. All the shown data on Table 3-2 are related with the A320 aircraft (A/C) family [62], [63]. The three examined LMs (HSLM, BLM and CLM) are different use cases of the same application, therefore the data are the same for all the three materials. The GHG during the UP depends solely on the mass of the TC and the mass of the entire A/C as well as on some parameters related to the entire aircraft.

During the EoLP all the TCs of each latching mechanism are treated in the same way. Due to the fact that all of the mentioned materials are metals, the biggest percentage of the technical component's mass is deemed recyclable, while the remaining is considered as landfill. Since no such data were found in the literature, the emission factor during the recycling of a TC, is assumed to be 10% of the total emissions during the initial PP. The related emission factors and the respective percentages can be found on Table 3-3. Only the emission factor during the recycling phase defers among the different materials. The emission factor that is associated with the landfill [64] and the percentages of the recyclable and non-recyclable portion of the TC's mass are assumed to be same for all the materials.

Greenhouse Gas Emissions Data - Production Phase

Material	*Production Process*	*Value*	*Unit*
Titanium	*Ore Mining*	*1.116*	*(kg of CO2e / kg of Titanium)*
	Titanium Slag Smelting	*5.084*	*(kg of CO2e / kg of Titanium)*
	Chlorination and Refining	*9.133*	*(kg of CO2e / kg of Titanium)*
	Reduction and Distillation	*4.051*	*(kg of CO2e / kg of Titanium)*
	Electrolysis	*12.053*	*(kg of CO2e / kg of Titanium)*
	Machining - Milling	*0.990*	*(kg of CO2e / kg of Titanium)*
Steel	*Iron ore sinter plant*	*0.405*	*(kg of CO2e / kg of Steel)*
	Blast furnace	*0.809*	*(kg of CO2e / kg of Steel)*
	Lime production plant	*0.051*	*(kg of CO2e / kg of Steel)*
	Basic oxygen furnace	*0.034*	*(kg of CO2e / kg of Steel)*
	Continuous casting plant	*0.000*	*(kg of CO2e / kg of Steel)*
	Hot rolling	*0.107*	*(kg of CO2e / kg of Steel)*
	Machining - Milling	*0.880*	*(kg of CO2e / kg of Steel)*
Aluminium	*Bauxite Mining*	*0.070*	*(kg of CO2e / kg of Aluminium)*
	Refining	*2.400*	*(kg of CO2e / kg of Aluminium)*
	Smelting	*12.200*	*(kg of CO2e / kg of Aluminium)*
	Casting	*0.180*	*(kg of CO2e / kg of Aluminium)*

Table 3-1 GHG environmental metric data - Different processes and emission factors for each considered material during the Production Phase

Greenhouse Gas Emissions Data - *Use Phase*

Parameter	*Value*	*Unit*
Fuel Efficiency	0.015	(Kg / km-passenger)
Kerosene Emission Factor Every 1 burned kg	3.010	(kg of CO2e / kg of fuel)
Total Passenger-km	10388812500	(km- passenger)

Table 3-2 GHG environmental metric data - Different parameters related with the Use Phase

3.1.1.2 Energy Consumption Environmental Metric

This section summarises all the factors needed to estimate the consumed energy of each TC during its entire life cycle. The same processes as explained in section 3.1.1.1, have been taken into account to estimate the energy consumption during the PP for each TC. However, in this case, all the factors are associated to the consumed energy by each different process to produce

Greenhouse Gas Emissions Data - End of Life Phase

Parameter	*Value*	*Unit*
Recycling Emission Factor (Titanium)	3.240	(kg of CO2e / kg of Titanium)
Recycling Emission Factor (Steel)	0.229	(kg of CO2e / kg of Steel)
Recycling Emission Factor (Aluminium)	1.490	(kg of CO2e / kg of Aluminium)
Landfill Emission Factor	0.0220	(kg of CO2e / kg of Material)
Recyclable Mass Portion	95	%
Non-Recyclable Mass Portion	5	%

Table 3-3 GHG environmental metric data – Recycling emission factor of each material, landfill emission factor and considered recyclable / non-recyclable mass portion of each TC during the EoLP

the specific TC and not with the pollutants emitted. All the different factors for each material are reported in Table 3-4 [58], [60], [61].

Energy Consumption Data - Production Phase

Material	*Production Process*	*Value*	*Unit*
Titanium	*Ore Mining*	*1.050*	*(kWh / kg of Titanium)*
	Titanium Slag Smelting	*4.700*	*(kWh / kg of Titanium)*
	Chlorination and Refining	*2.550*	*(kWh / kg of Titanium)*
	Reduction and Distillation	*4.850*	*(kWh / kg of Titanium)*
	Electrolysis	*14.500*	*(kWh / kg of Titanium)*
	Machining - Milling	*4.890*	*(kWh / kg of Titanium)*
Steel	*Iron ore sinter plant*	*0.079*	*(kWh / kg of Steel)*
	Blast furnace	*0.026*	*(kWh / kg of Steel)*
	Lime production plant	*0.003*	*(kWh / kg of Steel)*
	Basic oxygen furnace	*0.028*	*(kWh / kg of Steel)*
	Continuous casting plant	*0.011*	*(kWh / kg of Steel)*
	Hot rolling	*0.040*	*(kWh / kg of Steel)*
	Machining - Milling	*0.685*	*(kWh / kg of Steel)*
Aluminium	*Bauxite Mining*	*0.005*	*(kWh / kg of Aluminium)*
	Refining	*0.591*	*(kWh / kg of Aluminium)*
	Smelting	*16.000*	*(kWh / kg of Aluminium)*
	Casting	*0.354*	*(kWh / kg of Aluminium)*

Table 3-4 EC environmental metric data – Energy intensity of each distinct process for each considered material during the PP

As mentioned, the mechanism under investigation is integrated into the LDCD of an A/C. In order to be able to estimate the consumed energy by each TC during the UP, the total consumed energy by the A/C during its lifetime must first be evaluated. The factor which is presented in Table 3-5 represents the total consumed energy by the by the A/C during its lifetime. The mass ratio between the technical component's mass and the aircraft's mass can be estimated. Consequently, the consumed energy by each TC during the UP can be calculated by multiplying the mass ratio with the total energy consumed by the A/C during its entire life cycle. In addition, this factor is independent of the technical component’s material and is thus the same for all of them during that phase (UP) of this metric (EC).

Concerning the EoLP, it is assumed that the station handling all those TCs is coal-fired. The relevant factor for such a plant is shown in Table 3-6. Combining the outcome of the same phase (EoLP) from the previous metric (GHG) with the provided emission factor, it is possible to estimate the consumed energy by each TC during the EoLP [61], [65]. This phase (EoLP) is also independent from the component's material and therefore only one factor is provided.

Energy Consumption Data - ***Use Phase***

Parameter	*Value*	*Unit*
Total A/C Consumed Energy	*10837838*	*(kWh)*

Table 3-5 Total consumed energy by the aircraft for its entire lifetime during the Use Phase in kWh

Energy Consumption Data - ***End of Life Phase***

Parameter	*Value*	*Unit*
Coal Emission Factor	*0.390*	*(kg of CO2e / kWh)*

Table 3-6 Considered coal emission factor during the End of Life Phase

3.1.1.3 Waste Generation Environmental Metric

The third environmental metric that has been examined across the entire life cycle of a TC is the Waste Generation. This specific metric, describes the mass of material lost or discarded during the various phases of the component's production. Therefore, since this metric is directly and strongly associated to the Production Phase of the TCs, the remaining two life cycle phases (UP and EoLP) are disregarded in the current analysis. A summary of all the related factors for all the three different materials during the PP of each material are reported in Table 3-7 [58], [60], [61].

Waste Generation Data - Production Phase

Material	*Production Process*	*Value*	*Unit*
Titanium	*Ore Mining*	27.930	*(kg / kg of Titanium)*
	Titanium Slag Smelting	0.042	*(kg / kg of Titanium)*
	Chlorination and Refining	0.000	*(kg / kg of Titanium)*
	Reduction and Distillation	0.093	*(kg / kg of Titanium)*
	Electrolysis	0.000	*(kg / kg of Titanium)*
	Machining - Milling	0.000	*(kg / kg of Titanium)*
Steel	*Iron ore sinter plant*	0.390	*(kg / kg of Steel)*
	Blast furnace	0.201	*(kg / kg of Steel)*
	Lime production plant	0.390	*(kg / kg of Steel)*
	Basic oxygen furnace	1.126	*(kg / kg of Steel)*
	Continuous casting plant	0.752	*(kg / kg of Steel)*
	Hot rolling	1.420	*(kg / kg of Steel)*
	Machining - Milling	0.000	*(kg / kg of Steel)*
Aluminium	*Bauxite Mining*	0.000	*(kg / kg of Aluminium)*
	Refining	4.550	*(kg / kg of Aluminium)*
	Smelting	0.057	*(kg / kg of Aluminium)*
	Casting	0.011	*(kg / kg of Aluminium)*

Table 3-7 WG environmental metric data – Waste Generation during the different production processes of each material

3.1.1.4 Resource Depletion Environmental Metric

Finally, the last considered environmental metric is the Resource Depletion. In the following three tables (Table 3-8, Table 3-9, Table 3-10), the most important and necessary raw materials needed to produce a titanium, steel or aluminium component are presented accordingly. Since it is linked exclusively with the manufacturing stage of the TCs, the Use Phase and End of Life Phase are ignored [58], [60], [61].

Resource Depletion Data - Production Phase

Material Description	*Value*	*Unit*
Raw Ore	91.100	kg of material/kg of Titanium
Fresh Water	30.540	kg of material/kg of Titanium
Petroleum Coke	1.153	kg of material/kg of Titanium
Raw Coal	3.540	kg of material/kg of Titanium
Magnesium	0.041	kg of material/kg of Titanium

Table 3-8 RD environmental metric data – Considered raw materials for the production of Titanium TCs

Resource Depletion Data - Production Phase

Production Process	*Value*	*Unit*
Iron ore sinter plant	*1.956*	*(kg / kg of Steel)*
Blast furnace	*1.620*	*(kg / kg of Steel)*
Lime production plant	*0.123*	*(kg / kg of Steel)*
Basic oxygen furnace	*1.464*	*(kg / kg of Steel)*
Continuous casting plant	*1.056*	*(kg / kg of Steel)*
Hot rolling	*0.407*	*(kg / kg of Steel)*
Machining - Milling	*0.000*	*(kg / kg of Steel)*

Table 3-9 RD environmental metric data – Considered raw materials for the production of Steel TCs

Resource Depletion Data - Production Phase

Material Description	*Value*	*Unit*
Bauxite	*7.390*	*(kg of material / kg of Aluminium)*
Carbon	*0.500*	*(kg of material / kg of Aluminium)*
Coal	*73.600*	*(kg of material / kg of Aluminium)*

Table 3-10 RD environmental metric data – Considered raw materials for the production of Aluminium TCs

3.1.2 Technical Components' Environmental Sustainability Index Evaluation

All the necessary data to estimate the overall Environmental Sustainability Index of each Technical Components (ESI_{TCtot}) have been provided in section 3.1.1. The calculation of that index is proposed as the sum of four contributions as indicated in the following formula:

$$ESI_{TC_{tot}} = WF_1 GHG_{TC_{tot}} + WF_2 EC_{TC_{tot}} + WF_3 WG_{TC_{tot}} + WF_4 RD_{TC_{tot}}$$

Equation 3-1

where,

- WF_1, WF_2, WF_3, WF_4, represent the weighting factor of each metric (GHG, EC, WG, RD) respectively. The sum of the four weighting factors must be equal to one (1).
- GHG_{TCtot}, EC_{TCtot}, WG_{TCtot}, RD_{TCtot}, represent the total contribution of each TC to that specific metric for all the different life cycle phases (PP, UP, EoLP) respectively

The first term of the Equation 3-1 is evaluated by the following formula:

$$GHG_{TC_{tot}} = WF_1\left(\left(\sum_{i=1}^{Mp} m_{TC} f_{material,i}\right) + \left(\frac{m_{TC}}{m_{\frac{A}{C}}} f_{fuel} e_k pkm\right) + \left(r_p m_{TC} e_r + (1 - r_p) m_{TC} e_l\right)\right)$$

Equation 3-2

where,

- i: Index representing each process (From 1 to Mp, where Mp is the total number of processes applied to the material during the PP)
- m_{TC}: Mass of the TC
- $f_{material, i}$: Emission factor for the material associated with process i
- $m_{A/C}$: Total mass of the aircraft
- f_{fuel}: Fuel efficiency (Amount of fuel consumed per km per passenger)
- e_k: Kerosene emission factor
- pkm: Total A/C passenger kilometres
- r_p: Recyclable percentage of the component's mass (as a fraction between 0 and 1)
- e_r: Recycling emission factor
- e_l: Landfill emission factor

The second term of the Equation 3-1 is evaluated by the following formula:

$$EC_{TC_{tot}} = WF_2\left(\left(\sum_{i=1}^{Mp} m_{TC} e_{material,i}\right) + \left(\frac{m_{TC}}{m_{\frac{A}{C}}} E_{A/C}\right) + \left(\frac{r_p m_{TC} e_r}{e_c}\right)\right)$$

Equation 3-3

where,

- $e_{material,i}$: Energy intensity of process i (Amount of energy consumed per unit mass of material processed)

- $E_{A/C}$: Total energy consumed by the A/C during its lifetime
- e_C: Coal fired plant emission factor

The third term of the Equation 3-1 is evaluated by the following formula:

$$WG_{TC_{tot}} = WF_3\left(\sum_{i=1}^{Mp} m_{TC}w_{waste,i}\right)$$

Equation 3-4

where,

- $w_{waste,i}$: Waste generation rate for process i

The last term of the Equation 3-1 is evaluated by the following formula:

$$RD_{TC_{tot}} = WF_4\left(\sum_{z=1}^{M} m_{TC}a_z\right)$$

Equation 3-5

where,

- z: Index representing each raw material (From 1 to M, where M is the total number of raw materials required for the component)
- a_Z: Amount of raw material z required per kilogram of the component's material

As mentioned previously in section 3.1.1, the metrics which describe the waste generation and the resource depletion are exclusively associated with the production phase and thus, Equation 3-4 andEquation 3-5 consist of just one term.

A specific weighting factor is assigned to each of the considered metrics (Greenhouse Gas Emissions, Energy Consumption, Waste Generation and Resource Depletion). That factor indicates the importance of the relevant metric. Based on Table 3-11, it is evident that the Greenhouse Gas Emissions metric is assumed the most important one with 45%, due to the fact that Greenhouse Gas Emissions are a primary contributor to climate change and require urgent mitigation efforts. Energy Consumption metric follows with 25%, highlighting the need to use renewable energy sources since conventional energy production methods emit carbon dioxide as well. Then, a weighting factor of 20% is assigned to the Waste Generation metric. This percentage underlines the importance of the implementation of circular economy practices to minimise pollution. Finally, the remaining 10% is given to the Resource Depletion metric, which reflects the need to find sustainable alternatives that minimise the possibility of depletion and abuse of raw materials. All assigned percentages are based on personal judgement, with the highest percentage indicating that specific metric as the most important one whereas the lowest percentage as the least important. For the correct application of the current methodology, it is essential to ensure that the sum of the different weighting factors is equal to one-hundred (100).

Weighting Factors

Description	Value	Unit
WF1 (Related with GHG Metric)	45	%
WF2 (Related with EC Metric)	25	%
WF3 (Related with WG Metric)	20	%
WF4 (Related with RD Metric)	10	%

Table 3-11 Assigned weighting factor (percentage) for each environmental metric

By combining the five equations that have been described in this section (Equation 3-1 - Equation 3-5) with the weighting factors from Table 3-11, the ESI_{TCtot} for each one TC that compose the investigated latching mechanism can be estimated. In the following three tables (Table 3-12, Table 3-13, Table 3-14) the contribution of each examined metric to the final ESI_{TCtot} are available for all the investigated mechanisms (HSLM, BLM, CLM). Additionally, in these tables the ESI_{TCtot} of all the TCs that compose each mechanism is available.

TC's Environmental Sustainability Index - HSLM

Identification	GHG_{TCtot}	EC_{TCtot}	WG_{TCtot}	RD_{TCtot}	ESI_{TCtot}
TC 131	6.85E-04	4.30E-04	2.87E-04	5.62E-04	1.96E-03
TC150	9.21E-02	5.78E-02	3.85E-02	7.55E-02	2.64E-01
TC151	1.17E-01	7.33E-02	4.89E-02	9.57E-02	3.35E-01
TC 132	3.06E-03	1.92E-03	1.28E-03	2.51E-03	8.77E-03
TC 22	5.91E-03	4.16E-03	1.50E-02	7.49E-03	3.25E-02
TC 24	2.31E-02	1.63E-02	5.87E-02	2.93E-02	1.27E-01
TC 26	7.89E-02	5.55E-02	2.00E-01	1.00E-01	4.34E-01
TC 20	9.99E-03	7.02E-03	2.53E-02	1.27E-02	5.50E-02
TC 40	3.35E-03	2.35E-03	8.48E-03	4.24E-03	1.84E-02
TC 42	1.83E-03	2.35E-03	4.65E-03	2.32E-03	1.12E-02
TC 31	1.97E-03	1.39E-03	4.99E-03	2.50E-03	1.08E-02
TC 47	2.18E-02	1.53E-02	5.52E-02	2.76E-02	1.20E-01
TC 130	2.93E-03	2.06E-03	7.43E-03	3.72E-03	1.61E-02
TC 21	1.35E-01	7.47E-02	5.22E-02	8.98E-03	2.71E-01
TC 25	3.86E-02	2.14E-02	1.50E-02	2.58E-03	7.76E-02
TC 27	3.04E-02	1.69E-02	1.18E-02	2.03E-03	6.11E-02
TC 28	3.26E-02	1.81E-02	1.26E-02	2.17E-03	6.55E-02
TC 29	4.50E-01	2.50E-01	1.75E-01	3.01E-02	9.05E-01
TC 30	1.82E-01	1.01E-01	7.05E-02	1.21E-02	3.65E-01
TC 23	5.06E-03	2.81E-03	1.97E-03	3.38E-04	1.02E-02
TC 41	1.12E-01	6.25E-02	4.37E-02	7.51E-03	2.26E-01
TC 44	1.26E-02	6.99E-03	4.89E-03	8.40E-04	2.53E-02
TC 45	1.09E-03	6.08E-04	4.25E-04	7.31E-05	2.20E-03
TC 46	1.09E-03	6.08E-04	4.25E-04	7.31E-05	2.20E-03

Identification	GHG_{TCtot}	EC_{TCtot}	WG_{TCtot}	RD_{TCtot}	ESI_{TCtot}
TC 133	1.32E-03	7.35E-04	5.13E-04	8.83E-05	2.66E-03
TC 32	8.44E-03	4.82E-03	3.33E-03	1.84E-03	1.84E-02
TC 43	5.47E-03	3.13E-03	2.16E-03	1.19E-03	1.19E-02

Table 3-12 Overall contribution of each environmental metric to the final environmental sustainability index of each technical component - Hook Spool Latching Mechanism

TCs' Environmental Sustainability Index - BLM

Identification	GHG_{TCtot}	EC_{TCtot}	WG_{TCtot}	RD_{TCtot}	ESI_{TCtot}
TC 152	2.37E-01	1.49E-01	1.13E-01	1.00E-01	5.99E-01
TC 131	8.41E-04	5.28E-04	4.02E-04	3.55E-04	2.13E-03
TC 132	3.76E-03	2.36E-03	1.80E-03	1.59E-03	9.50E-03
TC 20	1.23E-02	8.62E-03	3.55E-02	8.00E-03	6.44E-02
TC 52	8.10E-03	5.69E-03	2.35E-02	5.29E-03	4.26E-02
TC 54	5.62E-03	3.95E-03	1.63E-02	3.67E-03	2.96E-02
TC 59	7.25E-03	5.10E-03	2.10E-02	4.74E-03	3.81E-02
TC 40	4.10E-03	2.89E-03	1.19E-02	2.68E-03	2.16E-02
TC 42	2.25E-03	1.58E-03	6.52E-03	1.47E-03	1.18E-02
TC 130	3.60E-03	2.53E-03	1.04E-02	2.35E-03	1.89E-02
TC 157	2.60E-02	1.83E-02	7.53E-02	1.70E-02	1.37E-01
TC 21	1.65E-01	9.17E-02	7.34E-02	5.68E-03	3.36E-01
TC 50	4.84E-02	2.69E-02	2.15E-02	1.67E-03	9.85E-02
TC 53	1.73E-03	9.63E-04	7.71E-04	5.97E-05	3.53E-03
TC 55	1.25E-02	6.96E-03	5.57E-03	4.31E-04	2.55E-02
TC 56	1.94E-01	1.08E-01	8.60E-02	6.66E-03	3.94E-01
TC 57	3.89E-02	2.16E-02	1.73E-02	1.34E-03	7.92E-02
TC 58	2.52E-03	1.40E-03	1.12E-03	8.66E-05	5.12E-03
TC 23	6.21E-03	3.45E-03	2.76E-03	2.14E-04	1.26E-02
TC 60	6.71E-04	3.73E-04	2.98E-04	2.31E-05	1.37E-03
TC 41	1.38E-01	7.67E-02	6.13E-02	4.75E-03	2.81E-01
TC 70	3.97E-03	2.21E-03	1.76E-03	1.37E-04	8.08E-03
TC 71	3.83E-02	2.13E-02	1.70E-02	1.32E-03	7.78E-02
TC 44	1.54E-02	8.58E-03	6.86E-03	5.31E-04	3.14E-02
TC 45	1.34E-03	7.46E-04	5.97E-04	4.62E-05	2.73E-03
TC 46	1.34E-03	7.46E-04	5.97E-04	4.62E-05	2.73E-03
TC 133	1.62E-03	9.01E-04	7.21E-04	5.58E-05	3.30E-03
TC 153	4.50E-01	2.50E-01	2.00E-01	1.55E-02	9.15E-01
TC 154	1.69E-01	9.38E-02	7.50E-02	5.81E-03	3.43E-01
TC 32	1.04E-02	5.91E-03	4.67E-03	1.16E-03	2.21E-02
TC 43	6.71E-03	3.84E-03	3.03E-03	7.53E-04	1.43E-02

Table 3-13 Overall contribution of each environmental metric to the final environmental sustainability index of each technical component - Bar Latch Mechanism

TC's Environmental Sustainability Index - CLM

Identification	GHG_{TCtot}	EC_{TCtot}	WG_{TCtot}	RD_{TCtot}	ESI_{TCtot}
TC 131	1.67E-03	9.26E-04	7.41E-04	3.70E-04	3.70E-03
TC 155	4.50E-01	2.50E-01	2.00E-01	1.00E-01	1.00E+00
TC 156	3.21E-01	1.78E-01	1.43E-01	7.13E-02	7.13E-01
TC 132	7.44E-03	4.14E-03	3.31E-03	1.65E-03	1.65E-02
TC 20	2.43E-02	1.51E-02	6.54E-02	8.35E-03	1.13E-01
TC 22	1.44E-02	8.94E-03	3.87E-02	4.94E-03	6.70E-02
TC 24	2.25E-02	1.40E-02	6.06E-02	7.73E-03	1.05E-01
TC 31	4.79E-03	2.98E-03	1.29E-02	1.65E-03	2.23E-02
TC 91	3.78E-02	2.35E-02	1.02E-01	1.30E-02	1.76E-01
TC 93	4.31E-02	2.68E-02	1.16E-01	1.48E-02	2.01E-01
TC 40	8.14E-03	5.06E-03	2.19E-02	2.80E-03	3.79E-02
TC 100	2.44E-02	1.52E-02	6.57E-02	8.39E-03	1.14E-01

Identification	**GHG_{TCtot}**	**EC_{TCtot}**	**WG_{TCtot}**	**RD_{TCtot}**	**ESI_{TCtot}**
TC 104	4.55E-02	2.83E-02	1.22E-01	1.56E-02	2.12E-01
TC 42	4.46E-03	2.77E-03	1.20E-02	1.53E-03	2.08E-02
TC 130	7.13E-03	4.44E-03	1.92E-02	2.45E-03	3.32E-02
TC 157	5.15E-02	3.20E-02	1.39E-01	1.77E-02	2.40E-01
TC 102	4.61E-02	2.87E-02	1.24E-01	1.59E-02	2.15E-01
TC 50	9.60E-02	4.72E-02	3.96E-02	1.74E-03	1.85E-01
TC 23	1.23E-02	6.05E-03	5.08E-03	2.23E-04	2.37E-02
TC 90	3.53E-02	1.73E-02	1.45E-02	6.38E-04	6.78E-02
TC 98	7.68E-02	3.78E-02	3.17E-02	1.39E-03	1.48E-01
TC 92	4.22E-02	2.08E-02	1.74E-02	7.65E-04	8.12E-02
TC 94	1.28E-01	6.31E-02	5.30E-02	2.32E-03	2.47E-01
TC 95	1.30E-01	6.39E-02	5.37E-02	2.35E-03	2.50E-01
TC 96	2.18E-01	1.07E-01	8.98E-02	3.94E-03	4.18E-01
TC 97	3.69E-02	1.81E-02	1.52E-02	6.69E-04	7.10E-02
TC 41	2.74E-01	1.34E-01	1.13E-01	4.95E-03	5.26E-01
TC 101	4.69E-02	2.31E-02	1.94E-02	8.49E-04	9.02E-02
TC 21	3.27E-01	1.61E-01	2.02E-02	5.92E-03	5.14E-01
TC 103	4.89E-02	2.40E-02	2.02E-02	8.85E-04	9.40E-02
TC 44	3.06E-02	1.50E-02	1.26E-02	5.54E-04	5.88E-02
TC 45	2.66E-03	1.31E-03	1.10E-03	4.82E-05	5.11E-03
TC 46	2.66E-03	1.31E-03	1.10E-03	4.82E-05	5.11E-03
TC 133	3.22E-03	1.58E-03	1.33E-03	5.82E-05	6.18E-03
TC 32	2.05E-02	1.04E-02	8.60E-03	1.21E-03	4.07E-02
TC 43	1.33E-02	6.73E-03	5.58E-03	7.85E-04	2.64E-02

Table 3-14 Overall contribution of each environmental metric to the final environmental sustainability index of each technical component – C-Latch Mechanism

3.1.3 Overall Environmental Sustainability KPI Estimation

Finally, the last step is the estimation of the overall Environmental Sustainability Index of each Latching Mechanism (ESI_{LM}). For this purpose, the calculation of this index is suggested as the sum of all the environmental sustainability indices of all the TCs that compose the mechanism under investigation. The proposed formula is available below:

$$ESI_{LM} = \sum_{j=1}^{N} ESI_{TC_{tot},j}$$

Equation 3-6

where,

- j: Indicates the identification number of each TC
- N: Total number of technical components in the mechanism
- $ESI_{TCtot,j}$:Environmental sustainability index of TC j

The final results from the analysis are listed in Table 3-15. The final environmental sustainability index for each mechanism is expressed in a normalized scale. More specifically, for the normalisation of this particular KPI, the max normalisation method is applied where, all the results are divided by the maximum value of the dataset. It is implemented very quickly and enables the comparison of the results obtained from the analysis based on a predefined scale with specific limits. The scale for this particular KPI is running from zero (0) to one (1). The lower limit of this scale (0) represents the most sustainable architecture, whereas the upper limit (1) represents the least sustainable architecture.

Sustainability Domain Results

Architecture	**ESI_{LM}**	**Units**
HSLM	0.566	-
BLM	0.590	-
CLM	1.000	-

Table 3-15 Final normalised environmental sustainability KPI result of each architectural design

3.2. Reliability Domain

Primary goal of this section is to estimate the Reliability KPI of the three latching mechanisms, focusing on their ability to perform their intended functions consistently over time without failure [66]. By analysing various factors, including potential failure modes, system behaviour under different conditions and historical data, this particular section of the thesis aims to provide a comprehensive understanding of the system's durability.

For the purposes of the research, the principals of the Failure Modes Effects and Criticality Analysis (FMECA) method are established for the estimation of this specific KPI. The FMECA is a systematic methodology that can identify potential failure modes (FMs) within a product, system or process [67]. It provides insights into the ways these failures could occur, their potential impact on functionality and the conditions under which they might arise. By analysing the effect, the mechanism of failure as well as the detection mechanism of each failure mode (FM), it is possible to identify and mitigate the most critical FMs [67]. In Figure 3-4 an overview of the different aspects related with FMCA methodology can be seen.

The FMECA methodology is composed of two essential steps that are collaborate together to produce the eventual result. These two steps are introduced below [67]:

1. **Implementation of the Failure Modes and Effects Analysis (FMEA) methodology**
2. **Implementation of the Criticality Analysis (CA) methodology**

Through the first step, the potential FMs for the investigated system are identified. Based on those FMs, the immediate effects on the system under consideration, the most significant

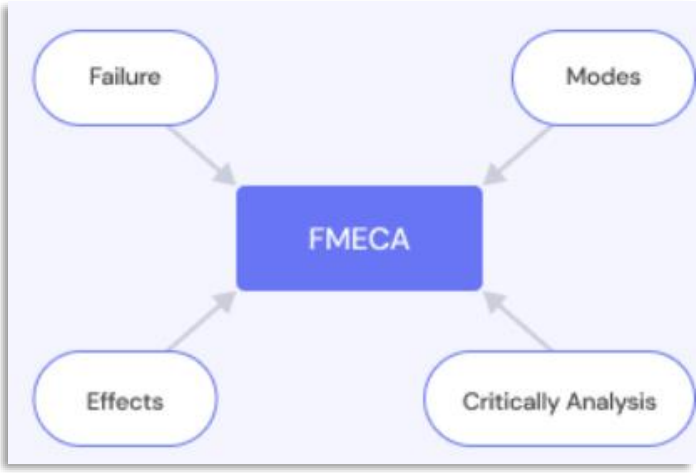


Figure 3-4 Decomposition of FMECA acronym

mechanisms of failure as well as the detection mechanisms of each one mode can be defined and assessed. In order to be able to conduct this first step, three key metrics are considered in the current analysis. Each one of the following metrics is assessed for each identified FM of the examined architectural design.

1. **Severity of FM (S_{FM})**
2. **Occurrence of FM (O_{FM})**
3. **Detectability of FM (D_{FM})**

By the assessment of these metrics it is then possible to calculate the Risk Priority Number of each FM (RPN_{FM}). The estimation of the RPN_{FM} is mandatory due to the fact that based on that numeric value the architecture's most critical FMs can be identified and prevention measures can be suggested.

Regarding the CA, there are two (2) primary approaches that can be employed in order to perform such an analysis [67], [69]. The two approaches are listed below:

1. **Qualitative Analysis**
2. **Quantitative Analysis**

The qualitative analysis approach, relies on experts' judgment and descriptive assessments to classify failure modes based on their potential impact on the entire system whereas, the quantitative analysis approach, uses mathematical models and numerical data in order to evaluate the criticality metrics, providing precise and data-driven prioritization of the FMs. Both of them are involved in the current analysis [67], [69].

An overview of the applied methodology for the assessment of the Reliability KPI, for each particular latching mechanism, is demonstrated in Figure 3-5. Further details for the considered metrics and the presented methodology are provided in the upcoming sections.

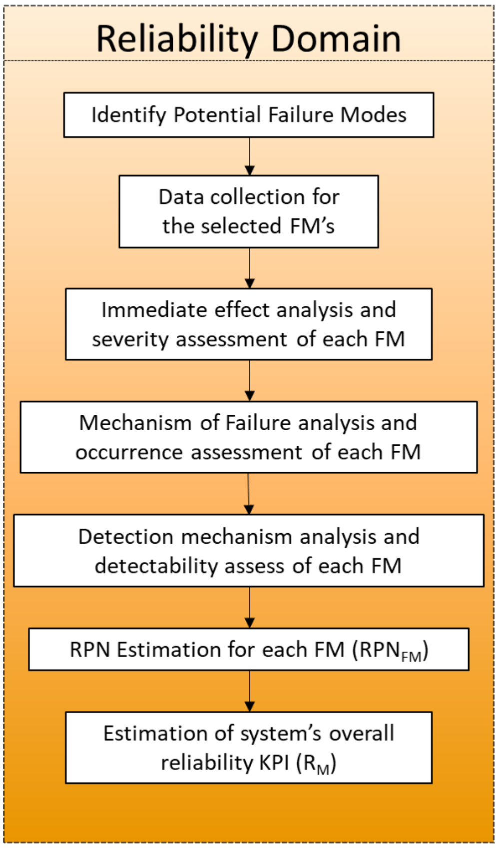


Figure 3-5 Overall process for the reliability KPI estimation of each architectural design

3.2.1 Reliability Metrics Assessment

This section provides a detailed summary of the relevant data needed for the evaluation of each mentioned metric (S_{FM}, O_{FM}, D_{FM}). Especially for the HSLM and BLM, data have been provided by an industrial partner of DLR. However, for the latching mechanism where the necessary data are not available (C-Latch Mechanism), a different method is adopted to evaluate its overall Reliability KPI. The datasets and the related documents that have been provided are not available for public distribution due data protection policies. To this end, only the final results of the implemented methodology are presented.

Failure Modes' Effect Analysis and Severity Assessment

The severity of a failure mode is determined by the extent of its impact on the system's functionality and the consequences that it poses to safety or performance [69]. For each mentioned FM, the immediate effect on the entire system is identified and analysed. Based on the description and the immediate effect of each FM on the entire mechanism, the severity of the examined FM is evaluated. The severity assessment of each FM involves subjective classification and thus qualitative analysis is performed. This metric is dimensionless and its scale ranges from one (1) to ten (10). One expresses that, that particular FM has no effect on the entire latching mechanism, whereas ten (10) means that the effect is catastrophic on the latching mechanism [67].

Through the analysis carried out and on basis of the provided data, four (4) distinct immediate effects are detected. To be able to assess the severity of each FM the scale of this metric (1-10) has been divided into four (4) different ranges. Each one of those severity ranges is associated with a specific immediate effect. In Table 3-16, these four couples are presented with their relative description.

Immediate Effect	**Severity Range**	**General Impact**
Door not usable (DNU)	7<DNU<=10	Impacts the functionality and halts operations. Immediate downtime and potentially significant financial and safety risks
Higher Loads on the remaining structure (HL)	5<HL<=7	Risk of structural failure over time. Catastrophic consequences
Incorrect indication (II)	3<II<=5	Wrong decisions or actions
Operative (0)	1<=O<=3	Can be solved by troubleshooting or maintenance

Table 3-16 Description of the four possible effects of a failure mode on the entire system and presentation of the related assigned severity range of each identified immediate effect

In order for the analysis to be valid, among the different architectural designs, only FMs resulting from common sub-assembly units are compared. In particular, all the FMs accounted are associated with one of the following sub-assembly units: Latching Unit, Locking Unit, Visual Indication Unit. Seventeen (17) FMs have been accounted for the HSLM whereas, eighteen (18) for the BLM. The severity value that has been assigned to each examined FM can be found on Table 3-17 for the HSLM and in Table 3-18 for the BLM.

Effect and Severity of each FM - HSLM

Identification	***Effect of FM (E_{FM})***	***Severity of FM (S_{FM})***
FM001	Door not usable	7.125
FM002	Door not usable	7.250
FM003	Door not usable	7.500
FM004	Operative	2.125
FM005	Door not usable	7.375
FM006	Door not usable	8.500
FM007	Door not usable	7.875
FM008	Operative	3.000
FM009	Operative	2.875
FM010	Higher loads on the remaining	5.500
FM011	Door not usable	7.375
FM012	Door not usable	7.625
FM013	Operative	2.750

Identification	*Effect of FM (E_{FM})*	*Severity of FM (S_{FM})*
FM014	Operative	2.750
FM015	Incorrect sensor indication in open position	4.500
FM016	Incorrect sensor indication in closed position	4.750
FM017	Incorrect sensor indication in closed position	4.000

Table 3-17 Immediate effect of each examined failure mode on the entire mechanism and corresponding assigned severity value - HSLM

Effect and Severity of each FM - BLM		
Identification	*Effect of FM (E_{FM})*	*Severity of FM (S_{FM})*
FM001	Operative	2.375
FM002	Door not usable	7.125
FM003	Operative	2.500
FM004	Door not usable	8.750
FM005	Door not usable	7.500
FM006	Door not usable	7.250
FM007	Operative	2.875
FM008	Door not usable	8.175
FM009	Door not usable	8.500
FM010	Door not usable	8.250
FM011	Operative	3.000
FM012	Operative	2.750
FM013	Door not usable	7.250
FM014	Door not usable	7.250
FM015	Incorrect Indication	4.500
FM016	Door not usable	7.500
FM017	Door not usable	7.500
FM018	Incorrect Indication	4.750

Table 3-18 Immediate effect of each examined failure mode on the entire mechanism and corresponding assigned severity value - BLM

Failure Modes' Cause Analysis and Occurrence Assessment

The root cause and the mechanism of failure of a FM are thoroughly analysed to ensure a comprehensive understanding of the underlying issues and the processes leading to the failure. The cause states the reason that leads to a failure mode. Commonly, the reasons that lead to failure are related with one of the following domains: Design Domain, Operational Domain, Manufacturing Domain. The mechanism of failure describes the process or sequence of events that leads to the failure [70], [71]. The cause, the mechanism of failure as well as the expected probability of each FM have been identified through the provided documents. Combined these three parameters the occurrence of each FM is assessed. The assessment of the occurrence metric typically involves grouping or ranking the likelihood of a failure mode into predefined categories and thus, for the evaluation qualitative and quantitative analyses are applied [71]. It is a dimensionless metric and is rated on a descriptive scale from one (1) to ten (10) where, 1 means that, that FM is almost impossible to be occurred, whereas 10 means that it is almost certain to be occurred [67].

As has been done with the previous examined metric (severity), to be able to assess the occurrence of each FM the scale of this metric (1-10) has been divided into four (4) different ranges based on the observed maximum and minimum expected probabilities of the examined FMs. Every single expected probability range is then related with a specific occurrence range. After comprehensive comparisons, an occurrence value is assigned to each examined FM. If the expected probabilities of two (or more) FMs are the same, the number of the related FMs are considered to assess the occurrence of those FMs. Table 3-19, reports the four possible expected probability ranges and the respective occurrence range. The mechanism of failure and the final assigned occurrence value of each FM for the HSLM are presented inTable 3-20 and for the BLM in Table 3-21.

Expected Probability Range	**Associated Occurrence Range**
5.50E-07 <= EP <= 2.00E-06	7<OR<=10
1.00E-07 <= EP < 5.50E-07	5<OR<=7
4.00E-08 <= EP < 1.00E-07	3<OR<=5
0.00E+00 <= EP < 4.00E-08	1<=OR<=3

Table 3-19 Distributing the expected probability of each failure mode (based on maximum and minimum expected probability) into four distinct ranges. Each expected probability range is accompanied by another specific occurrence range against which the occurrence of each failure mode is evaluated

Cause and Occurrence of each FM - HSLM

Identification	***Cause and Mechanism of Failure***	***Occurrence of FM (O_{FM})***
FM001	Fracture	1.850
FM002	Fracture, Loss of bolt, Jamming	5.250
FM003	Fracture, Loss of bolt, Jamming, Adjustment too long	5.450
FM004	Fracture, Jamming	8.000
FM005	Latching hook is not locked	1.375
FM006	Fracture, Loss of bolt	3.375
FM007	Jamming	7.250
FM008	Loss of bolt, Fracture, Gas leakage	8.500
FM009	Fracture	1.750
FM010	Failure of one latching hook assembly	1.375
FM011	Loss of bolt, Fracture, Jamming, Adjustment too long or too short	7.875
FM012	Fracture, Overload, Abrasion crack, Jamming	4.500
FM013	Hard movement, Jamming	1.900
FM014	Loss of bolt, Fracture, Gas leakage	5.125
FM015	Fracture, Loss of bolt	1.125
FM016	Fracture, Adjustment is too long, Loss of bolt, Fitting body, Deformation	2.250
FM017	Fracture, Loss of bolt, Fitting body, Deformed, Broken	2.000

Table 3-20 Description of the cause and the mechanisms of failure of each particular failure mode and the corresponding assigned occurrence value – HSLM

Cause and Occurrence of each FM - BLM

Identification	***Cause and Mechanism of Failure***	***Occurrence of FM (O_{FM})***
FM001	Fracture, Jamming	5.550
FM002	Fracture, Jamming	1.900
FM003	Fracture, Loss of bolt, Jamming	6.500
FM004	Fracture, Loss of bolt, Jamming	3.115
FM005	Fracture, Loss of bolt, Jamming, Adjustment too long	2.025

Identification	*Cause and Mechanism of Failure*	*Occurrence of FM (O_{FM})*
FM006	Loss of bolt	1.850
FM007	Fracture, Jamming	5.550
FM008	Fracture, Jamming	3.875
FM009	Fracture, Loss of bolt	5.925
FM010	Fracture, Loss of bolt, Jamming	3.425
FM011	Jamming	3.115
FM012	Fracture, Loss of bolt, Jamming	2.100
FM013	Fracture, Loss of bolt, Jamming	9.125
FM014	Fracture, Loss of bolt, Jamming	8.875
FM015	Fracture, Loss of bolt	5.525
FM016	Fracture, Loss of bolt, Jamming, Adjustment too long	9.000
FM017	Fracture, Loss of bolt, Jamming, Adjustment too long	8.750
FM018	Fracture, Loss of bolt	2.200

Table 3-21 Description of the cause and the mechanisms of failure of each particular failure mode and the corresponding assigned occurrence value - BLM

Failure Modes' Detection Analysis and Detectability Assessment

The last metric that is assessed, is the detectability of each FM. To do so, the potential detection mechanisms of each FM are analysed. In general, the detection mechanism refers to the ability to identify a failure before it causes an impact [71]. By refining detection mechanisms, many organisations and companies can mitigate risks, enhance reliability, and optimize maintenance strategies. In order to evaluate this metric, the qualitative approach is applied. However, there are no available data within the provided documents. All the results presented later on in this section is the outcome of a comprehensive and collective analysis of the FMs but also on personal judgement that is supported by the extrapolation of the results of the other two metrics (severity, occurrence).

In order to be able to assign a detectability value to each FM, the corresponding scale of this metric (1-10) has been divided into four (4) ranges. Every single detectability range is directly connected to a detectability level. Each range captures distinct levels of visibility, from undetectable phenomena to those that are highly apparent. Based on the detection mechanism and the description of each FM, the relevant detectability level is determined. By reference to the relevant range, the detectability of the failure mode under investigation is evaluated. The four detectability levels and the related detectability ranges are described in Table 3-22.

Detectability Level	**Detectability Range (DR_{FM})**
Almost impossible to be detected	$7<D<=10$
Unlikely to be detected	$5<D<=7$
Likely to be detected	$3<D<=5$
Almost certain to be detected	$1<=D<=3$

Table 3-22 Description of the four different detectability levels and the related assigned detectability ranges

Regarding the HSLM, the assigned detectability value of each one of the examined FMs is presented in Table 3-23 whereas, for the BLM all the results are summarised in Table 3-24Table 3-24.

Detection Mechanism and Detectability of each FM - HSLM

Identification	*Detection Mechanism of FM (DM_{FM})*	*Detectability of FM (D_{FM})*
FM001	Visual indication, Unable to open/close the LDCD	1.500
FM002	Visual indication, Unable to latch/unlatch the LDCD	1.500
FM003	Visual indication, Unable to lock/unlock the LDCD	1.500
FM004	Hidden, Abnormal noises during the latching phase	5.500
FM005	Hidden, Locking Issues, During Regular Inspections, During Maintenance	4.500
FM006	Visual Indication, Unable to electrically or manually lock/unlock the LDCD	1.500
FM007	Hidden, Abnormal noises during the locking phase	5.500
FM008	Hidden, During maintenance, During inspections	4.500
FM009	Hidden, During maintenance, During inspections	6.750
FM010	Unable to electrically or manually unlatch the LDCD	1.750
FM011	Hidden, Visual indication, During the latching phases	2.250
FM012	Unable to electrically or manually latch/unlatch the LDCD	1.750
FM013	Hidden, Abnormal noises during the latching phase	5.500
FM014	Hidden, During maintenance, During inspections	4.000
FM015	Visual indication	3.125
FM016	Visual indication	3.125
FM017	Visual indication	3.125

Table 3-23 Description of the detection mechanisms of each particular failure mode and presentation of the corresponding assigned detectability value of the HSLM

Detection Mechanism and Detectability of each FM - BLM

Identification	*Detection Mechanism of FM (DM_{FM})*	*Detectability of FM (D_{FM})*
FM001	Hidden, During Regular Inspections, During Maintenance	3.500
FM002	Unable to electrically or manually unlatch the MDCD	1.750
FM003	Hidden, During Regular Inspections, During Maintenance	3.500
FM004	Visual Indication, Unable to electrically or manually latch/unlatch the MDCD	1.500
FM005	Visual Indication, Unable to electrically or manually latch/unlatch the MDCD	1.500
FM006	Unable to electrically or manually unlatch the MDCD	1.750
FM007	Hidden, During Regular Inspections, During Maintenance	3.750
FM008	Visual Indication (Locked Position), Unable to electrically or manually lock/unlock the MDCD	1.500
FM009	Visual Indication (Locked Position), Unable to electrically or manually lock/unlock the MDCD	1.500
FM010	Visual Indication (Locked Position), Unable to electrically or manually lock/unlock the MDCD	1.500
FM011	Hidden, During Regular Inspections, During Maintenance	4.500
FM012	Hidden, During Regular Inspections, During Maintenance	4.250
FM013	Unable to electrically latch/unlatch the MDCD	2.250
FM014	Unable to manually latch/unlatch the MDCD	2.500
FM015	Visual Indication	3.125
FM016	Unable to electrically lock/unlock the MDCD	2.250
FM017	Unable to manually lock/unlock the MDCD	2.500
FM018	Visual Indication	3.125

Table 3-24 Description of the detection mechanisms of each particular failure mode and presentation of the corresponding assigned detectability value of the BLM

3.2.2 Failure Modes' Risk Priority Number Estimation

In the previous section (3.2.1), all the interested reliability (severity, occurrence and detectability) metrics of each FM have been evaluated. By means these three metrics the Risk Priority Number of each FM (RPN_{FM}) can be calculated. The RPN_{FM} is a numerical value commonly utilized in risk management methodologies, such as FMEA, to prioritize and evaluate potential FMs [67], [71]. The RPN_{FM} provides a systematic and objective method for identifying which failure modes require immediate attention. This prioritisation ensures that critical issues are addressed first, enhancing overall system's reliability and safety.

The scale of the RPN_{FM} ranges from one (1) to one thousand (1000). To the lower limit (1), the ratings of the severity, occurrence and detectability metrics are all at their own minimum value. The upper limit (1000), represents the highest possible risk, where all reliability metrics are at their own maximum ratings. Based on that scale, a higher RPN_{FM} indicates a greater level of risk, signalling the need for prompt corrective actions or the necessity of preventive measures to be taken [67].

The calculation of RPN_{FM} is proposed as the product of those three mentioned metrics (S_{FM}, O_{FM}, D_{FM}), as indicated in the following formula [67][72]:

$$RPN_{FM,i} = \mathrm{S}_{\mathrm{FM,i}}\ \mathrm{O}_{\mathrm{FM,i}}\ \mathrm{D}_{\mathrm{FM,i}}$$

Equation 3-7

where,

- $S_{FM,i}$, $O_{FM,i}$, $D_{FM,i}$,, represent respectively the severity, occurrence and detectability of the indicated FM i

Table 3-25 presents a comprehensive summary of all the results derived from the analysis. The results are categorised for the two different architectures (HSLM, BLM). Based on the following table, detailed examination can be followed for the identification of the most critical FMs for each architectural design accordingly.

Failure Modes' Risk Priority Number

Identification	***HSLM***				***BLM***			
	$S_{FM,i}$	**$O_{FM,i}$**	**$D_{FM,i}$**	**$RPN_{FM,i}$**	**$S_{FM,i}$**	**$O_{FM,i}$**	**$D_{FM,i}$**	**$RPN_{FM,i}$**
FM001	7.125	1.850	1.500	19.8	2.375	5.550	3.500	46.1
FM002	7.250	5.250	1.500	57.1	7.125	1.900	1.750	23.7
FM003	7.500	5.450	1.500	61.3	2.500	6.500	3.500	56.9
FM004	2.125	8.000	5.500	93.5	8.750	3.115	1.500	40.9
FM005	7.375	1.375	4.500	45.6	7.500	2.025	1.500	22.8
FM006	8.500	3.375	1.500	43.0	7.250	1.850	1.750	23.5
FM007	7.875	7.250	5.500	314.0	2.875	5.550	3.750	59.8

Identification	*HSLM*				*BLM*			
	$S_{FM,i}$	**$O_{FM,i}$**	**$D_{FM,i}$**	**$RPN_{FM,i}$**	**$S_{FM,i}$**	**$O_{FM,i}$**	**$D_{FM,i}$**	**$RPN_{FM,i}$**
FM008	3.000	8.500	4.500	114.8	8.175	3.875	1.500	47.5
FM009	2.875	1.750	6.750	34.0	8.500	5.925	1.500	75.5
FM010	5.500	1.375	1.750	13.2	8.250	3.425	1.500	42.4
FM011	7.375	7.875	2.250	130.7	3.000	3.115	4.500	42.1
FM012	7.625	4.500	1.750	60.0	2.750	2.100	4.250	24.5
FM013	2.750	1.900	5.500	28.7	7.250	9.125	2.250	148.9
FM014	2.750	5.125	4.000	56.4	7.250	8.875	2.500	160.9
FM015	4.500	1.125	3.125	15.8	4.500	5.525	3.125	77.7
FM016	4.750	2.250	3.125	33.4	7.500	9.000	2.250	151.9
FM017	4.000	2.000	3.125	25.0	7.500	8.750	2.500	164.1
FM018	-	-	-	-	4.750	2.200	3.125	32.7

Table 3-25 Summary of results obtained from the reliability analysis (Severity, Occurrence and Detectability of each failure mode) and presentation of the final risk priority number for each failure mode (Both architectures).

3.2.3 Overall Reliability KPI Estimation

Once the RPN of all the considered FMs for each mechanism has been evaluated, the overall Reliability KPI (R_M) can be estimated. For this purpose, the estimation of this KPI is suggested as the sum of all the RPN of all the FMs which have been examined for the mechanism under investigation. On basis of the following formula, this KPI is computed for each mechanism.

$$R_{M,j} = \sum_{i=1}^{F} RPN_{FM,i}$$

Equation 3-8

- F: Total number of failure modes considered for the architectural design
- $RPN_{FM,i}$: Risk Priority Number of Failure Mode i

The outcomes of the conducted analysis are presented in Table 3-26. This table provides the unnormalized results of the investigated mechanisms.

Architecture	**R_M (Unnormalized)**	**Units**
HSLM	1146	-
BLM	1242	-

Table 3-26 Final normalised and unnormalized reliability KPI results regarding the HSLM and BLM architectural designs

CLM Reliability KPI Estimation

As has been mentioned in section 3.2.1 and as can be seen from Table 3-26, only two out of three Reliability KPIs have been obtained by the described methodology since necessary data for the CLM are not provided. To this end, the overall Reliability KPI of that mechanism is estimated by a different method. It is assumed that the overall Reliability KPI depends on the total number of different technical components that compose each mechanism.

To address the challenge posed by incomplete results, an extrapolation technique is adopted. This approach leverages the two available results to predict the third one, ensuring continuity and coherence in the analysis. By utilizing this method, the assessment maintains reliability while accounting for the missing data point, enabling a comprehensive evaluation of the present framework. For the purposes of the current analysis, a linear relationship is implemented which is outlined below:

$$R_{CLM} = a_0 X_{CLM} + a_1$$

Equation 3-9

where,

- a_0: Represents the rate of change (Slope of Curve)
- X_{CLM}: Represents the total number of different technical components which are compose the CLM
- a_1: Represents the base reliability

The parameter which is related with the rate of change (a0) is calculated by the following formula:

$$a_0 = \frac{R_{BLM} - R_{HSLM}}{TCs_{BLM} - TCs_{HSLM}}$$

Equation 3-10

The base reliability (a1) is calculated by the following formula:

$$a_1 = R_{HSLM} - a_0 X_{HSLM}$$

Equation 3-11

where,

- X_{HSLM}: Represents the total number of different technical components which are compose the HSLM

The total number of TCs for each architecture and the two available reliability KPIs are given in the following table:

Architecture	**Number of TCs**	R_M
HSLM	43	1146
BLM	47	1242
CLM	52	Unknown

Table 3-27 Available data enabling the reliability KPI of the C – Latching Mechanism to be evaluated

By combining the Equation 3-9, Equation 3-10 and Equation 3-11, with the provided data inTable 3-27, the overall Reliability KPI of the CLM is estimated. In Table 3-28, the overall results regarding the Reliability domain are summarised. These final results are expressed in normalized scale. As previously explained in section 3.1.3, the max normalisation method is used to normalise the results. Thus, all the analysis results are divided by the maximum obtained value. In terms of the normalized scale, varies between zero (0) and one (1). The lower limit of this scale (0) represents the most reliable architecture, whereas the upper limit (1) represents the least reliable architecture.

Reliability Domain Results

Architecture	R_M	Units
HSLM	0.841	-
BLM	0.912	-
CLM	1.000	-

Table 3-28 Final normalised reliability KPI result of each architectural design

3.3. Performance Domain

The third metric analysed in this study pertains to the total mass of each mechanism, offering critical insights into the system's structural and functional design. The mass of a mechanism directly influences its operational efficiency and overall feasibility in practical applications. A heavier mechanism may lead to challenges in energy consumption and mobility, whereas a lighter design could enhance performance but may compromise structural integrity. This balance necessitates a detailed examination of the Mass KPI and its effects on the mechanism's efficiency and durability.

The technical components that compose each mechanism are all well-established from a previous study, providing a solid foundation for this investigation. The mass, multiplicity and material of manufacture for each one of them are documented as well within an available study[2]. Thus, the total mass of each latching mechanism can be calculated. Figure 3-6, illustrates the comprehensive approach adopted for evaluating the overall Mass KPI of each mechanism.

3.3.1 Mass KPI Estimation

The calculation of the total mass of each latching mechanism ($Mass_{LM}$), is proposed to be the sum of the mass of each TC composing that mechanism multiplied by the corresponding multiplicity of that TC.

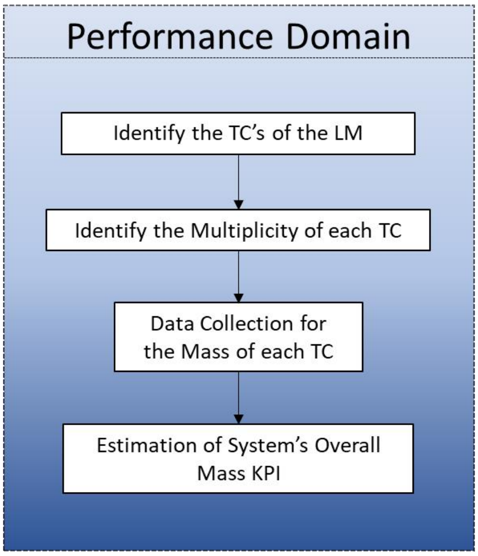


Figure 3-6 Overall process for the mass KPI estimation of each architectural design

The applied formula is explained below:

$$Mass_{LM} = \sum_{i=1}^{N} m_i q_i$$

Equation 3-12

where,

- N: Represents the total number of different TCs that compose the investigated mechanism
- m_i: Represents the mass of the TC i
- q_i: Expresses the multiplicity of the TC i

The results of the analysis undertaken are reported in Table 3-29. Due to some restrictions, these results are given only in normalised form. A max normalisation method has been applied for the purposes of the thesis. More details about that normalisation method are available in section 3.1.3. After the normalisation the scale of this particular KPI ranges from zero (0) to one (1). Zero represents the architectural design with the lowest overall mass while, one represents the architecture with the highest overall mass.

Performance Domain Results

Architecture	**$Mass_M$**	**Units**
HSLM	1.000	-
BLM	0.957	-
CLM	0.793	-

Table 3-29 Final normalised mass KPI result of each architectural design

3.4. Supply Chain Domain

Within this section, the formulation of models that support the supply chain domain is explored in greater depth. These models play a crucial role in optimizing various aspects of supply chain management, transportation logistics and supplier coordination. By leveraging mathematical and computational techniques, businesses can enhance efficiency, reduce costs, and improve decision-making processes.

Figure 3-7 illustrates the general methodology that is implemented, providing a comprehensive overview of the approach. It outlines the key steps and processes involved, ensuring a clear understanding of how various aspects interact to achieve the intended objectives.

The key outcome of this domain is the evaluation of the overall supply chain efficiency. Based on that, four characteristic KPIs are used to describe and evaluate the performance of this domain as already mentioned in section 2.2.4. These are the cost, time, risk and quality.

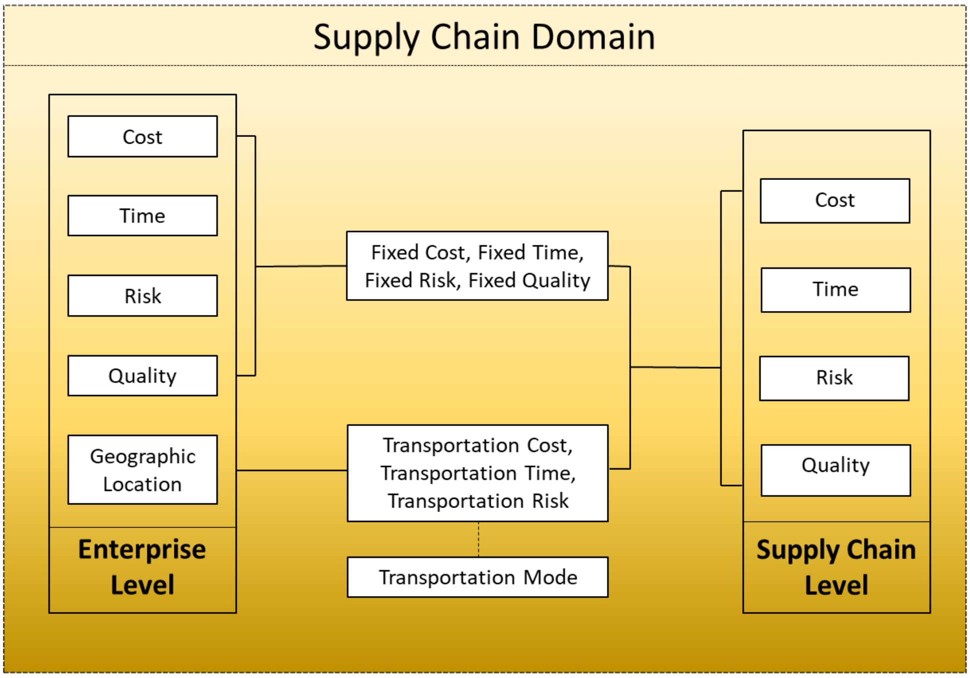


Figure 3-7 Overall process for the production KPIs (Cost, Time, Risk and quality) estimation of each architectural design

As indicated by the following equations (Equation 3-13), the estimation of the overall supply chain cost, time and risk is recommended as the sum of two distinct contributions while the overall supply chain quality is evaluated only from the contribution of one term [78]. With, SC is denoted the overall cost, time, risk and quality at the supply chain level as demonstrated in Figure 3-7.

$$Cost_{SC} = Cost_{Fixed} + Cost_{Transportation}$$

$$Time_{SC} = Time_{Fixed} + Time_{Transportation}$$

$$Risk_{SC} = Risk_{Fixed} + Risk_{Transportation}$$

$$Quality_{SC} = Quality_{Fixed}$$

Equation 3-13

The first term of these equations (Equation 3-13) depends solely on the production fixed cost, time, risk and quality of each individual enterprise, as well as on the production quantity that each enterprise has to produce. The required production quantity of each technical component is available from an already existed study regarding the systems of interest (i.e., a latching mechanism) [2]. Table 3-30 provides the description of each fixed term and the parameters taken into account for their assessment in the current analysis. All the mentioned parameters are absolutely depending on the enterprises' geographical location while usually, represent the inputs of the methodology.

Fixed Term	**Description**	**Considered Parameters**
Cost *Fixed*	Fixed costs refer to business expenses that do not change regardless of how much a company produces or sells [73], [74]	❖ Payment scales ❖ General Utilities
Time *Fixed*	Fixed time refers to a set and unchangeable period during which specific tasks or processes must be completed [75]	❖ Workforce efficiency
Risk *Fixed*	Fixed risk refers to risks that are constant and predictable over time during the production, mainly related with the enterprise location [76], [77]	❖ Workplace accidents ❖ Extreme weather events
Quality *Fixed*	Fixed quality can be understood as the enterprise's overall quality performance	❖ Economic stability ❖ Quality of life ❖ Access to talent

Table 3-30 Description of the different fixed terms and the related parameters accounted for their assessment

The supply chain in the current study consists of eight different qualified enterprises. Each of these enterprises is based on a different geographical location and has its own predetermined responsibilities. Specifically, one of the locations represents the region where the Original Equipment Manufacturer (OEM) is located, four of them represent the regions where the TIER I suppliers are located and three of them the regions of TIER II suppliers. On Table 3-31 the different geographical region of each including enterprise are clearly stated. It is not possible to share the exact selected locations due to some data protection restrictions. In addition, the hierarchy of the various suppliers and their responsibilities are illustrated in Figure 3-8.

Enterprise	Geographical Location
OEM	Central Europe
TIER I_I	East Europe
TIER I_II	South Asia
TIER I_III	East Asia
TIER I_IV	North America
TIER II_I	South Asia
TIER II_II	Latin America
TIER II_III	North America

Table 3-31 Description of the eight different suppliers with their respective geographical region

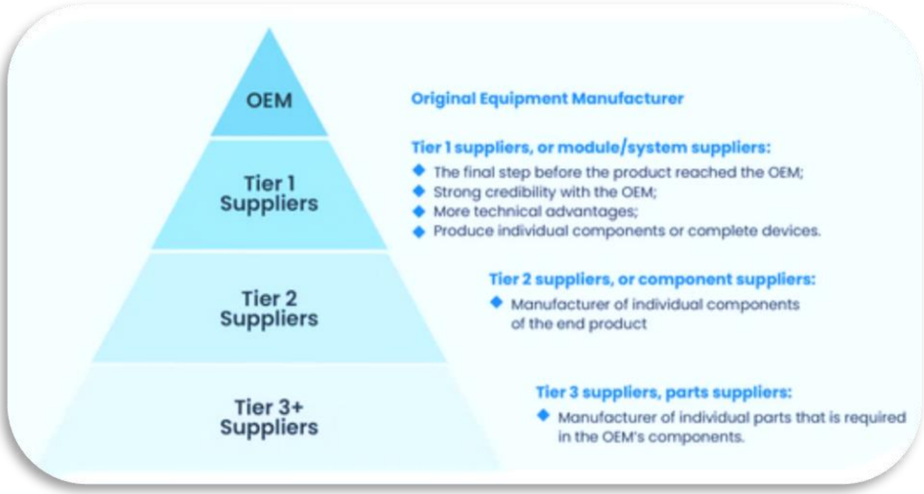


Figure 3-8 Illustration of the hierarchy of the different TIERS and their responsibilities

Based on the data collected for each of the parameters reported in Table 3-30, it is possible to evaluate the fixed cost, time, risk and quality of each involved enterprise. The assigned percentages are listed on Table 3-32. All the parameters' scales range from zero (0) to one hundred (100). Specifically, for the fixed cost, time and risk, the higher the assigned percentage the higher the production fixed cost, time and risk. Regarding the fixed quality, the higher the assigned percentage the higher the production fixed quality.

Enterprise	***Fixed Cost (0-100)***	***Fixed Time (0-100)***	***Fixed Risk (0-100)***	***Fixed Quality (0-100)***
OEM	80	60	50	80
TIER I_I	27	48	65	65
TIER I_II	24	48	85	71
TIER I_III	34	53	77	72
TIER I_IV	86	53	61	77
TIER II_I	20	44	53	81
TIER II_II	36	48	69	70
TIER II_III	64	53	57	74

Table 3-32 Assigned fixed production cost, time, risk and quality of each enterprise based on its geographical location

Combining the data from Table 3-32 with the related production quantity of the specific component that each enterprise has to produce, the fixed production performance at the supply chain level is estimated. Below the recommended equations for the estimation of each fixed term are given [78]:

$$Cost_{Fixed} = \prod_{j=1}^{n} Cost_{e_j} q_{i,e\_j}$$

$$Time_{Fixed} = \prod_{j=1}^{n} Time_{e_j} q_{i,e\_j}$$

$$Risk_{Fixed} = \prod_{j=1}^{n} Risk_{e_j} q_{i,e\_j}$$

$$Quality_{Fixed} = \prod_{j=1}^{n} Quality_{e_j} q_{i,e\_j}$$

Equation 3-14

where,

- $Cost_{ej}$, $Time_{ej}$, $Risk_{ej}$, $Quality_{ej}$ indicates respectively the fixed production cost, time, risk and quality of each enterprise depending on the enterprises' geographical location
- $q_{i, ej}$ is the production quantity of the component i manufactured by the enterprise ej

The second term of the first three mentioned equations ($Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ - Equation 3-13) considers the cost, time and risk associated with the transportation of a technical component from the production location, in which the manufacturing processes are carried out to the require assembly location, in which the different components are joined. To maximise the performance of the way in which the technical components are transported from the various production sites to the final assembly stations, a multi-modal transportation mode (Figure 3-7) is implemented. To this end, four distinct modes of transportation are involved for this analysis: air (a), water (w), road (r) and railway (rl).

The following equations are outlining the implemented transportation model:

$$Cost_{Transportation} = \sum_{g} (Cost(\sum_{i,j} d_{e_j,e_i} w_g)) \quad g = a, w, r, rl; \;\; i = 1, \dots, n; \;\; j = 1, \dots, k$$

$$Time_{Transportation} = \sum_{g}(Time(\sum_{i,j} d_{e_j,e_i} w_g)) \quad g = a, w, r, rl; \;\; i = 1, \dots, n; \;\; j = 1, \dots, k$$

$$Risk_{Transportation} = \sum_{g}(Risk(\sum_{i,j} d_{e_j,e_i} w_g)) \quad g = a, w, r, rl; \;\; i = 1, \dots, n; \;\; j = 1, \dots, k$$

Equation 3-15

where,

- $d_{ej,ei}$ is the distance between the production site i and the assembly site j, estimated by using the Haversine formula [78], [79]
- g represents the means of transportation adopted: air (a), water (w), road (r), rail (rl)
- w_g is the percentage of path carried out by the selected transportation mode
- Cost ($\sum_{i,j} d_{ej,ei}$), Time ($\sum_{i,j} d_{ej,ei}$), Risk ($\sum_{i,j} d_{ej,ei}$) are respectively the cost, time and risk to transport from production site i to the assembly site j using the mean of transportation g, estimated by using available linearized literature models [78], [80], [81] or/and not-linear functions provided by experts based on the experience.

By applying this model, it is possible to select an ideally optimum route for the required transportation, using more than one means of transportation for that a specific transport. Based on the latitude and longitude coordinates of the location of each enterprise, the overall distance among them it is possible to be estimated by applying the Haversine formula. Table 3-33 summarises the total distances among the different geographical locations. All distances on the below table are expressed in kilometres (km).

Overall Distances (km)

Enterprise	OEM	TIER I_I	TIER I_II	TIER I_III	TIER I_IV	TIER II_I	TIER II_II	TIER II_III
OEM	0.0	1904.7	7042.0	7586.6	7603.1	9470.7	9395.2	5769.2
TIER I_I	1904.7	0.0	5510.8	7283.4	9449.6	8320.5	11256.1	7636.7
TIER I_II	7042.0	5510.8	0.0	4463.3	14285.2	3120.5	15779.6	12488.1
TIER I_III	7586.6	7283.4	4463.3	0.0	11704.1	3326.1	12330.5	10532.2
TIER I_IV	7603.1	9449.6	14285.2	11704.1	0.0	15029.9	1812.3	1847.8
TIER II_I	9470.7	8320.5	3120.5	3326.1	15029.9	0.0	15489.3	13750.5
TIER II_II	9395.2	11256.1	15779.6	12330.5	1812.3	15489.3	0.0	3626.0
TIER II_III	5769.2	7636.7	12488.1	10532.2	1847.8	13750.5	3626.0	0.0

Table 3-33 Overall distances among different enterprises expressed in kilometres (km)

However, in order to apply Equation 3-15, the relative weights for each of the possible means of transportation for a given route are subtracted and for this purpose, it is necessary to set out the relative weights. A potential optimal route for transporting components has been selected for each estimated distance between two enterprises. Taking into account this assumption and the available means of transportation, specific weights have been assigned to each mean of transportation for the relevant route. These weights remain constant for all the scenarios to be examined later in this analysis. All four tables (Table 3-34, Table 3-35, Table 3-36, Table 3-37) below, show the weights for each mode of transportation respectively: air, water, road and railway.

Air Weights

Enterprise	OEM	TIER I_I	TIER I_II	TIER I_III	TIER I_IV	TIER II_I	TIER II_II	TIER II_III
OEM	0.000	0.000	0.928	0.000	0.000	0.947	0.949	0.000
TIER I_I	0.000	0.000	0.000	0.000	0.308	0.981	0.773	0.978
TIER I_II	0.928	0.000	0.000	0.000	0.000	0.978	0.826	0.808
TIER I_III	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.889
TIER I_IV	0.000	0.308	0.000	0.000	0.000	0.000	0.000	0.000
TIER II_I	0.947	0.981	0.978	0.000	0.000	0.000	0.000	0.000
TIER II_II	0.949	0.773	0.826	0.000	0.000	0.000	0.000	0.000
TIER II_III	0.000	0.978	0.808	0.889	0.000	0.000	0.000	0.000

Table 3-34 Assigned air weight for each preselected route between two geographical locations

Water Weights

Enterprise	OEM	TIER I_I	TIER I_II	TIER I_III	TIER I_IV	TIER II_I	TIER II_II	TIER II_III
OEM	0.000	0.997	0.000	0.997	0.997	0.000	0.000	0.988
TIER I_I	0.997	0.000	0.859	0.981	0.671	0.000	0.214	0.000
TIER I_II	0.000	0.859	0.000	0.868	0.941	0.000	0.147	0.160
TIER I_III	0.997	0.981	0.868	0.000	0.996	0.981	0.948	0.101
TIER I_IV	0.997	0.671	0.941	0.996	0.000	0.998	0.752	0.988
TIER II_I	0.000	0.000	0.000	0.981	0.998	0.000	0.000	0.000
TIER II_II	0.000	0.214	0.147	0.948	0.752	0.000	0.000	0.000
TIER II_III	0.988	0.000	0.160	0.101	0.988	0.000	0.000	0.000

Table 3-35 Assigned water weight for each preselected route between two geographical locations

Road Weights

Enterprise	OEM	TIER I_I	TIER I_II	TIER I_III	TIER I_IV	TIER II_I	TIER II_II	TIER II_III
OEM	0.000	0.003	0.003	0.003	0.003	0.002	0.002	0.012
TIER I_I	0.003	0.000	0.028	0.019	0.022	0.019	0.013	0.022
TIER I_II	0.003	0.028	0.000	0.006	0.002	0.022	0.027	0.031
TIER I_III	0.003	0.019	0.006	0.000	0.004	0.019	0.052	0.010
TIER I_IV	0.003	0.022	0.002	0.004	0.000	0.002	0.248	0.012
TIER II_I	0.002	0.019	0.022	0.019	0.002	0.000	0.000	0.000
TIER II_II	0.002	0.013	0.027	0.052	0.248	0.000	0.000	0.000
TIER II_III	0.012	0.022	0.031	0.010	0.012	0.000	0.000	0.000

Table 3-36 Assigned road weight for each preselected route between two geographical locations

Rail Weights

Enterprise	OEM	TIER I_I	TIER I_II	TIER I_III	TIER I_IV	TIER II_I	TIER II_II	TIER II_III
OEM	0.000	0.000	0.069	0.000	0.000	0.051	0.049	0.000
TIER I_I	0.000	0.000	0.113	0.000	0.000	0.000	0.000	0.000
TIER I_II	0.069	0.113	0.000	0.126	0.057	0.000	0.000	0.000
TIER I_III	0.000	0.000	0.126	0.000	0.000	0.000	0.000	0.000
TIER I_IV	0.000	0.000	0.057	0.000	0.000	0.000	0.000	0.000
TIER II_I	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TIER II_II	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TIER II_III	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3-37 Assigned rail weight for each preselected route between two geographical locations

Using the various data and techniques outlined in sections 3.1, 3.2, 3.3 and 3.4, it is possible to evaluate the seven key performance indicators required for the trade-off analysis. All the examined indicators provide valuable insights, helping to assess different options and make informed decisions based on their relative advantages and drawbacks. On the following section the Multi Attribute Utility Theory (MAUT) is introduced, which enables the aggregation of all the different indicators which have been examined.

3.5. Value Model

By applying the MAUT [43], [78], [82], it is possible to aggregate all the indicators mentioned and analysed previously into one dimensionless measure, that is value. Generally, the MAUT can be adopted only when the number of the examined attributes is higher than three. For this specific analysis, the theory is applicable, since seven different attributes (KPIs) are considered. The theory can be described by the following formula:

$$Value = \sum_{i=1}^{n} w_i v_i(x_i)$$

Equation 3-16

where,

- $v_i(x_i)$: Represents the value of alternative x on the i^{th} attribute (Utility Function)
- n: Represents the number of different attributes
- w_i: Is the importance weight of the i^{th} attribute:

$$0 < w_i < 1 \text{ and } \sum_{i=1}^{n} w_i = 1$$

Equation 3-17

Decision-making problems are typically framed as scenarios where a decision-maker evaluates a set of available alternatives while attempting to select the optimal choice. This process requires careful consideration of various relevant factors that influence the outcome. Attributes associated with each option play critical role. The most important attributes have a greater impact on the final decision. In addition, utility functions describe the preferences assigned to different choices based on their perceived value. They help quantify benefit, allowing decision-makers to compare alternatives objectively [82].

To merge different evaluation criteria having different units of measurement into a single dimensionless one the so-called value is used. Furthermore, for the creation of the reference case, a proper and fundamental assumption is made. Equal weights and linear utility functions are assigned to all the aggregated criteria [78]. In this way it is guaranteed that no preference is given to any of the criteria considered. (After that, different weighting factor and utility functions can be assigned to each attribute based on the preference of the decision maker). The assumptions mentioned previously for the application of the MAUT as well as different behaviour of a linear utility function can be seen in Figure 3-9. To the upper and lower limit which is the maximum and the minimum point respectively, a utility of 0 or 1 is assigned depending on the attribute under consideration. The behaviour of the utility functions depends solely on the tendency of the attribute under investigation. The tendency of each considered KPI for the current analysis, are presented in section 5.2. As presented in Figure 3-9, the related function may tend to increase in association with the attribute (left chart) or to decrease in association with the attribute (right chart).

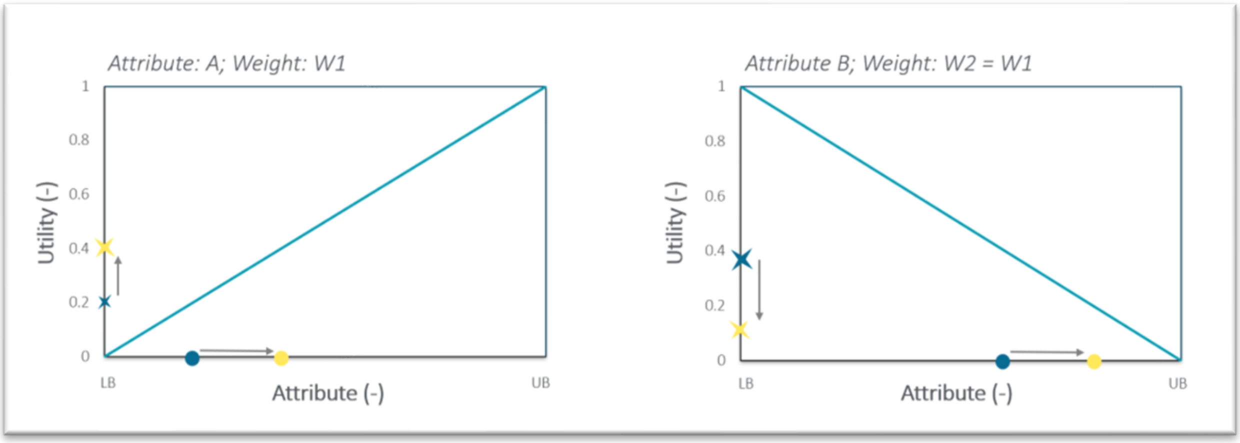


Figure 3-9 Illustration of linear utility functions with same weights, Left: Attribute with increasing trend, Right: Attribute with decreasing trend[78]

For instance, for an attribute such as time, a function with a decreasing trend is applied, meaning that higher time attribute corresponds to lower utility. However, for an attribute such as quality, a function with an increasing trend is used, meaning that higher quality corresponds to higher utility [78].

Generally, once weighting factors and utility functions (linear and non-linear) are assigned to all the considered criteria, a value-driven trade-space is generated that offers the possibility of comparing alternatives in a structured way. Each new combination, i.e. assignment of different weighting factors or utility functions, results in a different value-driven trade-space. The overall evaluation of an alternative is calculated by multiplying the weight by the attribute value for each attribute and summing these weighted attribute values over all attributes. In any case, the alternative with the highest multi-attribute utility should be the preferred one [43].

4. Methodology Implementation

This chapter of the thesis aims to outline the different tools that are used for the implementation of the different methodologies presented in Chapter 3. The needed inputs and the leading output/s of each tool are specified and explained. In total, three different software have been used for the implementation of those methodologies, which are reported below:

- Microsoft Office Excel
- PyCharm
- VALORISE

In the following three sections, the way that each of the aforementioned software has been applied in the current thesis, is explained.

4.1 Sustainability, Reliability and Mass KPIs' Implementation

In Chapter 3, many varying equations have been introduced in order to be able to evaluate the Sustainability, Reliability and Mass KPIs. In order to implement those equations, Microsoft Office Excel is employed as the central tool. As demonstrated in sections 3.1, 3.2 and 3.3, each one of the reported KPIs, is supported by its own input datasets and equations. However, all the computational procedures are implemented within Microsoft Office Excel.

As Sustainability, Reliability and Mass KPIs depend exclusively on the technical characteristics of the latching mechanism and not from the different production scenarios, by software all the necessary calculations can easily be performed. Moreover, it allows the decision-makers to maintain precision, ensuring consistency and comparability among the indicators.

Due to higher complexity of the remaining KPIs ($Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$) estimation, an additional software has been implemented in order to evaluate those KPIs. In the following section, further details are given regarding that software.

4.2 Supply Chain Domain KPIs' Implementation

The four KPIs describing the Supply Chain are not depend solely on the technical characteristics of the latching mechanism, but also on the examined Production and Assembly Scenario. Due to that, it is more difficult to estimate those KPIs just by using Microsoft Office Excel, and thus the PyCharm software is implemented.

PyCharm is an integrated development environment specifically designed specifically for Python programming. This software offers the ability to detect possible errors, integrate useful and powerful libraries such as Panda, NumPy and os.

To be able to automatize the estimation of these four KPIs ($Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$) based on the selected supply chain, five scripts written in Python Code, are collaborating to provide the overall supply chain performance. Additionally, four Excel files are needed to perform the analysis that are representing the input variables of the methodology. Within the first Excel file the various enterprises' latitude, longitude according to their geographical location (see Table 3-31), the fixed production cost, time, risk and quality of those enterprises (see Table 3-32) as well as the responsible supplier for the assembly of the handle unit and later on of the entire mechanism are stored. Based on the selected route that is being followed in order to transport the technical components from the production side to the assembly sides, specific weights have been given to the four available means of transportation (air, water, road and rail), representing the percentage of the distance that is being covered by that mean (see Table 3-34, Table 3-35, Table 3-36 and Table 3-37). These data are saved within the second Excel file. Inside the third Excel file all the technical components that compose each examined architectural design (HSLM, BLM and CLM) are reported with their demanded production quantity (multiplicity). Finally, the fourth Excel file houses all the parameters related with the estimation of the transportation cost, time and risk in order to transport technical components from the production sides to the assembly sides (see Equation 3-15).

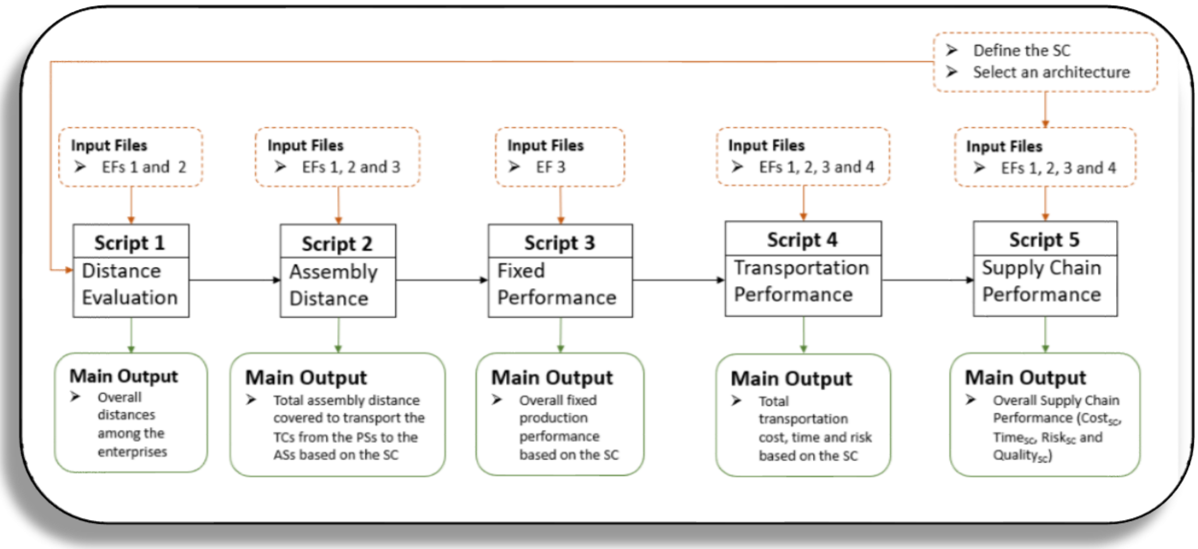


Figure 4-1 Illustration of the followed procedures in order to estimate the Overall Supply Chain Performance, by using PyCharm based on the selected Supply Chain (SC) and Architectural Design. The required input variables of each script as well as the main outcome of each one is denoted.

In Figure 4-1, a descriptive schema is illustrated, reporting the required input variables of each one of the five scripts that needed in order to execute the calculations written in that script. In that schema the EF indicates the related excel files that is used as an input, SC the selected Supply Chain (according to the investigated production and assembly scenario – see section 5.1), PS the selected production sides that produce the components and AS the chosen assembly sides. Additionally, the name and main outcome of each script are demonstrated on that figure. Once the desired supply chain and architectural design are selected, the overall supply chain performance based on those inputs, is available ($Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$).

4.3 Decision-Making Implementation

In order to perform a multi-criteria decision-making process and to generate a value-driven trade-space for the identification of the optimum alternative by trading stakeholders' expectation, the MAUT has been implemented in a specific tool, called VALORISE. Particularly, the decomposition of the acronym VALORISE leads to: Value-driven, trAdespace visuaLisatiOn, exploRatIon and aSsEssment in an interactive dashboard that has been developed by DLR. This dashboard, supports the modelling of the value-driven decision-making process, enables the analysis of realistic strategic scenarios and assists the exploration of the value-driven trade-space for the identification of the best solution. In addition, by VALORISE different combinations of weighting factors and utility functions assigned to the interested attributes can be investigated and analysed.

In order to be able to generate the desired trade-space and to allow the decision-maker to proceed with the decision-making, VALORISE requires an input file. That file must contain specifications of the criteria defined by decision-maker (e.g. name of the attribute and unit of measure), as well as the numerical estimation of such criteria for all the alternatives consisting the trade-space. For this particular application an EXCEL file has been used as an input, however, different format files can be accepted by it. Figure 4-2 demonstrating the inputs given to VALORISE, in order to be able to conduct a multi-criteria decision-making process.

Alternative	Architecture	CostSC (0-100)	TimeSC (0-100)	RiskSC (0-100)	QualitySC (0-100)	Sustainability (0-1)	Reliability (0-1)	Mass (0-1)
#1	HSLM	27	20.2	16.8	93.5	0.566	0.841	1
#2	BLM	23.8	17.8	14.9	94.1	0.59	0.912	0.957
#3	CLM	29.2	21.9	18.3	92.7	1	1	0.793

Figure 4-2 Demonstration of an EXCEL file, including information (i.e. description of the architectures, units of measurement, numerical values and identification number of each alternative) to perform multi criteria decision-making analysis

More specifically, the investigated 7 KPIs are presented with their related units and numerical values. The supply chain cost, time, risk and quality KPIs results are related with the Production and Assembly Scenario I as outlined in section 5.1, whereas sustainability, reliability and mass KPIs results are available in Table 3-15, Table 3-28 and Table 3-29 accordingly.

The desired weighting factors and utility functions can be assigned by decision-makers directly in VALORISE as illustrated in Figure 4-3. Decision-makers can interactively draw utility functions according to their expectations with respect to each selected attribute and set several weight combinations to analyse the scenario of interest. Many scenarios can be then investigated in real-time.

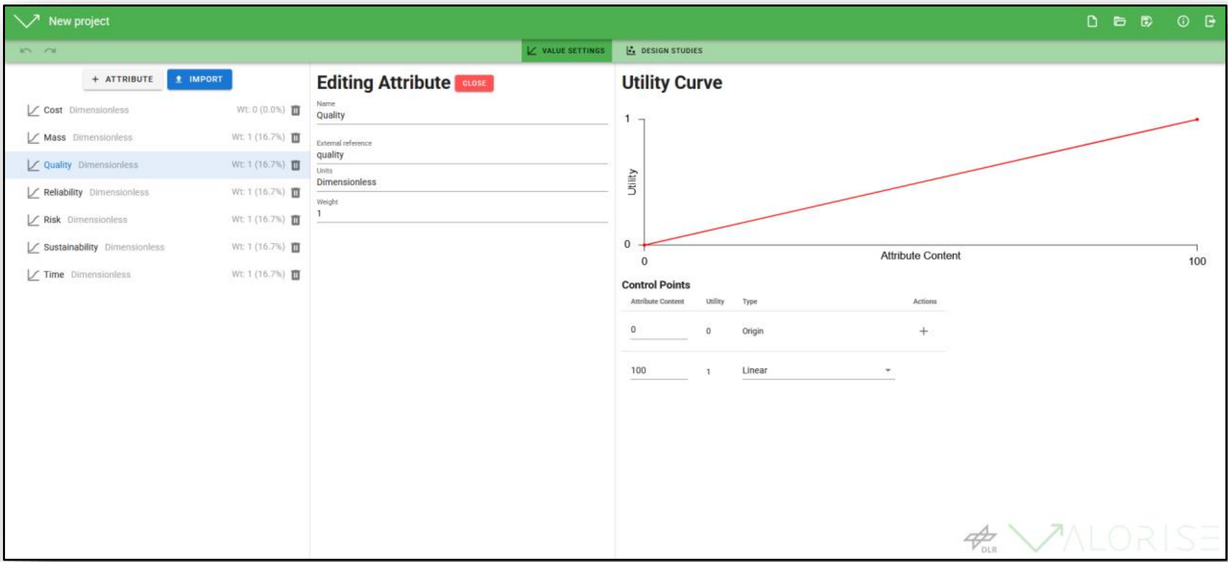


Figure 4-3 Assignment of weighting factor and utility function to an examined attribute (KPI)

Figure 4-4 shows all the different regions of the dashboard. More specifically, on the left side the different strategic scenarios are denoted, in the middle the generated trade-space is illustrated where the identification of the best alternative can be performed and the right side presents the section where the different settings of each attribute can be modified.

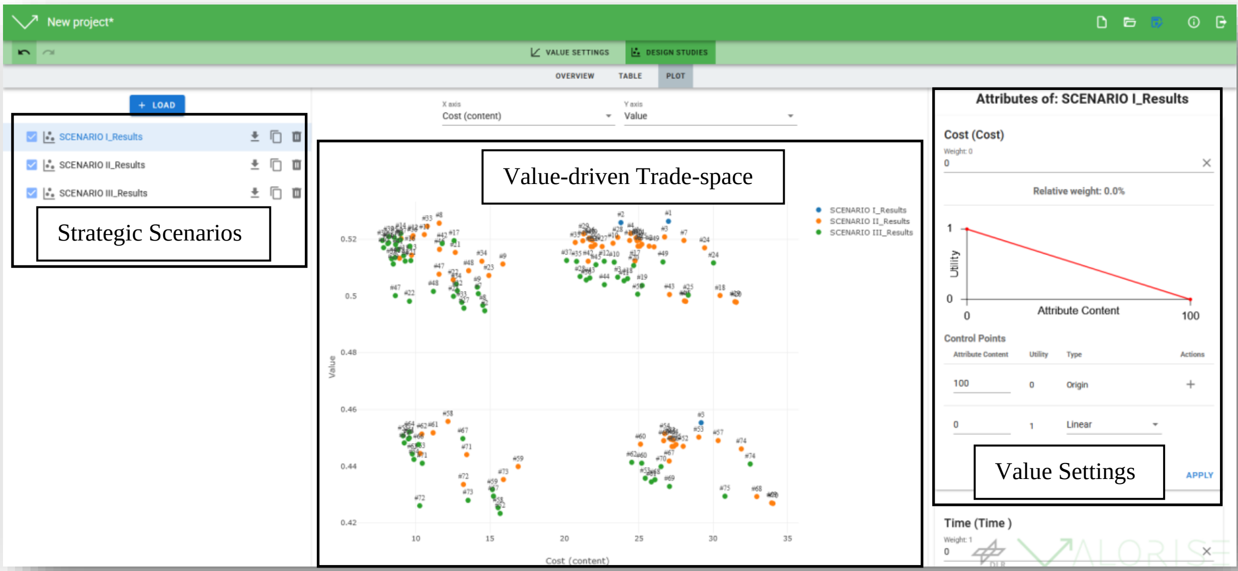


Figure 4-4 Demonstration of the different sections of the VALORISE dashboard

5. Methodology Results

This chapter, summarises all the results obtained from the assessment of the three latching mechanism architectures. However, the main purpose is to perform trade-off analyses by implementing the MAUT. As mentioned previously in section 2.2, the results derived from the sustainability, reliability and mass domains, do not depend on the considered production and assembly scenario of the different TCs of each architecture but solely, from their technical characteristics. Based on the presented methodologies in Chapter 3, all these three KPIs have been estimated for each one architectural design (HSLM, BLM and CLM). On the other hand, the results coming from the supply chain domain ($Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$) depend exclusively on the considered production and assembly scenario. As explained in section 3.4, the considered supply chain consists from eight qualified enterprises. Due to the fact that each one has specific responsibilities and is located in a different geographical location, many production and assembly scenarios, leading to different $Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$ every time, can be generated and investigated. In the following section the examined production and assembly scenarios are described in depth.

5.1 Supply Chain Production Scenarios

Primary purpose is to examine characteristic scenarios which are representative in reality. To this end, and based on the responsibilities that each one of the suppliers has, three distinct production and assembly scenarios are investigated. At this point, it is necessary to mention that each latching mechanism consists by different number of TCs. However, the TCs that compose the Handle Unit (HU) of each LM, are separated from the rest TCs. This happens because all those TCs are identical across all the three LMs (in terms of number, materials and multiplicities). Based on these statements, each one analysed scenarios is outlined below:

- **Production and Assembly Scenario I:** All the technical components of each architectural design are produced by OEM. The assembly of the handle unit as well as the final assembly of the entire mechanism are performed by OEM.
- **Production and Assembly Scenario II:** OEM is responsible to produce some technical components of each architecture. All the remaining TCs are produced either by one of the TIER's I or TIER's II suppliers or even a mix of them. The assembly of the handle unit of each architectural design can be performed by OEM or by one of the TIER's I suppliers. The final assembly of the entire mechanism is performed by the OEM.

- **Production and Assembly Scenario III:** TIER's I or TIER's II suppliers are responsible to produce all the technical components of each architectural design. The assembly of the handle unit is performed by one of the TIER's I suppliers. The final assembly of the entire mechanism is performed by OEM. (Figure 5-1 shows in a schematic way the Production and Assembly Scenario I and III respectively.)

As, for the second and third scenarios, all or some of the components are produced by one of the TIER's I or TIER's II suppliers, different means of transportation are used to transport the TCs from the production sides to the assembly sides. The implemented multi-modal transportation mode among the considered enterprises, which are located in geographical locations has been presented in 3.4.

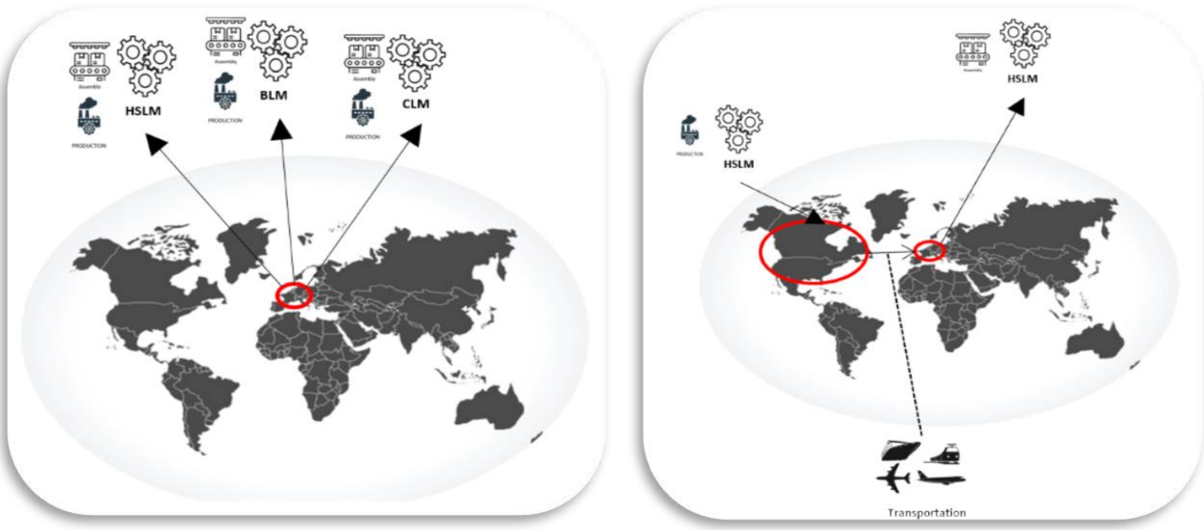


Figure 5-1 Demonstration of Production and Assembly Scenario I and III. Left: OEM is responsible to produce and assembly all the technical components of each latching mechanism, Right: All the components are produced by TIER I or TIER II suppliers and the final assembly is performed by OEM. An optimum route must be selected by using the air, water, road or rail for their transportation from the production sides to the assembly sides.

Since, in the first scenario all the TCs (including the components of the handle unit) of each architectural design (HSLM, BLM and CLM) are produced and assembled by OEM, **only one possible supply chain is obtained**, as only one enterprise is involved in that specific scenario. Regarding the second and third scenario, numerous possible supply chains can be generated as it is necessary to involve more than one enterprise according to their description. Every single supply chain is characterised by different performance ($Cost_{SC}$, $Time_{SC}$, $Risk_{SC}$ and $Quality_{SC}$). For this application, **twenty-five (25) different supply chains** have been generated for each considered scenario (Scenario II and III). In order to be able to compare the resulting alternatives associated with each architecture, each examined supply chain is implemented for all the three LMs. Thus, seventy-five (75) alternatives are included in scenario II and III respectively. To this end, a specific range is given to each architectural design, where all the alternatives of that LM are included in. All the alternatives from 1 to 25 are linked to the HSLM, from 26 to 50 are associated with the BLM whereas, from 51 to 75 are related with the CLM. All the different supply chains regarding the accounted scenarios are listed in Table 5-1, Table 5-3 and Table 5-4.

Supply Chain of Production and Assembly Scenario I

Architecture	**Responsible enterprise for the production of Handle's unit TCs**	**Responsible enterprise for the production of the remaining TCs**	**Responsible enterprise for the assembly of the HU**	**Responsible enterprise for assembly of the entire mechanism**	**Alternative's Identification Number**
HLMS	OEM	OEM	OEM	OEM	#1
BLM	OEM	OEM	OEM	OEM	#2
CLM	OEM	OEM	OEM	OEM	#3

Table 5-1 Description of the supply chain according to the Production and Assembly Scenario I principles. On the presented table the alternative with the identification number #1 is linked with the HSLM, with the #2 is associated with the BLM, whereas with the #3 is related with the CLM.

Thereby, by combining the provided data and equations that stated in section 3.4, it is possible to evaluate the overall supply chain cost, time, risk and quality of each reported supply chain. Once all the seven different KPIs are available, trade-offs can be performed among the LMs.

5.2 KPIs' Tendencies and Examined Case Studies

As has been mentioned, the MAUT is implemented for the aggregation of the considered KPIs. For this application, seven KPIs have been evaluated for three different latching mechanisms. A necessary step before the implementation of the MAUT by using VALORISE software, is to assign weighting factors and utility functions to all KPIs. As stated in section 3.5, the behaviour of the utility functions **depends solely on the tendency of the attribute** under investigation. For the current analysis, two distinct tendency types are used: increasing and decreasing. To Sustainability, Reliability, Mass, $Time_{SC}$ and $Risk_{SC}$ KPIs, the decreasing tendency is applied, meaning that a higher value of that attribute corresponds to lower utility.

Key Performance Indicator	***Utility Function's Tendency***
Sustainability	Decreasing
Reliability	Decreasing
Mass	Decreasing
$Time_{SC}$	Decreasing
$Risk_{SC}$	Decreasing
$Quality_{SC}$	Increasing

Table 5-2 Tendency related with each considered KPI

Supply Chain of Production and Assembly Scenario II

Related Architectures	Responsible enterprise for the production of Handle's unit TCs	Responsible enterprise for the production of the remaining TCs	Responsible enterprise for the assembly of the Handle unit	Responsible enterprise for assembly of the entire mechanism	Alternative's Identification Number
HSLM/BLM/CLM	TIER II_I	OEM	OEM	OEM	#1/#26/#51
HSLM/BLM/CLM	TIER II_II	OEM	OEM	OEM	#2/#27/#52
HSLM/BLM/CLM	TIER II_III	OEM	OEM	OEM	#3/#28/#53
HSLM/BLM/CLM	TIER I_I	OEM	TIER I_I	OEM	#4/#29/#54
HSLM/BLM/CLM	TIER I_II	OEM	TIER I_II	OEM	#5/#30/#55
HSLM/BLM/CLM	TIER I_III	OEM	TIER I_III	OEM	#6/#31/#56
HSLM/BLM/CLM	TIER I_IV	OEM	TIER I_IV	OEM	#7/#32/#57
HSLM/BLM/CLM	OEM	TIER II_I	OEM	OEM	#8/#33/#58
HSLM/BLM/CLM	OEM	TIER II_II	OEM	OEM	#9/#34/#59
HSLM/BLM/CLM	OEM	TIER II_III	OEM	OEM	#10/#35/#60
HSLM/BLM/CLM	TIER I_I and OEM (50 - 50)	TIER II_I	TIER I_I	OEM	#11/#36/#61
HSLM/BLM/CLM	TIER I_I and OEM (75 - 25)	TIER II_I	TIER I_I	OEM	#12/#37/#62
HSLM/BLM/CLM	TIER I_II and OEM (75 - 25)	TIER II_I	TIER I_II	OEM	#13/#38/#63
HSLM/BLM/CLM	TIER II_I	OEM	TIER I_I	OEM	#14/#39/#64
HSLM/BLM/CLM	TIER II_I	OEM	TIER I_II	OEM	#15/#40/#65
HSLM/BLM/CLM	TIER II_I	OEM	TIER I_III	OEM	#16/#41/#66
HSLM/BLM/CLM	TIER II_I	OEM	TIER I_IV	OEM	#17/#42/#67
HSLM/BLM/CLM	OEM and TIER I_IV (50 – 50)	TIER I_IV	TIER I_III	OEM	#18/#43/#68
HSLM/BLM/CLM	OEM and TIER I_IV (50 – 50)	TIER I_IV	TIER I_II	OEM	#19/#44/#69
HSLM/BLM/CLM	OEM and TIER I_IV (25 – 75)	TIER I_IV	TIER I_II	OEM	#20/#45/#70
HSLM/BLM/CLM	OEM	TIER I_I	OEM	OEM	#21/#46/#71
HSLM/BLM/CLM	OEM	TIER I_II	OEM	OEM	#22/#47/#72
HSLM/BLM/CLM	OEM	TIER I_III	OEM	OEM	#23/#48/#73
HSLM/BLM/CLM	OEM	TIER I_IV	OEM	OEM	#24/#49/#74
HSLM/BLM/CLM	TIER II_I and TIER I_I (50-50)	OEM	TIER I_I	OEM	#25/#50/#75

Table 5-3 Description of the twenty-five different supply chains according to the Production and Assembly Scenario II principles. On the presented table the alternatives with an identification number from #1 to #25 are linked with the HSLM, from #26 to #50 are associated with the BLM, whereas from #51 to #75 are related with the CLM.

On the other hand, for the $Quality_{SC}$ KPI the increasing tendency is applied, meaning that a higher value of that attribute corresponds to a higher utility. All the tendencies of each KPI are summarised in Table 5-2 except one. The only KPI that is not reported is $Cost_{SC}$. The particular KPI, is used as an **independent variable** for the creation of the value-cost trade-space, as it is assumed a key parameter to perform decision-making. The graphical integration of this KPI as an independent variable in the entire value model as well as the **aggregation** of the other **six.**

Supply Chain of Production and Assembly Scenario III

Related Architectures	**Responsible enterprise for the production of Handle's unit TCs**	**Responsible enterprise for the production of the remaining TCs**	**Responsible enterprise for the assembly of the Handle unit**	**Responsible enterprise for assembly of the entire mechanism**	**Alternative's Identification Number**
HSLM/BLM/CLM	TIER II_I	TIER II_I	TIER I_I	OEM	#1/#26/#51
HSLM/BLM/CLM	TIER II_II	TIER II_II	TIER I_II	OEM	#2/#27/#52
HSLM/BLM/CLM	TIER II_III	TIER II_III	TIER I_III	OEM	#3/#28/#53
HSLM/BLM/CLM	TIER II_I	TIER II_I	TIER I_IV	OEM	#4/#29/#54
HSLM/BLM/CLM	TIER II_I	TIER II_I	TIER I_II	OEM	#5/#30/#55
HSLM/BLM/CLM	TIER II_I	TIER II_I	TIER I_III	OEM	#6/#31/#56
HSLM/BLM/CLM	TIER II_II	TIER II_II	TIER I_I	OEM	#7/#32/#57
HSLM/BLM/CLM	TIER II_II	TIER II_II	TIER I_III	OEM	#8/#33/#58
HSLM/BLM/CLM	TIER II_II	TIER II_II	TIER I_IV	OEM	#9/#34/#59
HSLM/BLM/CLM	TIER II_III	TIER II_III	TIER I_I	OEM	#10/#35/#60
HSLM/BLM/CLM	TIER II_III	TIER II_III	TIER I_II	OEM	#11/#36/#61
HSLM/BLM/CLM	TIER II_III	TIER II_III	TIER I_IV	OEM	#12/#37/#62
HSLM/BLM/CLM	TIER I_II	TIER II_I	TIER I_III	OEM	#13/#38/#63
HSLM/BLM/CLM	TIER I_I	TIER II_I	TIER I_I	OEM	#14/#39/#64
HSLM/BLM/CLM	TIER I_II	TIER II_I	TIER I_II	OEM	#15/#40/#65
HSLM/BLM/CLM	TIER I_III	TIER II_I	TIER I_III	OEM	#16/#41/#66
HSLM/BLM/CLM	TIER I_IV	TIER II_I	TIER I_IV	OEM	#17/#42/#67
HSLM/BLM/CLM	TIER I_IV	TIER II_III	TIER I_III	OEM	#18/#43/#68
HSLM/BLM/CLM	TIER I_IV	TIER II_III	TIER I_II	OEM	#19/#44/#69
HSLM/BLM/CLM	TIER I_IV	TIER II_III	TIER I_I	OEM	#20/#45/#70
HSLM/BLM/CLM	TIER I_I	TIER I_I	TIER I_I	OEM	#21/#46/#71
HSLM/BLM/CLM	TIER I_II	TIER I_II	TIER I_II	OEM	#22/#47/#72
HSLM/BLM/CLM	TIER I_III	TIER I_III	TIER I_III	OEM	#23/#48/#73
HSLM/BLM/CLM	TIER I_IV	TIER I_IV	TIER I_IV	OEM	#24/#49/#74
HSLM/BLM/CLM	TIER II_I and TIER II_II (50-50)	TIER I_IV	TIER I_II	OEM	#25/#50/#75

Table 5-4 Description of the twenty-five different supply chains according to the Production and Assembly Scenario III principles. On the presented table the alternatives with an identification number from #1 to #25 are linked with the HSLM, from #26 to #50 are associated with the BLM, whereas from #51 to #75 are related with the CLM.

KPIs into **a single value**, is illustrated in Figure 3-1.Thus, the tendency and the related utility function of $Cost_{SC}$ KPI are not presented. All the reported tendencies are remained constant during the investigation of the following case studies.

In order to perform trade-off analyses among the LMs, various case studies are defined and examined. More specifically, four distinct case studies are investigated where each one of them, is characterised by specific weighting factors and utility functions. Every single Case Study (CS) is described below:

- **Case Study I (Reference Case Study):** Equal weights and linear utility functions are assigned to all KPIs
- **Case Study II:** Equal prioritisation of two KPIs (Sustainability and $Quality_{SC}$), equal weights to all the remaining KPIs and linear utility functions are assigned to all KPIs
- **Case Study III:** Equal prioritisation of two KPIs (Reliability and $Risk_{SC}$), equal weights to all the remaining KPIs and linear utility functions are assigned to all KPIs
- **Case Study IV:** Equal prioritisation of two KPIs ($Time_{SC}$ and Mass), equal weights to all the remaining KPIs and linear utility functions are assigned to all KPIs

The first case study is denoted as the reference one. In that particular case, equal weighting factors and linear utility functions are assigned to all the considered KPIs. Thereby, no priority is given to any of them and thus the results obtained are not influenced by any factor. In other scenarios that are discussed in the current thesis (as stated above), prioritisation is given to selected indicators at a time. All the examined case studies are compared and commented on in terms of the reference case study (Case Study I).

The various combinations previously reported as case studies, have been formed in such a way that there is uniformity among the trade-off analyses. Particularly, the HSLM is the most sustainable and reliable architecture, whereas the CLM is the one with the lowest mass. On the other hand, BLM is the one that in every single examined supply chain, performs the best. So, it is not meaningful to prioritise the sustainability and reliability KPIs or the $Time_{SC}$ and $Risk_{SC}$ KPIs in the same case study and thus are separated.

1. ***Case Study I***

According to CS I description, equal weighting factors and linear utility functions are assigned to all the examined KPIs. In Figure 5-2, the importance, the relative weight, the utility function and the scale of each indicator is illustrated. The importance of each variable is defined in the section under the heading "weight". Once in this CS equal weights are required, the importance of all the KPIs is set to be 1. As the $Cost_{SC}$ is treated as an independent variable, each one of the remaining KPIs is weighted with 16.7%. That percentage represents the relative weight of each KPI. Further to the importance and the relative weights, in that figure the utility functions are demonstrated. By the usage of Table 5-2 where the tendency of each attribute is described, all the utility functions are set respectively. All of them are linear, following their respective tendency (increasing or decreasing). Lastly, the scale of the Sustainability, Reliability and Mass

KPI ranges from 0 to 1 (3.1.3), whereas for the supply chain's KPIs ranges from 0 to 100 (3.4).

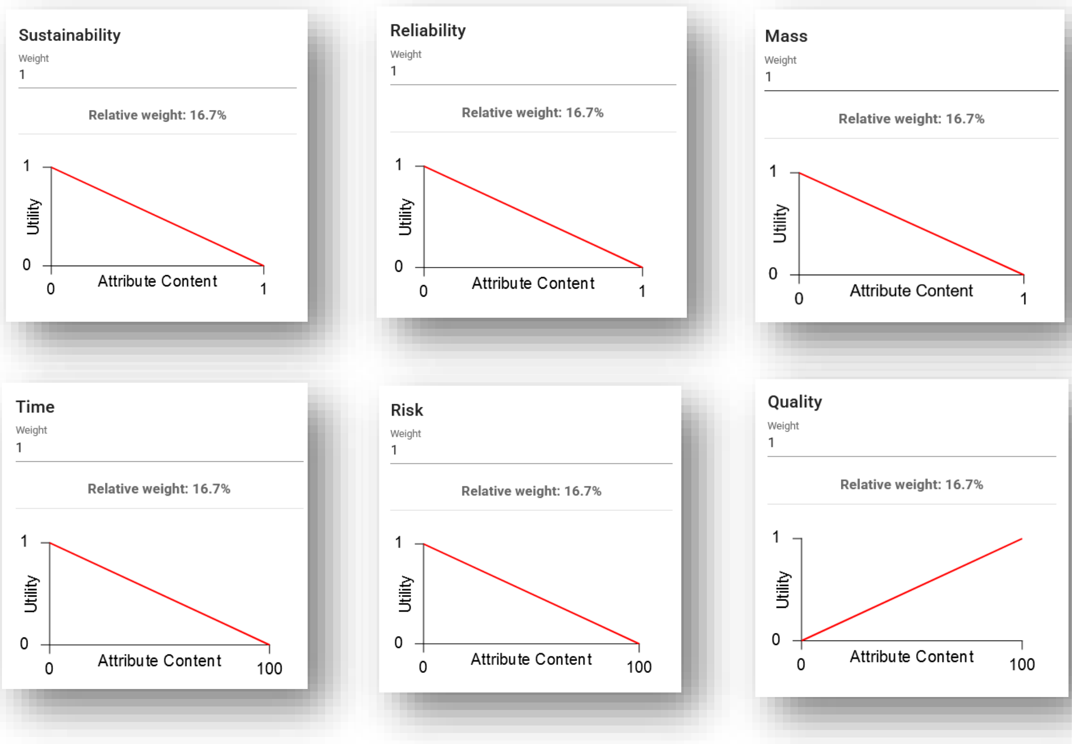


Figure 5-2 Demonstration of the assigned relative weights and utility functions to each one of the considered KPIs – Case Study I

Once the weighting factors and utility functions (according to the investigated CS) have been assigned to all the considered KPIs, a value-cost trade-space is generated, that offers the possibility of comparing alternatives in a structured way. In Figure 5-3, the value-cost trade-space of the first CS is depicted.

As already mentioned, the main purpose of the analysis is to identify the best alternative **based on its value and Cost$_{SC}$**. As can be seen from the generated value-cost trade-pace in Figure 5-3, the respective value of each alternative is indicated in the vertical axis while the Cost$_{SC}$ in the horizontal axis. **The alternative with the highest value and the lowest Cost$_{SC}$ is deemed as the optimum one**. It is obvious that the results of this CS, are classified into four distinct regions: **Upper Left, Upper Right, Lower Left and Lower Right**. Thus, **there is not a unique alternative** that can be identified as the best one, but a trade-off must be performed between the resulting value and Cost$_{SC}$.

On closer inspection, the alternatives that fall in the **lower left and right regions are all linked to the CLM**, since they all belong to the third interval as indicated in Table 5-1, Table 5-3 and

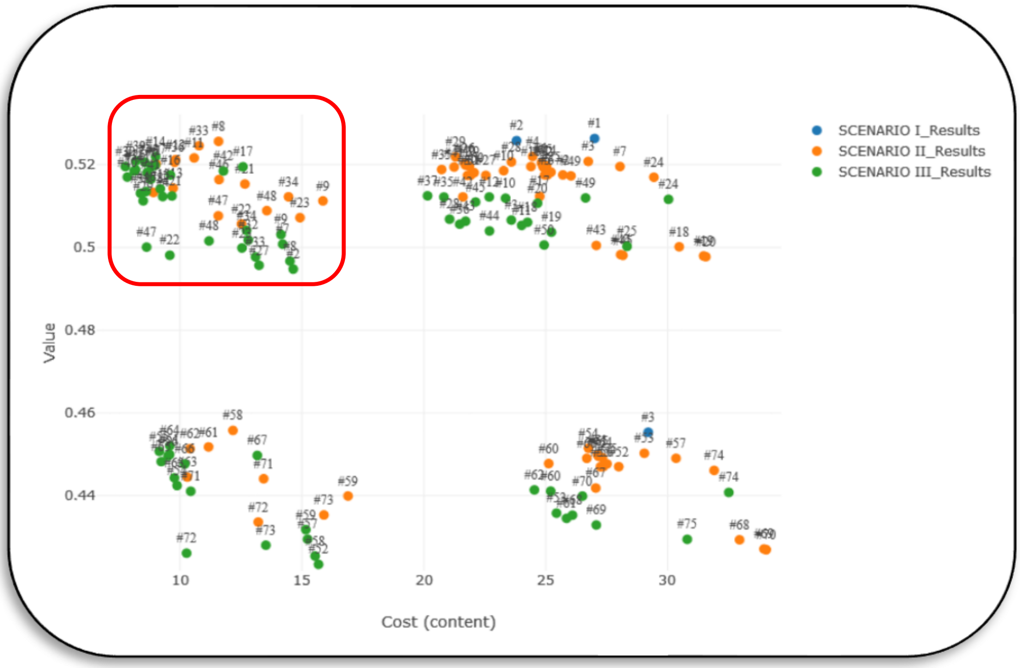


Figure 5-3 Comprehensive value-cost trade-space of Case Study I

Table 5-4. This can be explained by three facts. According to the current analysis, CLM is the **less reliable and sustainable** architecture among the examined ones (see 3.1.3 and 3.2.3), leading to zero utilities according to the assigned utility functions as indicated by Figure 5-2. In addition, among the three latching mechanisms, it is the one that **consists of the most technical components**. As a result, each of the examined supply chains associated with that mechanism, presents comparatively the lowest performance in terms of cost, time, risk and quality since, more components have to be manufactured, transported and assembled. Ultimately, this mechanism is judged as the least efficient since in every examined CS, all its resulting alternatives have a significantly lower value compared to the alternatives associated with the other two architectures (i.e. the alternatives that fall in the upper left and upper right region). Therefore, the lower left and right region are of no interest and in the upcoming case studies, they are completely ignored.

Concerning the upper right region, the alternatives falling in that region have a high value but in parallel a high cost. Alternatives from both alternate architectures (HSLM and BLM) fall in that region. However, since the upper left region contains alternatives with a similar, perhaps even higher value but in the same time lower cost, for the purposes of the thesis the upper right region is disregarded as well. Therefore, on the upper left side the region of greatest importance is identified, where the included alternatives, maintain a high value and low cost.

The mentioned region is denoted with a red rectangle in Figure 5-3, a closer look of it, is illustrated in Figure 5-4.

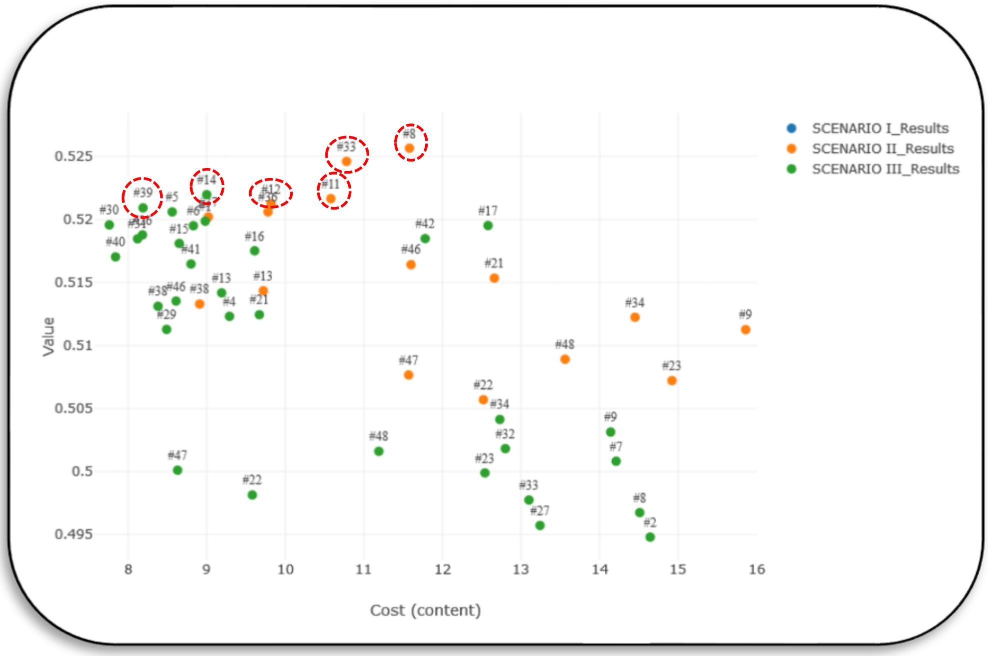


Figure 5-4 Illustration of the region associated with the alternatives that are of greatest importance according to Case Study I

Based on the region of interest, the six alternatives with the highest value, which are identified as the optimum ones are reported in Table 5-5 (They are highlighted with red dashed circles in Figure 5-4). In addition, the associated $Cost_{SC}$, the related production and assembly scenario as well as the relative architecture are presented in mentioned table. As already mentioned, the supply chain cost ($Cost_{SC}$) is treated as **independent variable**. On the other hand, all the other KPIs **are aggregated into one single value** by implementing the MAUT.

Alternative	***Architecture***	***Value (0-1)***	***$Cost_{SC}$ (0-100)***	***Production/Assembly Scenario***
#8	HSLM	0.5257	11.6	Scenario II
#33	BLM	0.5246	10.8	Scenario II
#14	HSLM	0.5220	9.0	Scenario III
#11	HSLM	0.5217	10.6	Scenario II
#12	HSLM	0.5212	9.8	Scenario II
#39	BLM	0.5209	8.2	Scenario III

Table 5-5 Presentation of the six alternatives with the highest value, their respective Supply Chain Cost, the related production scenario as well as the associated Latching Mechanism - Case Study I

As can be observed, **alternative #8** is the one with the highest value and thus it can be concerned as the optimum for this particular CS. However, it has the highest $Cost_{SC}$ among all the presented alternatives. In addition, the differences among the values are not significantly great, almost negligible. Due to these facts, it could be reasonable to identify the **alternative #14** as the optimal one, as the overall value **is comparable high** whereas the **Cost$_{SC}$ is lower** than the alternatives #8 and #33. So, the identification of a region that the optimum solutions are included in, it is crucial step that allows the decision makers to perform trade-offs based on the value and cost of each alternative (according to this methodology).

An interesting point, is to examine the supply chain that is associated with each alternative, as different supply chain leads to different Cost$_{SC}$, as it is evidenced by Table 5-5. The supply chain performance depends exclusively on the examined production and assembly scenario where specific enterprises are involved in each one of them. To this end, the related supply chain of each one of the optimum alternatives are outlined in Table 5-6. All the supply chains have been defined earlier for each examined production and assembly scenario in Table 5-1, Table 5-3 and Table 5-4 accordingly. However, the following table, contains only the supply chains of the six mentioned alternatives.

Alternative's Identification Number	***Responsible enterprise for the production of Handle's Unit TCs***	***Responsible enterprise for the production of all the remaining TCs***	***Responsible enterprise for the assembly of the Handle Unit***	***Responsible enterprise for the entire assembly of the LM***
#8	OEM	TIER II_I	OEM	OEM
#33	OEM	TIER II_I	OEM	OEM
#14	TIER I_I	TIER II_I	TIER I_I	OEM
#11	TIER I_I and OEM (50-50)	TIER II_I	TIER I_I	OEM
#12	TIER I_I and OEM (75-25)	TIER II_I	TIER I_I	OEM
#39	TIER I_I	TIER II_I	TIER I_I	OEM

Table 5-6 Enterprises that compose the supply chain of the alternatives #8, #33, #14, #11, #12 and #39

It is observed that, supply chains that involve OEM supplier during the production stage of the various TCs (i.e. those that are related with the alternatives #8, #33, #11 and #12, since they have been generated under the principles of Production and Assembly Scenario II), present slightly higher supply chain cost. This can be explained by Table 3-32, as the fixed cost of the OEM supplier is the second highest among the different suppliers. Thus, alternatives #8, #33, #11 and #12 result in higher Cost$_{SC}$. On the other hand, alternatives #14 and #39 have been created under the Production and Assembly Scenario III principles, where it is not necessary to involve OEM during the production phase and thus lower Cost$_{SC}$ is obtained.

2. ***Case Study II***

According to CS II description, the Sustainability and Quality$_{SC}$ KPIs must be slightly prioritised among the other KPIs while in parallel, linear utility functions are assigned to all of them. In order to achieve such a thing, the importance of those two KPIs (Sustainability and Quality$_{SC}$) is set to be 2 instead of 1. In that way prioritisation is given to them, as the relative weight of each one becomes 25% while, the relative weight of each one of the remaining KPIs is 12,5%. The relative weight as well as the utility function of each KPI are demonstrated in Figure 5-5.

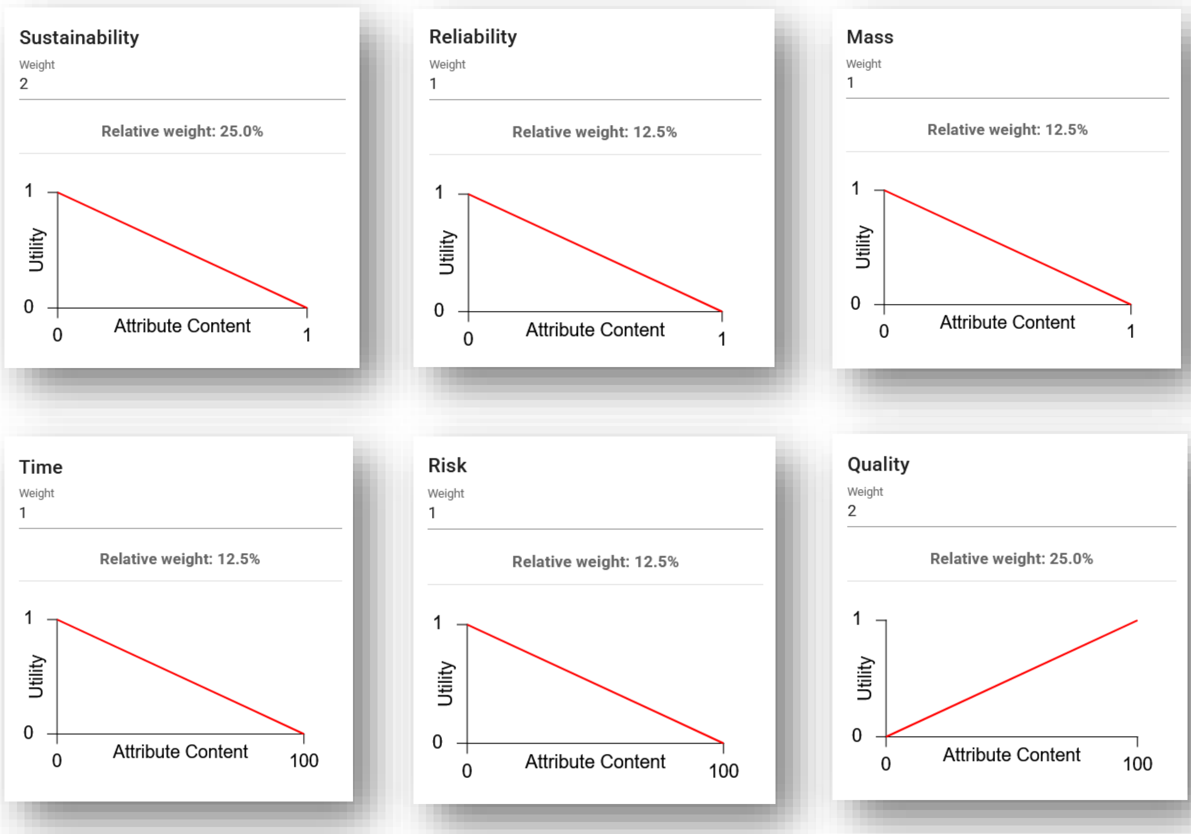


Figure 5-5 Demonstration of the assigned relative weights and utility functions to each one of the considered KPIs – Case Study II

As Case Study I has been defined as the reference one, all the obtained results from the current Case Study are compared to those from Case Study I. In addition, only the region of high importance is presented, due to the fact that the other three regions as has been explained in CS I, are not of high interest and thus are disregarded for the purposes of the thesis. Figure 5-6 illustrates the generated value-cost trade-space, resulting according the principles of CS II. In the same chart, the results associated with the CS I, are presented as well. However, different colours (purple and brown) indicate the alternatives resulting from the current case study. By slightly prioritising the Sustainability and Quality$_{SC}$ KPIs, the alternatives included in the region of high importance **remain exactly the same** as those in CS I. However, the associated value of each alternative is **higher** than the one presented in CS I. Additionally, the respective Cost$_{SC}$ of each alternative remains uninfluenced, due to fact that it is treated as an independent variable.

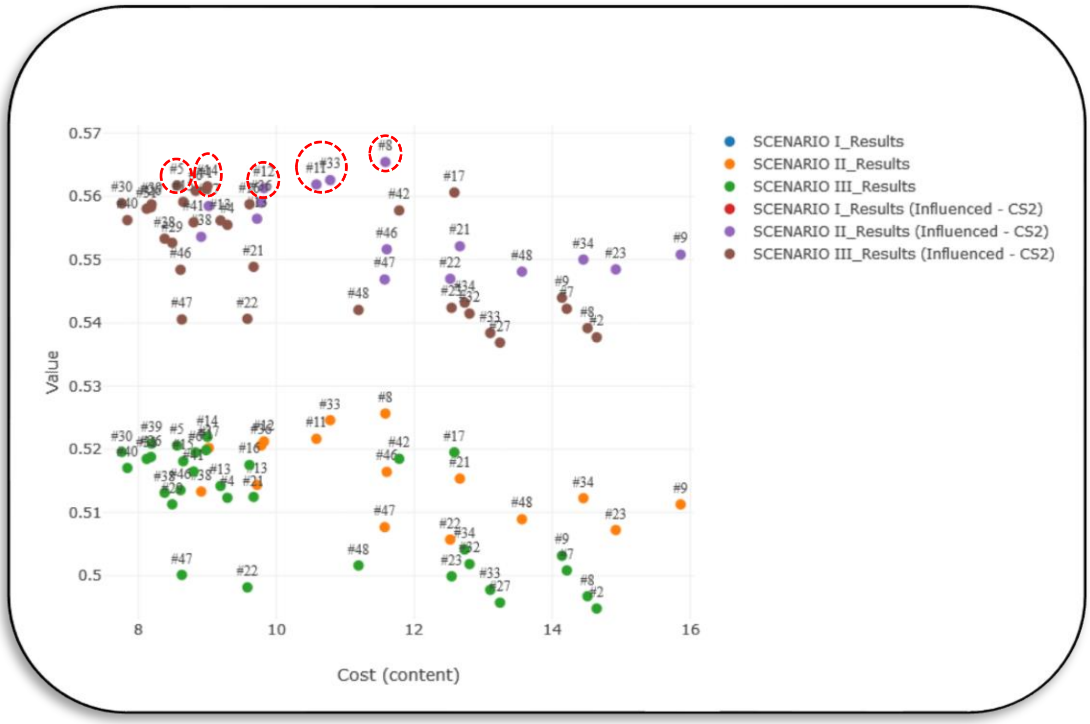


Figure 5-6 Illustration of the region associated with the alternatives that are of greatest importance according to Case Study II including the results obtained from Case Study I

In Table 5-7, the six alternatives performing the best according to CS I and CS II (i.e. these with the highest value), are presented. Observing that table, it is evidenced that the 5 out of 6 alternatives **(#8, #33, #11, #14 and #12)** that are reported as the optimum ones, are the same in both case studies. By prioritising the Sustainability and Quality$_{SC}$ **alternative #39** is no further identified as one of the six best solutions, while it is replaced by alternative #5. Based on Table 5-6, the TCs of handle unit for alternative #39 are produced by TIER I_I, whereas for alternative #5 are produce by TIER II_I (see Table 5-4). However, **TIER I_I** supplier is the one with **the lowest fixed production quality**, whereas **TIER II_I supplier the highest one** and thus, by prioritising the Quality$_{SC}$ higher utility is obtained for **alternative #5** (The fixed production quality of each supplier can be found in Table 3-32).

Additionally, alternative #39 is linked to the BLM. That mechanism evidenced less sustainable than HSLM. Therefore, due to greater importance is given to Sustainability KPI, all the alternatives which are related with the HSLM are in advantageous position, as HSLM is the most sustainable one.

Alternative	*Architecture*	*Value (0-1)*	*Cost$_{SC}$ (0-100)*	*Production/Assembly Scenario*
#8	HSLM	0.5257	11.6	Scenario II
#33	BLM	0.5246	10.8	Scenario II
#14	HSLM	0.5220	9.0	Scenario III
#11	HSLM	0.5217	10.6	Scenario II
#12	HSLM	0.5212	9.8	Scenario II
#39	BLM	0.5209	8.2	Scenario III
#8	HSLM	0.5654	11.6	Scenario II – CS II
#33	BLM	0.5626	10.8	Scenario II – CS II
#11	HSLM	0.5619	10.6	Scenario II – CS II
#5	HSLM	0.5617	8.6	Scenario III – CS II
#14	HSLM	0.5616	9.0	Scenario III – CS II
#12	HSLM	0.5613	9.8	Scenario II – CS II

Table 5-7 Presentation of the six alternatives with the highest value, their respective Supply Chain Cost, the related production scenario as well as the associated Latching Mechanism - Case Study I and II The six optimum alternatives of Case Study II are denoted by red dashed circles.

All in all, **alternative #8** can be identified as the best solution as it has the highest value. **Alternative #5** is better solution than alternatives #14 and #12, due to resulting higher value and lower Cost$_{SC}$. Additionally, **alternative #8** is the one with the highest Cost$_{SC}$ due to the relatively high fixed and transportation cost, resulting from that supply chain (the TCs of the handle unit are produced and assembled by OEM whereas, the remaining TCs must be transported from TIER II_I to OEM for the final assembly – see Table 5-6). Thus, **alternative #5** might be a good solution for decision-makers as the decrease in value is negligible compared to the reduction in Cost$_{SC}$.

3. *Case Study III*

In this part the third CS is investigated and commented. Following the description of that particular CS, prioritisation must be given to Reliability and Risk$_{SC}$ KPIs, while, linear utility functions are assigned to all KPIs. As has been explained in CS II, the relative weights of those two KPIs resulting in 25%, as their importance is set to 2 instead of 1. All the remaining KPIs are weighted with 12.5%. The assigned linear utility functions as well as the weighting factors of every single KPI are demonstrated in Figure 5-7. The outcomes of this CS are compared to those resulting from the reference case study, as those ones have not been influenced, due to the fact that to all the KPIs equal weighting factors and linear utility functions are appointed. The value-cost trade-space that is obtained, according the principles of this CS III is illustrated in Figure 5-8. The six optimum alternatives of Case Study

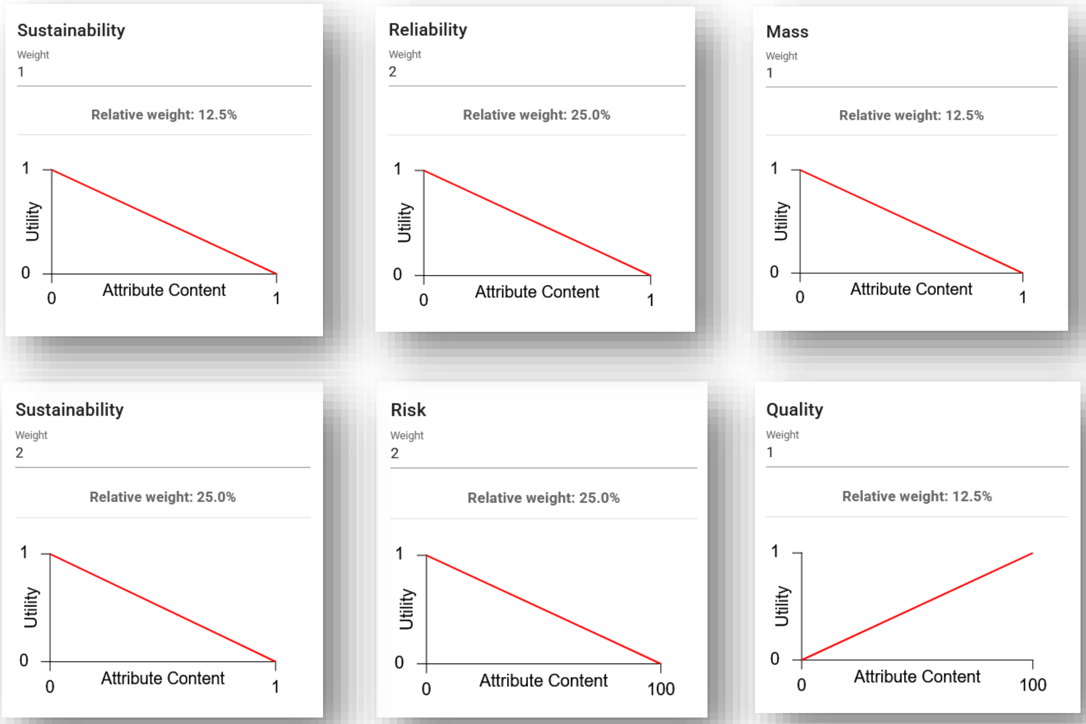


Figure 5-7 Demonstration of the assigned relative weights and utility functions to each one of the considered KPIs – Case Study III

III, are denoted by red dashed circles as well. In order to be able to compare them with those from the reference study, the outcomes of CS I are included in the shown chart as well. Comparing the outcomes of these tow case studies, it can be observed that **same alternatives** are comprised the region of high importance. However, based on the presented trade-space of the current case study, the associated value of each alternative is lower than the one obtaining by Case Study I, whereas the overall supply chain cost remains unchangeable. Thus, all the alternatives are shifted vertically.

The prioritisation of Reliability and $Risk_{SC}$ KPIs, means that **their utilities influence** the overall value **more** than the others. Table 5-8 reports the six optimum alternatives according to Case Study I and III. It is evidenced that, **none** of the alternatives representing the BLM are identified as one of the optimum, and consequently all of them represent the HSLM. Alternatives #33 and #39 have been replaced by **alternatives #5** and **#6.** The related supply chains of these alternatives(#33,#39,#5 and #6), are maintaining low supply chain risk, as during the production phase of the different TCs only **OEM, TIER I_I and TIER II_I** are involved (see Table 5-3 and Table 5-4). Based on table Table 3-32, these suppliers are demonstrating low fixed production risk, while in parallel, the transportation risks are comparatively low. So, as the overall supply chain risk does not significantly influence the results, consequently the difference lies on the Reliability KPI of each latching mechanism. Among the examined latching mechanisms, the HSLM is the most reliable one and thus by prioritising that KPI, the alternatives which are associated with that architecture are very likely to rise on top.

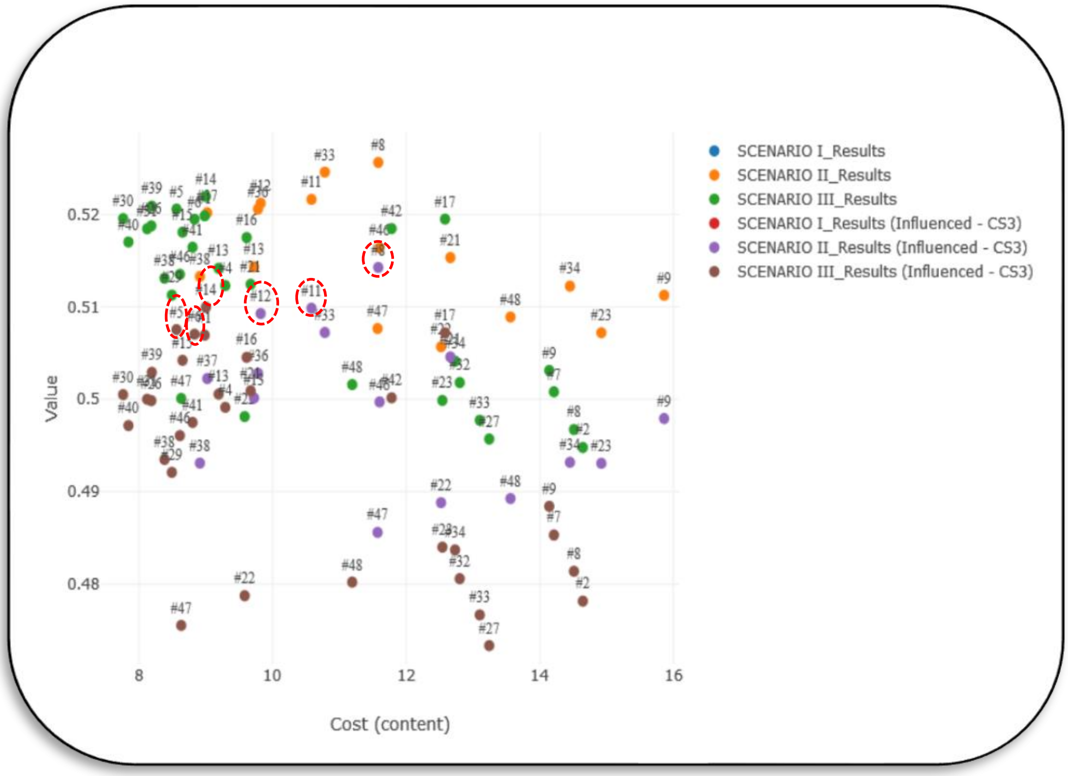


Figure 5-8 Illustration of the region associated with the alternatives that are of greatest importance according to Case Study III including the results obtained from Case Study I. The six optimum alternatives of Case Study III are denoted by red dashed circles.

Alternative	***Architecture***	***Value (0-1)***	***Cost$_{SC}$ (0-100)***	***Production/Assembly Scenario***
#8	HSLM	0.5257	11.6	Scenario II
#33	BLM	0.5246	10.8	Scenario II
#14	HSLM	0.5220	9.0	Scenario III
#11	HSLM	0.5217	10.6	Scenario II
#12	HSLM	0.5212	9.8	Scenario II
#39	BLM	0.5209	8.2	Scenario III
#8	HSLM	0.5143	11.6	Scenario II – CS III
#14	HSLM	0.5100	9.0	Scenario III – CS III
#11	HSLM	0.5099	10.6	Scenario II – CS III
#12	HSLM	0.5093	9.8	Scenario II – CS III
#5	HSLM	0.5076	8.6	Scenario III – CS III
#6	HSLM	0.5071	8.8	Scenario III – CS III

Table 5-8 Presentation of the six alternatives with the highest value, their respective Supply Chain Cost, the related production scenario as well as the associated Latching Mechanism - Case Study I and III

According to the generated trade-space and the provided data in Table 5-8, **alternative #8** can be highlighted as the optimum one. By a closer look, **alternative #14** could be a good selection as the best solution, because the decrease of the value compared with the cost reduction can be assumed ignorable. Additionally, **alternative #5**, might be also a sufficient selection for a decision-maker for the exact same reason.

4. Case Study IV

The last investigated CS is the one that Mass and Time$_{SC}$ are prioritised among the other KPIs. Each one of them is weighted with 25%, whereas all the remaining attributes are weighted with 12,5%. Based on the description of this fourth CS, all the reported tendencies (Table 5-2) are expressed by linear utility functions. Figure 5-9 demonstrates the different weights and utility functions of each KPI.

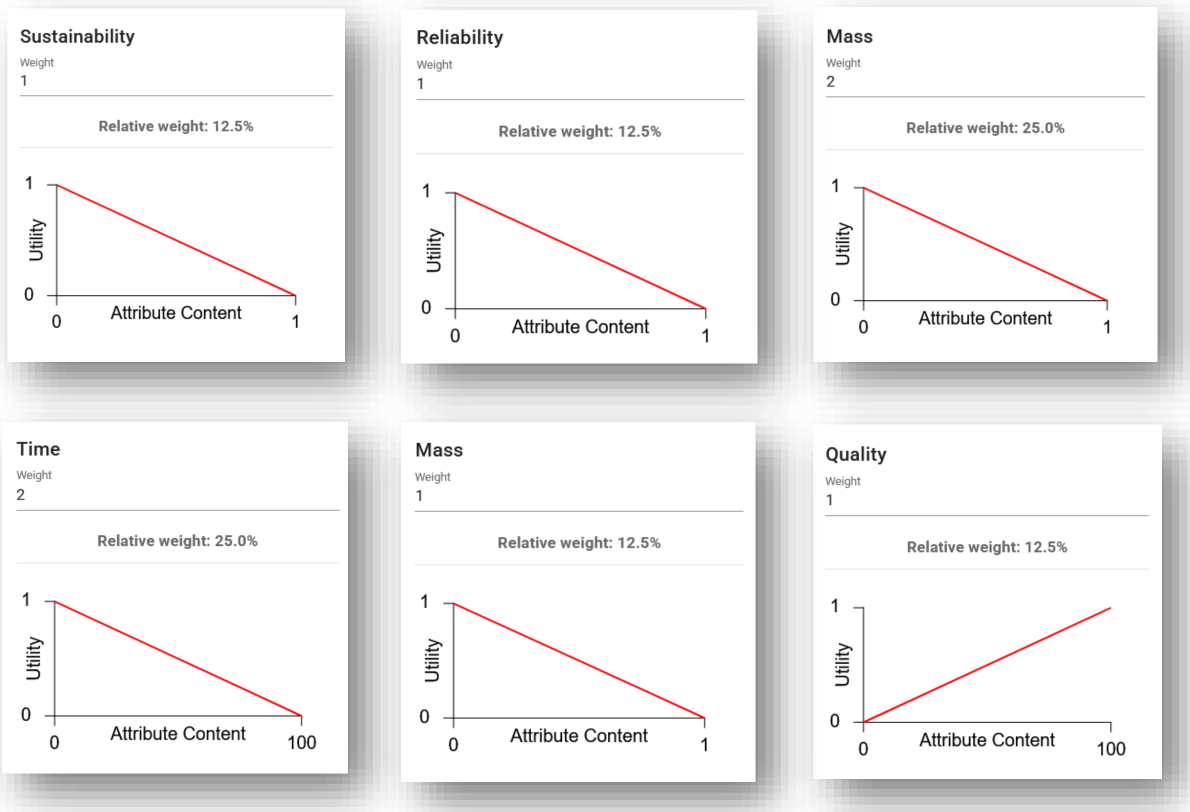


Figure 5-9 Demonstration of the assigned relative weights and utility functions to each one of the considered KPIs – Case Study IV

The derived value-cost trade-space, by applying the principles of Case Study IV, is depicted in Figure 5-10. During the explanation of the first CS, it has been stated that, only the **upper left** region is of high importance as the alternatives included there, are maintaining high value and low cost (1). Despite that, for the specific CS, the **upper left** and **lower left regions** are

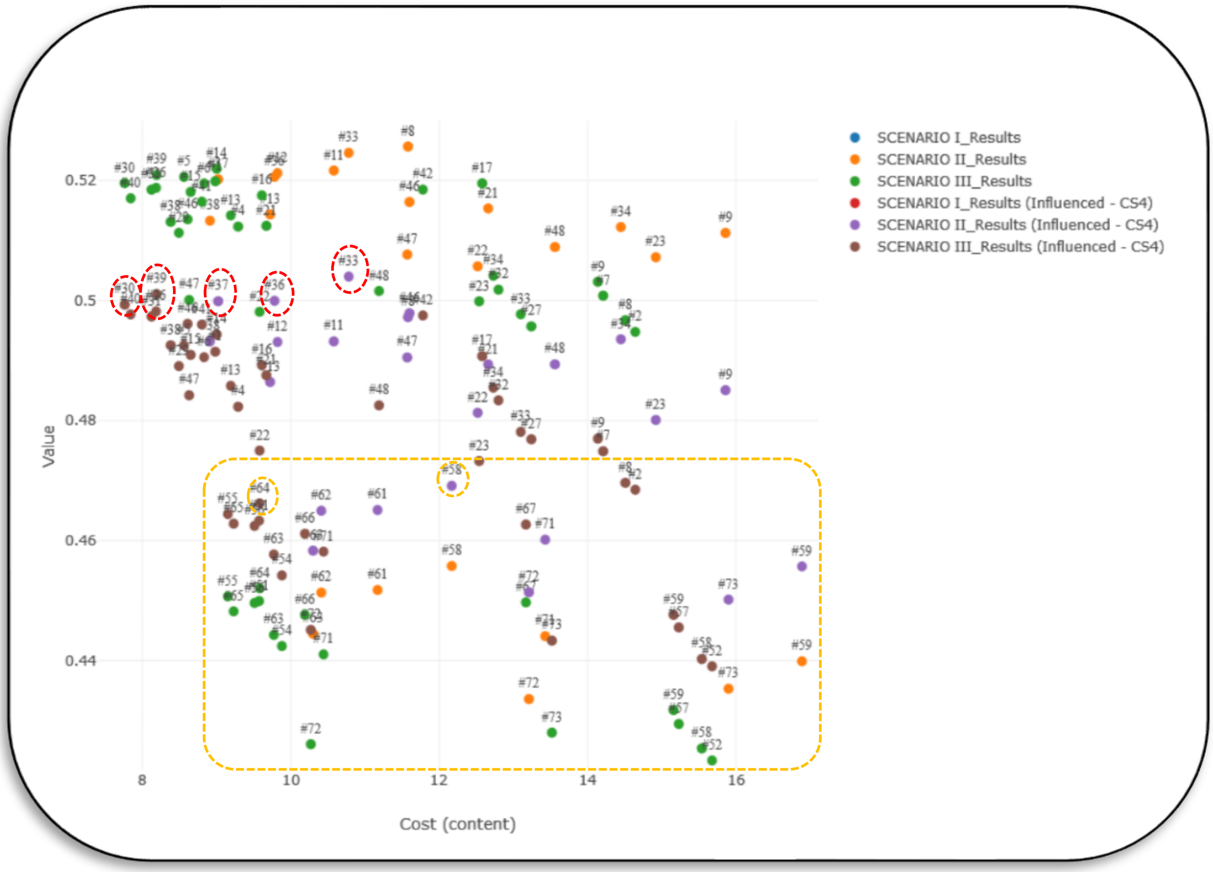


Figure 5-10 Illustration of the region associated with the alternatives that are of greatest importance according to Case Study IV including the results obtained from Case Study I. The six optimum alternatives of Case Study IV are denoted by red dashed circles.

illustrated. That aims to underline the significance of prioritising a specific attribute (KPI) while using the MAUT. The mentioned region is denoted by an orange dashed rectangle. All the alternatives contained in that region are associated with **CLM**. Additionally, the red dashed circles are highlighting the best alternatives according to Case Study IV.

As observed, by prioritising the Mass and $Time_{SC}$ KPIs, all the alternatives correlated with the HSLM and BLM are shifted down, whereas all those linked with CLM are displaced up. Based on provided data [2], CLM indicates the lowest overall mass among the examined architectural designs (Table 3-29). Despite all, the way that this particular CS is formed and according to the given relative weights to each KPI, all the alternatives related with the CLM are resulting in significantly lower overall value. Concerning the overall supply chain cost, it can be seen that some alternatives of that architecture are characterised by comparatively low cost. Concluding, if a decision-maker decides to assign a greater importance (more than 25%) or a different utility function (not linear) to Mass KPI, potentially, some alternatives such as #58 and #64 could be appeared in the region of high importance (high value and low cost).

Those alternatives are indicated by orange dashed circles in Figure 5-10 (detailed explanation about the region of high importance is given in the first case study (1)).

Table 5-9 shows the six alternatives that can be considered as the optimum ones, based on the generated trade-space for the current CS. In contrast with Case Study III, **none** of the reported as optimum alternatives are associated with HSLM. All the alternatives are related with the BLM. By inspecting the different supply chains of those six solutions, it is evidenced that mostly **TIER I_I** and **TIER II_I** suppliers are involved during the production stage of the different TCs (see Table 5-3 and Table 5-4). More specifically **TIER II_I** supplier, as indicated in Table 3-32, is the one with the **lowest fixed production time**. Thus, by prioritising the $Time_{SC}$ KPI, all the supply chains which are demonstrating low production time are expected to rise on top.

Alternative	*Architecture*	*Value (0-1)*	*$Cost_{SC}$ (0-100)*	*Production/Assembly Scenario*
#8	HSLM	0.5257	11.6	Scenario II
#33	BLM	0.5246	10.8	Scenario II
#14	HSLM	0.5220	9.0	Scenario III
#11	HSLM	0.5217	10.6	Scenario II
#12	HSLM	0.5212	9.8	Scenario II
#39	BLM	0.5209	8.2	Scenario III
#33	BLM	0.5040	10.8	Scenario II – CS IV
#39	BLM	0.5011	8.2	Scenario III – CS IV
#36	BLM	0.5000	9.8	Scenario II – CS IV
#37	BLM	0.4999	9.0	Scenario II – CS IV
#30	BLM	0.4993	7.8	Scenario III – CS IV
#26	BLM	0.4982	8.2	Scenario III – CS IV

Table 5-9 Presentation of the six alternatives with the highest value, their respective Supply Chain Cost, the related production scenario as well as the associated Latching Mechanism - Case Study I and IV

By observing the provided results, solely considering the value of each alternative, **alternative #33** must be considered as the best solution, as it is the one with the highest value. Nevertheless, by comparing alternatives #33 and #39, it is reasonable to identify **alterative #39** as the optimum solution, because the difference between their overall value can be assumed negligible, while the reduction in cost cannot. A different opinion could be, that as all the obtaining values are so close to each other, purely cost could characterise the optimum solution. Thus **alternative #30** should be the optimum, as its $Cost_{SC}$ stands out (greatly lower). Through this paragraph it is highlighted that based on the preference of the decision-maker, a different alternative may be identified as the optimum one.

6. Conclusions

This last Chapter of the thesis summarises the key conclusions derived from the study performed, reflecting on the efficiency of the framed methodology. More specifically, the most important findings, the answers of the formulated research questions as well as some suggested activities as future work, are presented.

6.1 Most Significant Findings

Based on the current analysis, one of the most important findings by following the proposed methodology, is that during the trade-off analyses, the different alternatives are almost always classified into four distinct regions. Thus, the region of high importance (the one that includes alternatives with high value and low supply chain cost) can easily be identified. Accordingly, decision-makers can focus on that specific region and perform trade-offs by influencing the considered KPIs according to their expectations.

In addition, as can be seen from the demonstrated results, by investigating different case studies, alternatives #8, #33, #14, #11, #12, and #5, tend to be in the optimum ones. The reported alternatives are associated with both HSLM and BLM architecture. On the other hand, CLM can be judged as the less efficient architecture as, in none of the examined case studies an alternative associated with that architecture is identified in the region of high importance.

Concerning the trade-off analyses, a significant conclusion that must be pointed out is that, different prioritisation of the examined KPIs leads to different value correlated with each alternative. Previously the CLM has been reported as the less efficient architecture, however, as can be seen by the fourth examined case study, by prioritising the Mass KPI all the values related with that architecture are shifted up due to the fact that, it is the one with the lowest mass, resulting to a higher contribution the overall value. According to other decision-makers' expectations (e.g. higher assigned weighting factor to that KPI or different assigned utility function) some of the alternatives might be appeared in the region of high importance based on the new generated trade-space.

6.2 Research Questions Discussion

At the closing of Chapter 2, some research questions have been formulated based on the purpose of the thesis, literature review and scientific gaps. This specific section aims to address those questions. Below, the reported research questions are provided with their answers.

- **How can a multi-criteria decision-making process among four different domains can be achieved and the best alternative for a latching system be identified?**

  By following the proposed methodology, it is shown that a multi-criteria decision-making process that incorporates aspects across four different domains (Sustainability, Reliability, Mass and Supply Chain Domains) is being achieved for a latching system. In addition, a structured way in how the best alternative can be identified is hereby outlined.

- **How can a trade-off among different latching systems be performed and the best solution be identified?**

  In the current methodology, 7 KPIs have been assessed for three latching mechanisms (HSLM, BLM and CLM) in order to perform trade-offs and identify the optimum alternative. As demonstrated, six of them are aggregated into a single value whereas the supply chain cost is treated as an independent variable. By implementing the MAUT in VALORISE, decision-maker has the ability to assign different weighting factors and utility functions to all the examined KPIs. By this, trade-off analyses can be performed in order to finally identify the best alternative. To this end, a specific region of high importance (including alternatives characterised by high value and low cost) is firstly investigated and later on, by trading the value and the supply chain cost of each alternative, the optimum solution can be identified.

- **How can sustainability and reliability KPIs be evaluated for a latching system?**

  This thesis introduces adapted evaluation methodologies specifically developed for assessing the sustainability and reliability KPIs of a latching mechanism. Each of these methodologies incorporates distinct analytical frameworks, reflecting the different principles and functions represented by the mentioned indicators. By explicitly specifying the relevant input variables and using adjusted equations, the described methodologies ensure that both sustainability and reliability KPIs of a latching mechanism, are measured and evaluate in a systematic way. The developed frameworks provide flexibility and adaptability, allowing them to be applied to similar systems across different domains.

- **How can a different production and assembly scenario be investigated and assessed?**

  This can be achieved by separating the latching mechanism into different sub units. In the present thesis, the handle unit of the latching mechanism, is treated as an independent unit. Thus, by following the description of the second or third production and assembly scenario, the resulting supply chain performance differs. If, a new sub unit is defined with its own technical components, a specific scenario can be defined, investigated and assessed, by involving specific suppliers during the production and assembly phase in a similar way as presented in this thesis. Additional way to address this research question, is to prefix the production suppliers for some selected technical components of the latching unit, e.g., “All the technical components of the handle unit must be always produced by TIER I_I”.

6.3 Further Activities and Steps

Finally, the present thesis concludes with some suggested steps, that are mentioned for future work purposes. The aim of this section is to demonstrate some improvements that can be examined and addressed in the future. As many further steps might be identified, to this end, only few of them are reported below.

- In the current methodology, Life Cycle Assessment methodology has been employed in order to evaluate the overall Sustainability KPI of the latching mechanisms. That is an efficient methodology that concentrate mainly on assessing the environmental impact of a system (a latching system in current application) throughout its entire life cycle. However, it considers aspects related only with the environmental pillar. To this end, in order to perform a more comprehensive estimation of the overall Sustainability KPI, the principles of the Holistic Sustainability are suggested to be adopted. By that, aspects across the Society, Economy, Performance and Circular Economy pillars will be integrated, resulting to a more well-rounded assessment.
- Concerning the Supply Chain Domain, during the evaluation process of the different Supply Chain KPIs (Cost, Time, Risk and Quality) of each selected supply chain, two terms are taken into consideration: Fixed and Transportation. It would be useful if a third term could be included called manufacturing, describing the manufacturing aspects (i.e. manufacturing cost, time, risk and quality). That term will integrate critical and significant information in the overall performance of a specific supply chain, resulting into a more precise analysis.
- All the examined supply chains have been randomly chosen and generated. Based on those supply chains, the optimum alternatives of each examined case study have been identified. By generating only some possible combinations, it is not guaranteed that the optimum solution will be included in those ones. However, as there are lots of

unexamined supply chains, optimisation algorithms could be implemented in order to generate all the possible combinations and later on the optimum solution to be identified.

- Regarding the trade-off analyses, some case studies have been investigated in order to perform decision-making and identify the best alternative. In order to conduct a sensitivity analysis more combinations of different weighting factors and utility functions must be examined.

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