

Facilitating Quick Change Introduction for Aircraft Interiors Product

Utilizing DSM-Based Risk Change Analysis and Clustering Technique

Master's thesis in Mobility Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

MASTER'S THESIS 2023

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Master's Thesis 2023
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Cover: Part of the new product structure for modular design of stowage. Module one and module two are visible. Interface between modules identified as interaction between structure assembly and hinges is marked with blue arrow.

Typeset in L^AT_EX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

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Abstract

This thesis shows how a Design Structure Matrix can support the re-design process of an aircraft cabin interior component - stowage. It presents an approach to identifying challenges of design change introduction in aircraft products and demonstrates how a modular product design can address them. First, the stowage was modeled with a DSM and a risk analysis was performed on the baseline design. Specific stages of the Change Prediction Method (Clarkson et al., 2001) were used to evaluate interfaces between product components in different design domains. Furthermore, DSM served as an input for clustering operations, which were a foundation for modular stowage design. As a result, a modular product architecture was created including new re-designed interfaces. The results show that the modular design approach can reduce the risk of change while increasing product customization and the number of configuration alternatives.

Keywords: Design Structure Matrix (DSM), Change Prediction Method (CPM), Change Risk Analysis, Modular Design, Product Architecture, Interface, Clustering

Acknowledgements

I would like to express my deepest gratitude to my supervisor, Alejandro Pradas Gómez, and my examiner Lars Lindkvist from Chalmers University of Technology. Their invaluable guidance and support throughout the entire process allowed me to successfully complete this master's thesis and expand my knowledge in the product development field. Their expertise and insightful feedback have been essential in shaping the direction and quality of this research. I am truly grateful for their commitment to my success.

Furthermore, I would like to express my gratitude to my supervisor Fabio Dias Almeida from Heart Aerospace as well as all the individuals at the company who contributed to the research study by sharing their experiences and providing valuable data. Their knowledge has been invaluable in conducting this research and enriching its findings. It has been an incredible opportunity to work with such an experienced group of engineers and be a part of the Heart Aerospace team.

Lastly, I would like to acknowledge the support of my family throughout my academic journey. Their encouragement and constant belief in my abilities kept me motivated during challenging times. I am truly grateful that I can have such amazing people around me and I will carry their influence and support with me in my future endeavors.

Thank you all.

Klaudia Zambrzycka, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BOM	Bill of Materials
CPA	Change Propagation Analysis
CPM	Change Prediction Method
DSM	Design Structure Matrix
ICI	Incoming Change Impact
ICL	Incoming Change Likelihood
LOPA	Layout Passenger Arrangement
MDM	Multiple-Domain Matrix
OCR	Outgoing Change Risk
PN	Part Number
PLM	Product Lifecycle Management

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1

Introduction

The following chapter will cover the thesis background and define the aim of the project. Research questions will be clearly stated followed by limitations encountered during work. In the end, a detailed thesis outline will be specified.

1.1 Background

Paris Agreement from 2015 states that to mitigate impacts of climate change global temperature increase needs to be limited to 1.5°C above pre-industrial levels. In order to reach those targets, greenhouse gas emissions need to be reduced by 45% by 2030 and reach net zero by 2050. [2] According to research performed by Hannah Ritchie [3] transport sector is responsible for 24% of global CO_2 emissions (status for 2018), while aviation creates 11.6% of the emissions taking into consideration 4 different transport branches and freight transport. Companies and Countries are constantly working on new technologies and solutions that will allow them to reach Paris targets, significantly slow down climate change and stay competitive in the market at the same time.

Electrification has become essential for decarbonizing the industry and many investments are realized to support this trend. The aviation sector tends to be the most challenging to introduce battery technology, due to high energy density requirements and a need for airport infrastructure transformation. Applying electrification to the aviation industry appears to be a global challenge.

Heart Aerospace is a start-up company located at S ave Airport in Gothenburg, Sweden. Its founders recognized the climate issue that the industry is facing and discovered a market for introducing electric regional aircraft. The company is expanding at a rapid pace, gathering experts from all over the world to build the most sustainable and affordable means of transportation.

Heart Aerospace answers to this challenge by developing ES-30 which is an electric passenger aircraft that can accommodate up to 34 passengers. The innovative technology introduced with this new solution is the propulsion system. It is a combination of 4 electric motors and 2 reserve hybrid turbogenerators. This configuration allows the aircraft to deliver a full electric range of 200km and an electric + hybrid range up to 400km [4] fulfilling the EASA [5] and FAA [6] airworthiness requirements. The project is reaching the preliminary design stage and the company aims

to certify and introduce the aircraft into service by 2028. The structures and Interiors department is constantly working on delivering detailed design requirements, analyzing every aspect of the aircraft structure, and deciding on specific features. Those requirements are prepared based on extensive type certification prerequisites and possible customer demands. The output of the ongoing work will facilitate the suppliers selection process. Additionally, it will help the team to proceed with the system-level design phase, and launch the production of the aircraft.

At this stage of the project, another important aspect has to be taken into consideration. Change of the product is an integral part of its lifecycle and a robust change process has to be defined at the early stage of the product development. Product change can be driven by motives defined by [7] such as: new technologies and innovations, manufacturing improvements, supplier changes, quality issues, and customer order-specific changes. Nowadays, customers expect increasing customization of products that can be tailored according to their needs. Industries offer a high variety of choices ensuring quick processing of orders while reducing their internal development and manufacturing costs. Despite the fact that the aerospace industry differs from other sectors with the complexity of the product, airworthiness requirements, and production volumes, it has to follow market trends and offer customization possibilities. Customer needs can be considered the main driver for change introduction into the design and product structure.

In terms of aircraft cabin interiors, creating a new design for each client would lead to a significant amount of time consumption and high costs related to certifying the new cabin configuration and revising the relevant documentation. According to the engineering team working at Heart Aerospace and their broad industry experience, such a change process can take up to 6 months considering only requirements update, re-design, and certification. The challenge for aerospace companies is to reduce this time as much as possible by various means of automation introduced at any stage of the design process. It calls for identifying the weak points of the process and defining improvement opportunities.

One of the solutions introduced by various industries is the modular product architecture described by K. Ulrich in [8]. The main idea behind modularization is to create a product in which each functional element is implemented by one physical element connected by well-defined interfaces [9]. According to the author, such an approach is essential for a quick change introduction to the defined product. Deciding on product architecture and the level of modularity is crucial for the entire company and impacts the whole product lifecycle.

1.2 Aim of the thesis

The aim of the thesis is to identify weak points and issues that extend the time of design change implementation and expand its scope. Additionally, the thesis will aim to demonstrate that the modular product architecture can:

- reduce the number of documents that need to be created or revised,

- increase variability and customization of the product,
- simplify a configuration change introduction to design and PLM system.

1.3 Research Questions

The general aim of the thesis will be focused on answering the following research questions:

1. What are the issues that the designers are facing when introducing an aircraft cabin interior design change?
2. Can the modular product architecture facilitate the configuration change introduction?

1.4 Limitations

Heart Aerospace company is in the early stage of development and expansion. It means that a limited amount of processes and systems are in place. The product structure is currently being defined by the product management team and many high-level decisions are being taken. Detail design is also a work in progress. The final configuration of the aircraft interior and LOPA (Layout Passenger Arrangement) is not yet confirmed. All those aspects make it challenging to clearly define current customer requirements, design, and certification processes established in the company, which could be a base for the research and investigation of improvements and time savings. The thesis inputs will be based on the extensive experience of people working in different departments and observation of ongoing works.

1.5 Thesis outline

The thesis consists of five chapters. In this chapter background and research questions are presented. Next, the literature review is summarized describing the related work in the field. In the third chapter methodology used in this paper is demonstrated starting with a change risk analysis outline, followed by a clustering application and redesign process. In the end, the results of the performed work are shown and conclusions are discussed in the final chapter.

2

Literature review

In the following chapter previous work in the field of change propagation and modular design will be considered. At the beginning broad literature review will be performed demonstrating methods used by researchers to facilitate change process analysis. Later, a concept of modular product architecture and modular design process will be presented. It will describe how such an approach can facilitate change introduction and increase the variety of the product. In the end, benefits recognized previously by researchers in this field will be summarized.

2.1 Change propagation

Change is an integral part of engineering design. Many researchers and industry engineers recognized the importance of change management, as it has a direct effect on redesign time and product cost. Identifying the need for change early in the design process and understanding the interfaces existing between different product domains is crucial in reducing the change impact [10].

As mentioned before, product change can be driven by motives well summarized by Gullander [7] such as: new technologies and innovations, manufacturing improvements, supplier changes, quality issues, and customer order-specific changes. Regardless of the source, a key aspect of the design change is that it propagates [15]. Eckert, Clarkson, and Zanker defined change propagation as a change to one part of an existing complex system resulting in multiple changes to the entire system [16].

Many approaches were created to analyze change propagation and model dependencies between product components in different domains, supporting the change management process. They were well summarized by Brahma and Wynn [15]. Their paper gives a detailed overview of previous work in the field and analyses the theory behind change propagation. They prepared an extensive list of design domains that might be involved in change propagation, outlined aspects that have a significant impact on it, and pointed out use cases for change propagation analysis (CPA). Compiled methods to gather and organize inputs, process data and visualize the results of CPA were demonstrated in their work. Based on this comprehensive report suitable methods to perform a change propagation analysis in this paper were chosen. It also became a great source of references for further research and deeper investigation of proposed approaches.

The main idea for the change risk analysis was built on the work of Clarkson, Simons, and Eckert [10]. They investigated the change behavior using a case study of a complex rotorcraft design. By developing a model of this system, they were able to predict a change risk utilizing concepts of likelihood and impact. Inputs for the CPA were represented using Design Structure Matrix (DSM). The product was first divided into subsystems with the help of experienced managers and engineers familiar with the design. Then those subsystems were combined into the DSM, which allowed for the assessment of dependencies and change relationships between components. For each interaction likelihood and impact of change were specified. The authors defined likelihood as the average probability that a change in the design of one subsystem will lead to a design change in another by propagation across their common interfaces. Likewise, the impact was defined as the average proportion of the design work that will need to be redone if the change propagates [10]. Those two values combined give a direct risk of a specific design change. Such analysis can deliver useful information about the design dependencies within the product and highlight weak interfaces, not susceptible to change.

It is worth noting that Clarkson, Simons, and Eckert go a step further in their work and consider a predictive model including not only a direct change risk but also propagation of change to other subsystems resulting in indirect risk. However, this paper will be limited to the notion of direct risk, since it was presented as sufficient by the case-by-case analysis performed in previous work [10]. Performing change prediction method (CPM) utilizing software tool developed by Clarkson, Simons, and Eckert can be an idea for future work in this field. Data achieved through direct risk assessment are tailored to act as inputs for the CPM approach proposed by the authors.

The change analysis process presented in this report was further supported by methods outlined by Koh, Caldwell, and Clarkson. Their paper focuses on change propagation effects on product attributes during the design of complex products and shows a modelling method that allows for assessing those effects [17]. Authors extend the work presented in the previous paper [10] and introduce a concept of analyzing the product interfaces (here a jet engine fan) in terms of different design domains: requirements, change options, and product components. This analysis is facilitated by Multiple-Domain Matrix (MDM), which is a square matrix modelling dependencies within and between different domains. Each dependency is rated according to interviews with product experts and historic data gathered in the company database. Following the CPM approach and using a calculation method introduced by the authors, the change option best fulfilling product requirements can be derived. This approach justifies a multi-domain analysis as feasible and sufficient to achieve valid information about change propagation between interfaces within different design aspects. This notion was used during change analysis in this paper and will be described in detail in section 3.2.

Cheng and Chu presented a quantitative approach performing an assessment of three indices: degree-changeability, reach-changeability, and between-changeability [18]. They used a network concept to visualize interfaces between product compo-

nents and created a rating scale to assess the dependencies between them. Using this rating system they were able to assign a value between 0 and 9 for each relationship evaluating its sensitivity to change. A similar approach to chose a suitable dependency rating system was undertaken in this report and will be in detail explained in section 3.2. Cheng and Chu in their work stressed the importance of impact assessment for change propagation as a way to create cost-efficient designs and assign resources in a robust manner.

Koh, Caldwell, and Clarkson analyzed the changeability of design systems to identify which of them can be made more changeable in order to address constantly changing market requirements [19]. They followed previously presented techniques, dividing the product into components and combining dependencies in DSM. They performed the relationships rating assessment and executed the extended CPM process including not only propagated changes but also planned changes. To be able to analyze the results and identify product sensitivity to change, they introduced three indices: incoming change likelihood (ICL), incoming change impact (ICI), and outgoing change risk (OCR). ICL describes the possibility of component change due to other changes, ICI defines the consequences of changing a system due to other changes, and OCR shows the scale of how one system will affect other systems when changed. All three of them are calculated as an average of ratings assigned for each identified relationship. This method allows to place the components on the change risk graph and visualize the specific system's ability to change and the impact of this change. It facilitates verifying if the component is suitable for standardization, product platform, or if a change of this system should be entirely avoided. The method shown in this report was based on a similar approach and was ground to decide which product components should be further investigated in terms of modular design. Detailed methodology and calculations performed will be presented in section 3.2.

2.2 Modular design

Modular product architecture can be considered as a solution for challenges outlined through change process analysis shown in section 4.1. This concept became a research subject investigated by several scholars. Ulrich defined product architecture as a scheme by which product functions are allocated to the physical components. According to the author, modular product architecture includes one-to-one mapping from functional to physical elements and specifies decoupled interfaces between components, allowing for specific component change independently from surrounding components [8]. Sanchez and Mahoney expanded the definition of modularity as a form of design that intentionally creates a high degree of independence between components by standardizing the interfaces [14]. Modular product architecture divides product structure into modules which were defined by Hölttä as structurally independent building blocks of a larger system with well-defined interfaces [23]. The specification of modular architecture indicates that it could be essential for building an efficient product development process and designing for change approach. Applying the modularity concept could facilitate identifying design solutions that

absorb possible product changes and decrease the redesign efforts to a minimum. Modularity emerged as an answer to issues distinguished by change process analysis.

2.2.1 Modular architecture benefits

Researchers in their previous work listed numerous benefits of choosing modular architecture for one's product. Ulrich thoroughly investigated a broad range of product development and lifecycle aspects that could gain from modularization [8]. Other authors such as Bonvoisin et. al [24], Hölltä [23] as well as Sanchez and Sudharashan [27] presented advantages of modular design that fit into the categories proposed by Ulrich. Five areas were determined: product change, product variety, product performance, design, and company organization.

Modular products allow product components to be changed independently by changing only the component realizing the desired function. Such product structure facilitates localizing required change to the minimum possible number of components [8]. Due to well-designed interfaces and modularity on the level of the entire system, the introduction of product change can be efficient both in time and design effort. Modular design is essential in the case of real-time market research introduced by Sanchez and Sudharashan [27]. It enables developing and adjusting the product quickly, by analyzing the response of the market to the newly launched product.

Moreover, product variety is influenced by the modular design choice. According to Ericsson and Erixon, modularity is one common way of providing a flexibility that enables product variations and technology development without changes to the overall design [26]. Ulrich cites Upton's definition of flexibility as: "... the ability to change or adapt with little effort, time, or penalty" [25]. The level of product variety is usually connected to the ease of adapting the manufacturing tools and processes to constantly changing products. However, Ulrich argues that the flexibility of product structure realized by modular architecture is as much important to achieve economic benefits from product variety [8].

Additionally, modular product structure has a positive impact on product performance which was defined as how well the product implements its functional elements to fulfill such characteristics as speed, efficiency, life, or noise[8]. Modularity allows for local optimization of product performance by using standard components that can be upgraded or redesigned quickly. It also enables refining and testing the modules in a more focused way without affecting or involving other functional components and interfaces. All of that leads to an increase in component performance, hence in advance of overall product performance [8].

In terms of design operations modular product architecture enables developing the product modules almost independently and in parallel [8]. One product can be created by various manufacturers simultaneously, provided communication channels between each development team are well-defined and efficiently managed. Furthermore, Bonvoisin et.al [24] described breaking down product complexity as a means

to reduce development time by allowing parallel design which leads to shorter time-to-market and reduced costs.

The benefits of the modular design approach are also visible in terms of company organization and product development management aspects. Highly modular designs allow to create focus groups by dividing development and production organizations [8]. Once the interface complexity is reduced, the distribution of design tasks becomes more efficient, and communication between teams develops into a more direct and undisturbed process[24]. It results in effective resource management and consequently a cost reduction.

It is worth noting that the modular architecture approach might require a better functioning system engineering team within the organization and well-developed planning skills [8]. Due to the specification of the modular product, narrow-focused groups have to communicate with each other and consider the whole system requirements and overall project objective. Such an approach requires good management practices as well as effective tools and team-building skills. Taking into consideration previously mentioned arguments, designers and product structure managers should aim to develop modular products, however, in most cases a balance between fully modular and fully integral products will be achieved.

3

Methodology

The following chapter will describe the methodology developed in this thesis. It consists of three parts: change process analysis, clustering, and redesign process. Each step will be presented in detail, starting with the objectives and methodology used for change analysis. Later, the application of the clustering method to a product architecture as a base for modular design operations will be demonstrated. In the end, the outline of the redesign process will be summarized.

3.1 Change analysis objectives

The cabin interior team at Heart Aerospace identified a need to improve the configuration change process as product customization became a common customer requirement in the modern market. Each airline has its specific color pallet and defined interior design options. Additionally, nowadays aircraft are often operating in terms of leasing contracts, and the cabin interior has to be reconfigured quickly and frequently. The ability to instantly conform to client requirements is a crucial asset for the company and allows it to follow the trends while staying competitive in the market.

However, a cabin interior change can be a very complex and time-consuming task. Modification of one component can have an impact on the entire aircraft's interiors and surrounding subsystems. It is also associated with testing and re-certification of a significant part of the product to fulfill airworthiness requirements. Due to those reasons, a robust method to configure and customize the interior cabin and its components have to be introduced.

In order to increase cabin changeability an assessment of product sensitivity to change has to be performed. Change propagation analysis becomes very useful in this case. The main objective of this procedure is to place product components on a change risk graph and map them according to their sensitivity to change and carried change impact. Such assessment can provide the engineering team with recommendations for their design architecture. It can define the strong relationships between product components in different domains and show high-risk interfaces that can be improved by design for change concepts such as standardization, modular design, or product platforms. Pointing out the dependencies with high change risk can justify a need for allocating more resources to redesign the product, so it would absorb future changes and allow for customization. According to Clarkson et al. [10] sub-

systems that are less likely to change are recommended for standardization, while components highly possible to change and affecting many other subsystems might be considered for early certification of different options or avoiding the change entirely. As a result of such analysis, a wider range of options can be determined and offered to customers. Additionally, a well-investigated change process at the early design stage can help mitigate high non-predicted costs and support important business decisions related to product structure.

For the purpose of this thesis, a change propagation analysis was performed resulting in a map of direct change risk for a given product. The aim was to determine which components should have been designed in accordance with the modularity concept. A secondary objective was to visualize the number of documents, tests, reports, and quantity of components that need to be revised or created when carrying out a specified change option. That information can facilitate the comparison and validation of new design solutions proposed in the further part of the study. An outline of the results is shown in section 4.1.

3.2 Change analysis methodology

The methodology developed to assess the risk of component change was built on previous work summarized in section 2.1. Input data were populated in DSMs and MDM. Multiple interviews with engineers and managers in respective fields helped generate the information needed for the analysis. The results were summarized in a risk graph. The following section describes step by step analysis process and demonstrates the decision process undertaken during work together with the assumptions made. It shows utilized calculation techniques and data population methods.

Due to the limited time for preparing the thesis, one product from the cabin interior was chosen for the analysis. Following the recommendations from design engineers working in the Interior Department, cabin stowage was selected for examination. This product had significant advantages that made it a suitable sample for investigation. First of all, it acts as one of the configuration options for the cabin interiors and is selectable by the customer. Moreover, it can be considered a highly configurable product in terms of geometry, color, material, and add-on features. Additionally, it demonstrates well the interfaces with components in different design domains, for example, affected documents and required tests. Even though it is a simple product with an uncomplicated structure compared to other interior systems, it includes all the necessary aspects needed for analysis and could have been examined in a reasonable amount of time.

3.2.1 Stowage

Stowage is a cabinet used to store luggage, clothes, or any equipment needed by the crew during the flight. It is usually placed in the front of the passenger cabin of an aircraft. It comes in different versions, varying in size, color, and add-on features. Due to the fact that the company does not have the design of a stowage ready at

this stage of the project, an example of stowage installed in the aircraft proposed by Diehl Aviation is visible in fig. 3.1. Further analysis was based on the structure of the presented stowage since Heart Aerospace will use a similar solution for its final design. The product structure built on this stowage example will be shown in fig.3.2 in section 3.2.2.1.



Figure 3.1: Different versions of stowage proposed by Diehl Aviation. Renderings retrieved from <https://www.diehl.com/aviation-highlights/en/cabin-highlights/fast-available-stowage/>.

3.2.2 Product division

In order to create inputs for change propagation analysis, the examined design domains had to be first defined. Structured interviews with design engineers supported this process as they were able to identify design aspects that could be affected by changes to stowage features. In accordance with their previous experience, the following areas were recommended as highly affected during product modifications:

- product components,
- documents such as 3D models, technical drawings, material specifications, diagrams,
- test and inspection reports,
- tests: flammability, static, stress,
- PLM system functions and product structure.

The next step was to divide each of those design domains into subsystems in order to populate respective DSMs. The theory behind Design Structure Matrices was well presented first by Eppinger, Whitney, Smith, and Gebala [20],[21] and then referenced by Clarkson et al.[10]. DSMs can provide information about how

change propagates between product components and help identify relationships between parts of the product or design tasks. Each matrix cell contains a numerical or binary representation of the link between one subsystem (column) and another subsystem (row). Components inserted in columns are treated as change initiating and components in rows are affected by change. This notion was applied in the analysis of interactions within the design domains listed above.

3.2.2.1 Product DSM

The product components matrix was built based on the stowage product structure shown in fig. 3.2

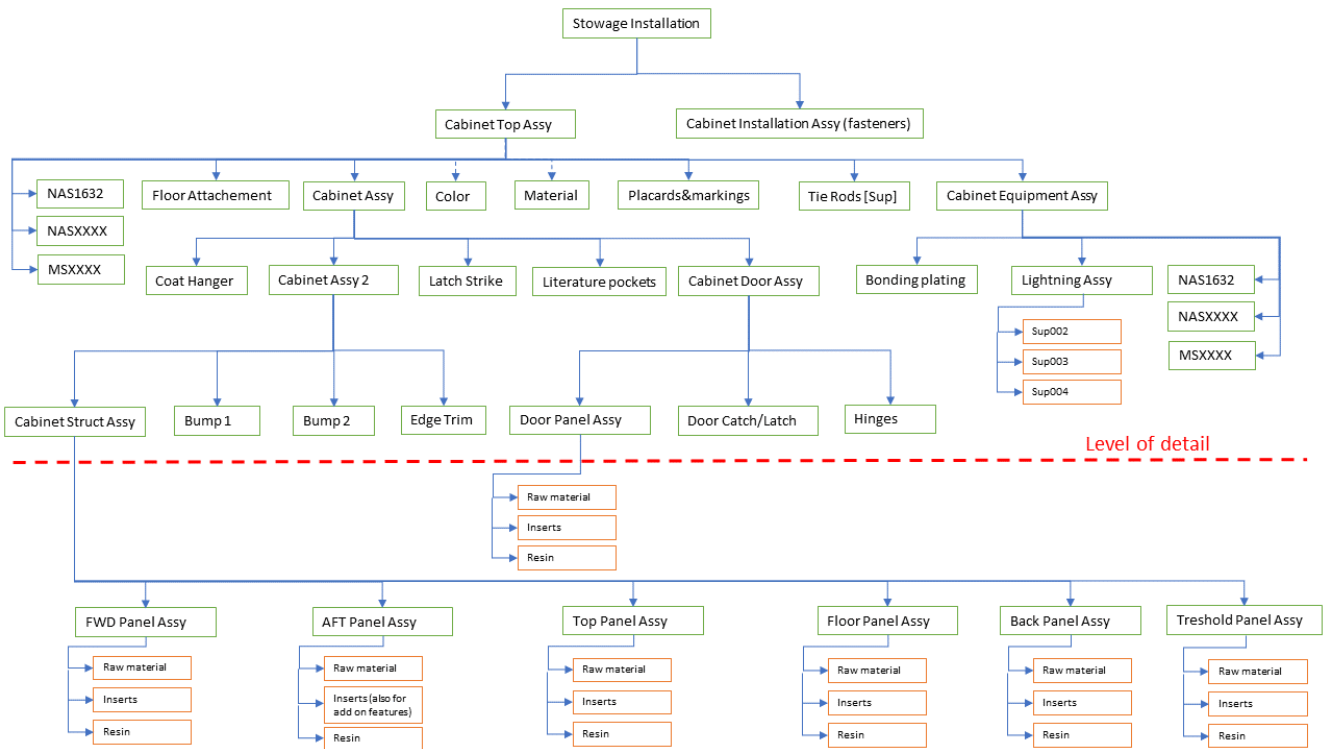


Figure 3.2: Baseline stowage product structure.

According to Cheng and Chu the granularity of decomposition has a significant impact on assessment quality [18]. The level of stowage structure assembly and door panel assembly in the product tree was chosen as a suitable division degree. Considering the lower level of the product structure would require breaking down the stowage structure assembly into six individual panels and analyzing interfaces between each of them separately. Since those relationships were highly dependent and would generate many similar dependencies, structure assembly was treated as one component. As a result, the product structure matrix became a square matrix with 18 rows and 18 columns representing each studied subsystem 3.3.

Dependency		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Structure assembly	1	X			X	X		X	X	X	X	X	X	X	X	X	X	X	X
Door panel assembly	2	X	X	X	X	X									X	X	X		X
Door catch/latch	3	X																	X
Door hinges	4	X																	X
Latch strike	5	X	X																X
Bump 1	6	X	X																X
Bump 2	7	X																	X
Edge Trim	8	X																	X
Coat hanger	9	X																	X
Light assembly	10	X																	X
Tie rods	11	X																	X
Floor attachment	12	X												X					X
Installation fasteners	13	X											X						X
Color (Finishing)	14														X			X	X
Material	15													X				X	X
Placards&markings	16	X	X						X	X				X	X				X
Literature pockets	17													X	X				X
Bolts/rivets/bonding	18	X	X		X	X	X	X	X	X	X	X	X	X			X	X	

Figure 3.3: Product DSM.

3.2.2.2 Documents and tests DSM

Documents, tests, and reports were treated with a similar approach. A list of documents affected by changes in stowage components as well as a list of reports and tests that would need to be performed in case of product modification were submitted by engineers, based on their experience and wide knowledge of the field. Each possibly impacted document or test was inserted into the matrix row and combined with product components placed in columns. Since documents and tests would be only considered as affected systems and would not be a cause of change, they were inserted into matrix rows. It is worth emphasizing that those DSMs were not square matrices and allowed inputs in the diagonal cells, due to the fact that the number of documents and tests affected could have been different than the number of identified product components.

3.2.2.3 PLM and product structure DSM

A separate matrix was created to assess the dependencies between product components and PLM functions affected by a change to one of them. Three functions were indicated by the manager familiar with the field: part number re-identification, customer options, and product structure. Part number re-identification was recommended since with every change of product component a part number change is needed. Only revising the component was also recognized, but the worst-case scenario was taken into consideration to include the dependencies with the highest risk in the total risk assessment. Since it was impossible to distinguish in the DSM matrix if the part number will have to be only revised or re-identified, the latter function was evaluated. Furthermore, customer options and product structure are visualized and managed in the PLM system in the form of a breakdown tree including product parts. Product structure is a 150% Bill of Material (BOM) and configuration options are parts organized in a selectable way for the customer. Both of those functions were indicated as affected when changing product components and populated in the matrix. Similarly to previous DSMs, this matrix was not square and allowed for inputs in diagonal cells.

3.2.3 Dependencies assessment

Having matrices for all design domains populated with subsystems, direct interfaces between elements listed in rows and columns could have been identified. This method followed the notion of initiating and affected components. Each cell was marked with an "X" in case the change of the part in the respective column would affect the part in the respective row. It is worth noting that the product matrix was the only square matrix, hence only the off-diagonal cells were filled in, due to the fact that one component cannot affect itself when changed. As a result of this procedure, four dependency matrices were created visualizing direct interactions between subsystems in different design domains.

3.2.4 Likelihood and impact

Likelihood and impact were defined as universal criteria to assess the direct risk of product change, which is a quantified result of specific product modification. This concept followed the approach proposed by Clarkson et al. [10]. As cited before, according to the authors, likelihood is a possibility that the change of one component will propagate to the other component through common interfaces, while the impact is the amount of redesign work that needs to be done when change propagates [10]. Both of those indices were assigned a value according to chosen scale, which will be discussed in sections 3.2.4.1 and 3.2.4.2. Each interaction indicated through dependency assessment was evaluated in terms of likelihood and impact and new matrices with numerical inputs were created for each design domain. The product of likelihood and impact matrices resulted in a direct change risk matrix showing rated relationships between components. This approach supported identifying changes and interfaces with the highest risk.

As mentioned in section 2.1, methodology proposed by Clarkson, Simons and Eckert [10] included also analysis of predicted change, which models change using a propagation tree and calculate combined risk, combined likelihood, and combined impact. However, in this report, only the direct risk was taken into consideration due to time limitations and the fact that change analysis was not the main concern of this thesis. It served as a way to gather data and inputs for modular design solutions. Applying CPM software to support cabin interior design can be considered a future research area.

3.2.4.1 Likelihood scale

A scale to assign a value for each relationship between components in order to assess change likelihood had to be defined and kept consistent within all design domains. Two criteria were selected to evaluate the likelihood of a change of one component when the other is modified: interface complexity and historical data. Martin and Ishii [22] proposed that the stronger the coupling between parts, the more likely a change in one will cause a change in the other. The interface complexity index was chosen as a way to measure the degree of coupling between subsystems.

Four different levels of complexity were proposed. Each of those was assigned a number on a scale from 0 to 1. Levels were described for easier assessment and presented in table 3.1

Table 3.1: Interface complexity levels.

Complexity	Value
few and simple	0.3
few and complex	0.7
many and simple	0.8
many and complex	1.0

"Few and complex" interfaces were scaled similarly to "many and simple" interfaces due to the assumption that this complexity level could cause a change to propagate with comparable possibility. However, those two coupling degrees were still distinguished to broaden the range for evaluation and make the assessment of likelihood more detailed and exact. The interior design engineer was asked to classify each dependency and assign a suitable number according to his past experience and knowledge of the field.

The second selected criterion was historical data. The possibility that the change would propagate was evaluated based on the number of times a component changed during the product lifecycle. The assessment was performed using a scale from 0 to 1 shown in table 3.2.

Table 3.2: Number of component changes during product lifecycle

Historical data	Value
0-5 times	0.2
6-12 times	0.5
13-25 times	1.0

Again an expert in the field was asked to perform the evaluation. Each subsystem was classified and assigned a suitable value, in contrast to interfaces assessment, where dependencies between components were evaluated. Owing to this, fewer data had to be populated and classified, assessment became more time efficient and gathered data could have been applied to analyze the likelihood in all design domains. Due to the fact that each initiating component was provided with a number of past changes, it was assumed that the change will propagate to the affected component with the same frequency.

To achieve the total likelihood of change the weighted average of interface complexity and historical data indices was calculated. The historical data index was assigned a weight of 2, since it featured as a more direct representation of change possibility, while interface complexity is a more abstract concept.

It is worth noting that interface complexity assessment for documents, tests, and

reports was a two-step procedure. The difference between those three domains was that it was particularly complicated to assess the complexity between subsystems from different areas. In order to retain consistency in scale, additional criteria were selected and each subsystem was assigned a 0 or 1 value. For documents and reports the length of the document, the availability of a good system to revise it, and the number of people approving it was evaluated. For tests, the criteria were defined as clarity of procedure instructions, equipment needed, and the possibility to fail and retake the test. The results were summed and a number from 0 to 3 was assigned to the levels of interface complexity defined before. In that way, the values were re-scaled and the dependencies could have been assessed within the same range.

3.2.4.2 Impact scale

The impact was measured in terms of the time needed to redesign the affected subsystem when the initiating one was changed. For the product component domain the time measured in hours [h] taken into consideration included the time designated for analyzing the new design requirements, creating concepts, and prototyping (either virtually or in a real environment). For documents and reports, domain impact was measured in time for updating and revising them. For tests, it was the time needed to prepare and perform the given test, while for the PLM domain, it was the time to perform the re-identification and update of the structure in the company's PLM system. Four categories were selected for impact assessment and were summarized in table 3.3.

Table 3.3: Redesign time.

Time	Value
short: 0,5-4h	0.25
medium-short: 5-16h	0.5
medium-long: 17-30h	0.75
long: 31-80h	1.0

The assessment was performed by an interior design engineer in accordance with his past experience. The classification was provided for each dependency identified in all design domains. The time intervals were chosen in accordance with interviews with engineers. The scale was selected to be from 0 to 1 and the values were comparable with values defined for the likelihood index. Owing to this, the weights of likelihood and impact were maintained at equal levels when combined to direct risk.

3.2.5 ICL, ICI, OCR calculation

To analyze the results of likelihood and impact assessment three indices were introduced following the approach proposed by Koh, Caldwell and Clarkson [19]. ICL, ICI and OCR definitions were presented in section 2.1 and were used to evaluate each component's sensitivity to change (ICL and ICI) and total direct change risk (OCR). Combining likelihood versus impact index on a scattered plot supported visualizing which component would be the most likely to change while causing the

most impact and vice versa. The indices were calculated according to the formulas 3.1, 3.2 and 3.3:

$$ICL = \frac{\sum \text{likelihood row entries}}{\text{total number of components} - 1} \quad (3.1)$$

$$ICI = \frac{\sum \text{impact row entries}}{\text{total number of components} - 1} \quad (3.2)$$

$$OCR = \frac{\sum \text{risk column entries}}{\text{total number of components} - 1} \quad (3.3)$$

Koh et al. [19] stated that using a simple average implies that the indices calculation does not differentiate between components that are lightly affected by multiple components and the ones that are heavily affected by few components. They explain that there is no empirical evidence that any of those cases is more severe than the other. As a result, both are treated with the same significance. Furthermore, the denominator is defined as the total number of components minus the subsystem that is considered as initiating change in the specific instance.

In order to compare the component's change characteristics between each other, each index was normalized. It allowed to map the components with respect to the least and most affected or impacting ones. The following formula was used to calculate new indices and place the values in the range from 0 to 1.

$$CI_{norm} = \frac{CI - CI_{min}}{CI_{max} - CI_{min}} \quad (3.4)$$

CI stands for change index computed for a given subsystem, CI_{min} and CI_{max} represent lowest and highest values within all considered components.

3.2.6 Change option total risk

Direct risk analysis allowed to assess specific change option total risk and investigate which change option had to be further examined in order to reduce its risk or avoid that change entirely. Six different change options were proposed:

- stowage width change in a range from 12-30 inches,
- installing literature pockets on aft panel,
- changing coat hanger to shelves,
- dividing door panel into two panels,
- installing the lights inside stowage,
- changing the color of the stowage panels,
- changing the finishing material of the stowage panels,

Through interviews with the design engineer, each change option was linked with initiating product components that would be affected when change is introduced. Direct change risk was evaluated for each component before, hence the total risk of

change was calculated as a sum of direct risks of components linked to considered change. The results showing ranked change options were presented in section 4.1 and the change options together with affected components (marked with "x") were shown in fig. 3.4

Affected system	Change options						
	Width	Lit. pockets	Shelves	Doors	Lights	Color	Material
Structure assembly	x	x	x		x	x	x
Door panel assembly	x			x		x	x
Door catch/latch	x			x			
Door hinges	x			x			
Latch strike	x			x			
Bump 1	x			x		x	x
Bump 2	x					x	x
Edge Trim	x					x	x
Coat hanger	x		x				
Light assembly	x		x		x		
Tie rods	x		x				
Floor attachment	x						
Installation fasteners	x						
Color (Finishing)		x				x	
Material		x				x	x
Placards&markings	x		x	x	x		
Literature pockets		x				x	x
Bolts/rivets/bonding	x	x	x	x	x	x	x

Figure 3.4: Change options and affected systems.

3.2.7 Affected instances

A secondary objective of the change risk analysis was to define the number of components, documents, tests, and reports affected by the given change option. It was enabled by data populated in dependency matrices as well as an indication of links between the change option and product component. The total number of documents, tests, and reports was computed as a sum of those instances listed for each component. It is worth emphasizing that the sum of all instances was reduced by the number of common instances between all components, to avoid calculating the same document multiple times. It was performed in accordance with the assumption, that a document or test report would be updated only once including all changes of different components considered for a given change option.

3.3 Clustering

The next important step in the methodology used in this thesis was clustering. This section will present such a concept and the results will be demonstrated in section 4.2

In order to achieve high modularity on the level of the entire product, the design efforts should be focused on developing interfaces between components. Integration analysis utilizing clustering algorithm is a way to support modularization [28]. Clustering is based on reordering rows and columns of a DSM that includes product components and interactions between them in order to group the components with

the most interactions into modules while minimizing interactions between modules. Browning suggests that an additional objective of clustering should be to minimize the size of clusters as well as to keep the integrative components (such components that interact with many components) outside of clusters [28]. After clustering a new DSM representing modularized product architecture is obtained and any interactions outside clusters should be recommended for further analysis and individual consideration. Pimmler and Eppinger in their work used the clustering method when analyzing the design of automotive climate control system. They emphasized that the clustering algorithm served them as a base for generating alternative architectures from which the solution fulfilling their requirements could have been chosen [29]. A similar approach was utilized in this paper, using the results from clustering as a foundation to build an efficient product architecture.

A clustering algorithm developed by Thebeau [30] was used in this thesis. It was a Matlab code with clustering macro and preset parameters. The DSM including product components and interactions between them used for change process analysis acted as an input for the clustering algorithm. Adjustments of the code included extracting the integrative components: bolts/rivets/bonding and placards/markings from the analysis to achieve better results. The interactions with integrative components were recommended for separate analysis out of the clustering method. According to suggestions given by the author 10 runs were performed in order to achieve a sufficient database for clusters analysis and choose the best modular division for the considered product.

3.3.1 Clusters analysis

The clustering algorithm builds clusters by randomly selecting elements to group them into chunks. As a result, each run delivers a slightly different set of modules and only one run is not sufficient enough to produce the optimal solution [30]. Data from 10 runs were collected including new clustered DSMs and lists of components combined into clusters. Clusters likeness analysis was performed following the procedure described by Thebeau [30]. It was based on comparing clusters generated in each run with clusters from other runs and calculating the average total likeness of the analysis. This parameter was representing the level of similarity between achieved results. The more similar the results were between each other, the more optimal the analysis was.

The average total likeness of the clustering performed in this thesis was equal to 88%. It was considered a high value, compared to around 70% achieved by Thebeau for clustering of the elevator system. This parameter indicated that the clustering was optimal and could be investigated further. It is worth noting that the high value of likeness was caused by a relatively low number of components in the investigated product, reducing the number of possible clustering solutions and balancing the randomness included in the algorithm.

3.4 Redesign process

Clustering operations facilitated the division of the product into modules and indicated which interfaces should be selected for detailed investigation. Those were summarized in section 4.2. Owing to this a new modular product structure emerged and was shown in fig.4.11. Six high-risk interfaces within modules and four high-risk interfaces between modules were identified using results from change process analysis. Each interface was investigated individually together with an interior design expert engineer. Discussions during interviews allowed to collect detailed information about standard design solutions for stowage interfaces such as: used materials, specification of fasteners, requirements for sealant or resin, manufacturing, and installation techniques. Examples of design solutions were presented by interviewed engineer using installation drawings, components offered by suppliers available online as well as hand sketches. Such an approach supported determining which interfaces could have been improved to reduce the change risk and which could not have been modified. Finally, five out of ten interfaces were selected and new design solutions, reducing the likelihood and impact of change, were proposed. Those were achieved through investigating smart solutions available on the market, reviewing articles [31], and searching for interesting information in the aerospace design industry. Additionally, past design experience helped to create new types of interfaces between some components. All of those were consulted and evaluated by the interior design engineer in terms of the possibility to realize and potential issues. Results of the redesign process were described in section 4.3 and schematic sketches were prepared to visualize the new design solutions for comparison with standard interfaces design.

4

Results

In this chapter, the results of the implementation of the methods will be presented. First, the change process analysis results will be summarized and the total change risk will be shown. Moreover, clustering outputs will be visualized followed by a modular product structure graph. Additionally, new design solutions for selected interfaces will be proposed and re-evaluated through updated risk analysis. The outcome of this process will be presented at the end of this section.

4.1 Change process analysis results

Results of the change process analysis were visualized in the component change sensitivity graph, component change risk as well as a total change risk plot and number of instances bar graph. Furthermore, change options were ranked and the change with the highest total risk was identified. In addition, a product risk matrix was created (fig.4.1). It helped to distinguish interactions between components with the highest risk and indicate which of them should be considered for further investigation. Owing to this, interfaces most affecting the total change option risk could have been pinpointed and examined in order to reduce the total risk.

The component change sensitivity graph in fig.4.2 shows the likelihood versus impact indices: ICL and ICI normalized and combined together. It visualizes how likely the component will change and how much redesign of this specific component will be needed when the change is carried out. It can be noticed that indices for structure assembly and bolts/rivets/bonding components are significantly higher than for the rest of the elements. It implies that those elements are particularly likely to change and a significant amount of redesign work will be needed when change appears. Both of those components had multiple interfaces with other components which had a direct effect on change sensitivity. They can be recommended for design improvements reducing the impact or likelihood to change.

4. Results

Components	Product risk matrix																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Product components																		
Structure assembly	1	0.28		0.18	0.18		0.06	0.12	0.33	0.17	0.18	0.18	0.15	0.23	0.28	0.23	0.23	0.15
Door panel assembly	2	0.23	0.12	0.18	0.18	0.06								0.45	0.28	0.23		0.30
Door catch/latch	3		0.22															0.22
Door hinges	4		0.28															0.22
Latch strike	5	0.45	0.43															0.28
Bump 1	6	0.38	0.11															0.11
Bump 2	7	0.38																0.11
Edge Trim	8	0.75																0.15
Coat hanger	9	0.50																0.14
Light assembly	10	0.50																0.33
Tie rods	11	0.45																0.14
Floor attachment	12	0.68											0.28					0.28
Installation fasteners	13	0.70										0.18						0.15
Color (Finishing)	14														0.28			0.45
Material	15														0.45			0.45
Placards&markings	16	0.47	0.14						0.22	0.11				0.23	0.14			0.15
Literature pockets	17													0.45	0.28			0.14
Bolts/rivets/bonding	18	0.47	0.18		0.09	0.13	0.13	0.09	0.13	0.18	0.37	0.25	0.25	0.37			0.23	0.23
Documentation																		
Requirement Listed in the Requirements Management Tool	19	0.19	0.11		0.06	0.06			0.11	0.11	0.06	0.06		0.19	0.11	0.19	0.19	0.33
Requirement Approved in the Requirements Management Tool	20	0.38	0.22		0.12	0.12			0.22	0.22	0.12	0.12		0.38	0.22	0.38	0.38	0.22
Requirement Validated in the Requirements Management Tool	21	0.38	0.22		0.12	0.12			0.22	0.22	0.12	0.12		0.38	0.22	0.38	0.38	0.22
Requirement Verified in the Requirements Management Tool	22	0.93	0.60		0.40	0.40			0.60	0.60	0.40	0.40		0.93	0.60	0.93	0.93	0.60
MBD (3D) Installation level component	23	0.70	0.30	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.45	0.47	0.30	0.70	0.70	0.45
Placards & Markings drawings	24	0.68	0.43						0.43	0.43				0.68	0.43	0.68		0.43
Trim & Finish Specification - technical	25													0.70	0.45		0.70	0.45
Trim & Finish Specification - customer	26													0.70	0.45		0.70	0.45
Interior Options Guide - customer	27	0.70	0.45	0.30	0.30	0.30	0.30	0.30	0.45	0.45				0.70	0.45	0.70	0.70	
General Arrangement, Stowage S1	28	0.38	0.22	0.12	0.12	0.12	0.12	0.12	0.22	0.22	0.12	0.12	0.22	0.38	0.22	0.58	0.38	0.22
Stowage, System Architecture	29	0.58	0.33	0.18	0.18	0.18	0.18	0.18	0.33	0.33	0.18	0.18	0.33	0.58	0.33	0.58	0.58	0.33
Wiring Diagram	30	0.45										0.28						0.28
Weight & Balance Report	31	0.47	0.30	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.20	0.20	0.30	0.47	0.30	0.47	0.47	0.30
ICD - Interface Control Document	32	0.70							0.45	0.30	0.30	0.45						
Materials coupon (layers, layers for flammability test)	33	0.38	0.22	0.12	0.12	0.12	0.12	0.12	0.22	0.22				0.38	0.22	0.38	0.38	
Static Test article	34	0.77										0.23	0.23	0.43				
Tests and reports																		
Flammability test	35	0.70	0.45	0.30			0.30	0.30	0.30	0.45	0.45			0.70	0.45	0.70	0.70	0.45
Static test	36	0.58										0.18	0.18	0.33				
Cabin Inspection	37	0.68	0.43				0.28	0.28	0.28							0.68	0.68	
Stress analysis	38	0.58	0.33	0.18	0.18	0.18			0.33	0.33	0.18	0.18			0.33	0.58		0.33
Interior Certification Program	39	0.93																
Stowage Stress Analysis Report	40	0.70	0.45	0.30	0.30	0.30			0.30		0.45	0.30	0.30	0.45				0.45
Stowage Static Test Plan	41	0.90										0.37	0.37	0.57				
Stowage Static Test Conformity	42	0.45										0.18	0.18	0.28				
Stowage Static Test Report	43	0.90										0.37	0.37	0.57				
Stowage Flammability Test Plan	44	0.90	0.57	0.37			0.37	0.37	0.37	0.57	0.57			0.90	0.57	0.90	0.90	0.57
Stowage Flammability Test Conformity	45	0.45	0.28	0.18			0.18	0.18	0.18	0.28	0.28			0.45	0.28	0.45	0.45	0.28
Stowage Flammability Test Report	46	0.90	0.57	0.37			0.37	0.37	0.37	0.57	0.57			0.90	0.57	0.90	0.90	0.57
Cabin Inspection Plan	47	0.90	0.57				0.37	0.37	0.37							0.90	0.90	
Cabin Inspection Conformity	48	0.45	0.28				0.18	0.18	0.18								0.45	0.45
Cabin Inspection Report	49	0.90	0.57				0.37	0.37	0.37							0.90	0.90	
PLM																		
Part Number reidentification	50	0.06	0.11	0.06	0.06	0.06	0.06	0.06	0.11	0.28	0.06	0.06	0.11	0.23	0.11	0.19	0.19	0.11
Customer options	51	0.45	0.28	0.18					0.22	0.28				0.47	0.28	0.45	0.45	
Product Structure	52	0.38	0.11	0.06	0.06	0.18	0.18	0.18	0.22	0.30	0.18	0.18	0.28	0.47	0.28	0.45	0.45	0.28

Figure 4.1: Product risk matrix.

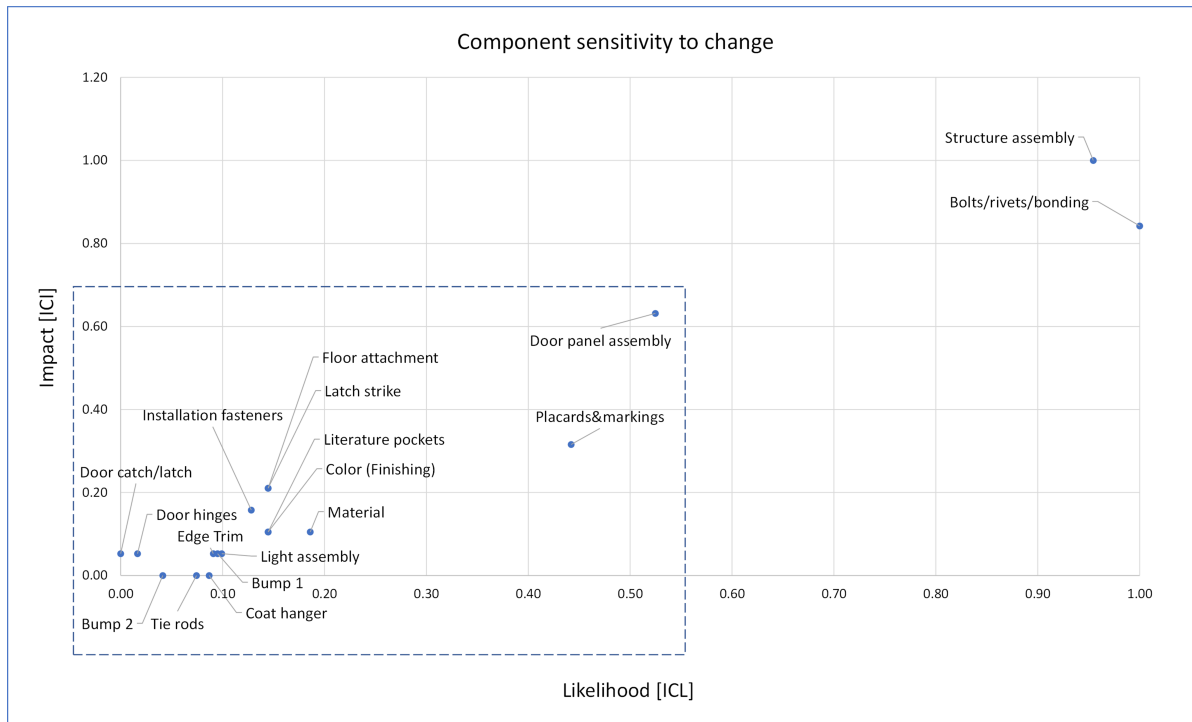


Figure 4.2: ICL versus ICI.

In order to investigate other components the graph was zoomed in excluding the two highest values (fig.4.3).

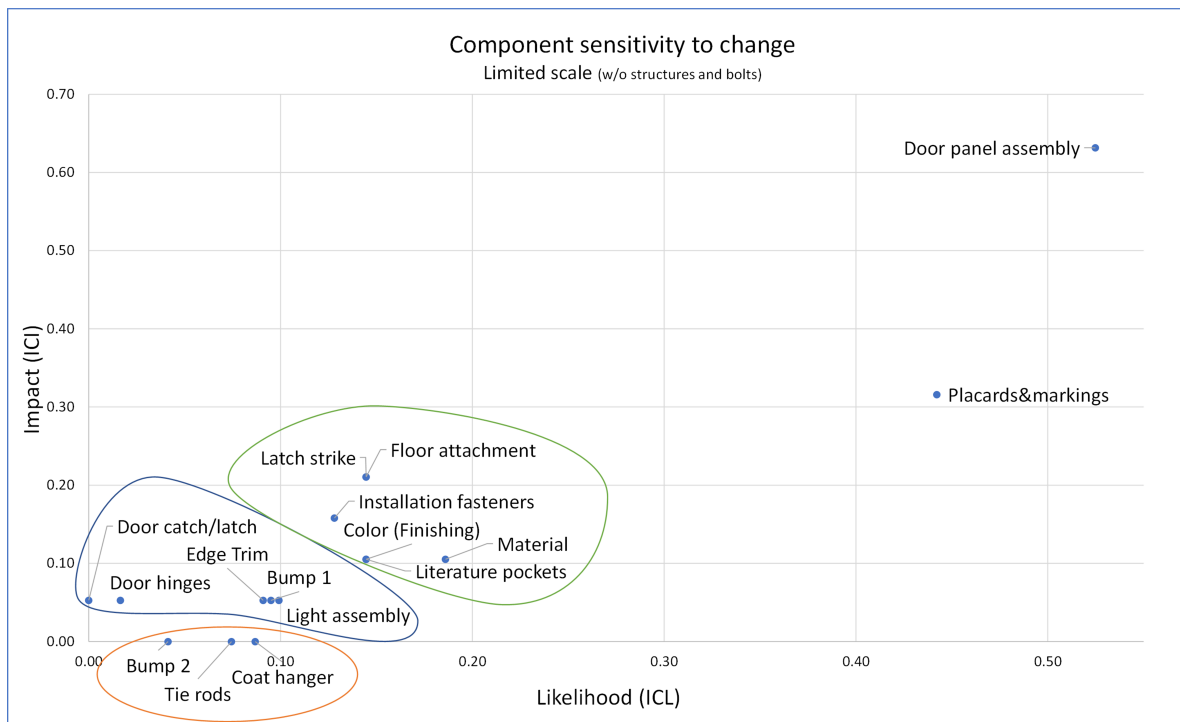


Figure 4.3: ICL versus ICI - limited scale.

This representation allows to compare the components with lower impact among

4. Results

each other. Door panel assembly and placards&markings emerge as components with a significant possibility to change and change impact. Many interfaces were recognized for those elements and they should be considered for design improvements and agile solutions when it comes to managing documents and tests related to them. Components placed in the left bottom part of the graph are characterized as less likely to change and requiring less redesign work. They can be recommended for standardization.

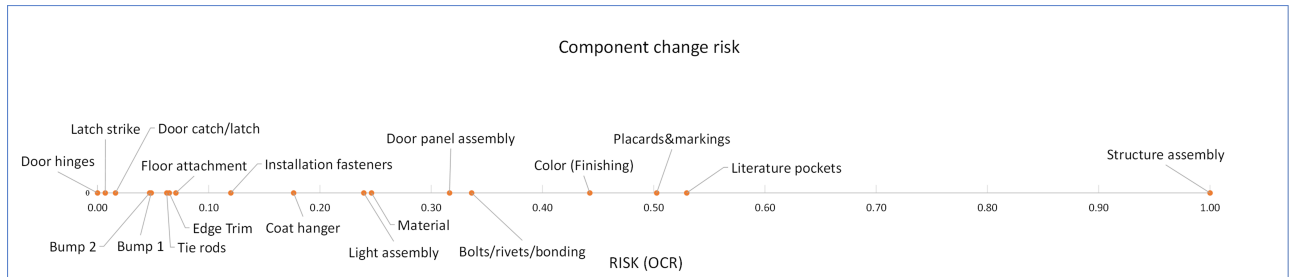


Figure 4.4: OCR.

The component change risk graph (fig.4.4) visualizes the OCR index, hence it shows which component change will affect the highest amount of components, resulting in the highest direct risk. Again, the structure assembly component has indicated the biggest risk, however, overall components distribution is different than shown on the sensitivity graph. It is worth noting that the literature pockets component has a high OCR value. It represents an add-on feature installed onto the finished stowage assembly. It implies that changing the final product would impact multiple design domains and require many revisions and updates. A robust design solution to facilitate such type of changes will be examined in further study in this thesis. Additionally, all components are building the same product, hence they are interdependent and will be all investigated to some extent for design improvements and risk reduction. However, the graph allows to identify which area requires the utmost attention.

Change option total risk is shown in fig.4.5. It is a visual summary of risk related to specific modifications mentioned in section 3.2.6. Change of stowage width influences a great number of elements and requires multiple documents update and retesting of many parts. Owing to this it can be considered as the highest risk modification. Variation of color and material drives a high risk as well, due to affecting multiple high-risk product components such as stowage assembly and literature pockets. Those are the areas that will be examined further in order to reduce the risk. On the other hand, doors change appeared as the lowest risk modification. It is in accordance with the results presented on the OCR graph. Door panel assembly had a lower risk value and did not affect as many components as other product components included in high-risk changes. Lower-risk modifications can be recommended to act as customer options in the future.

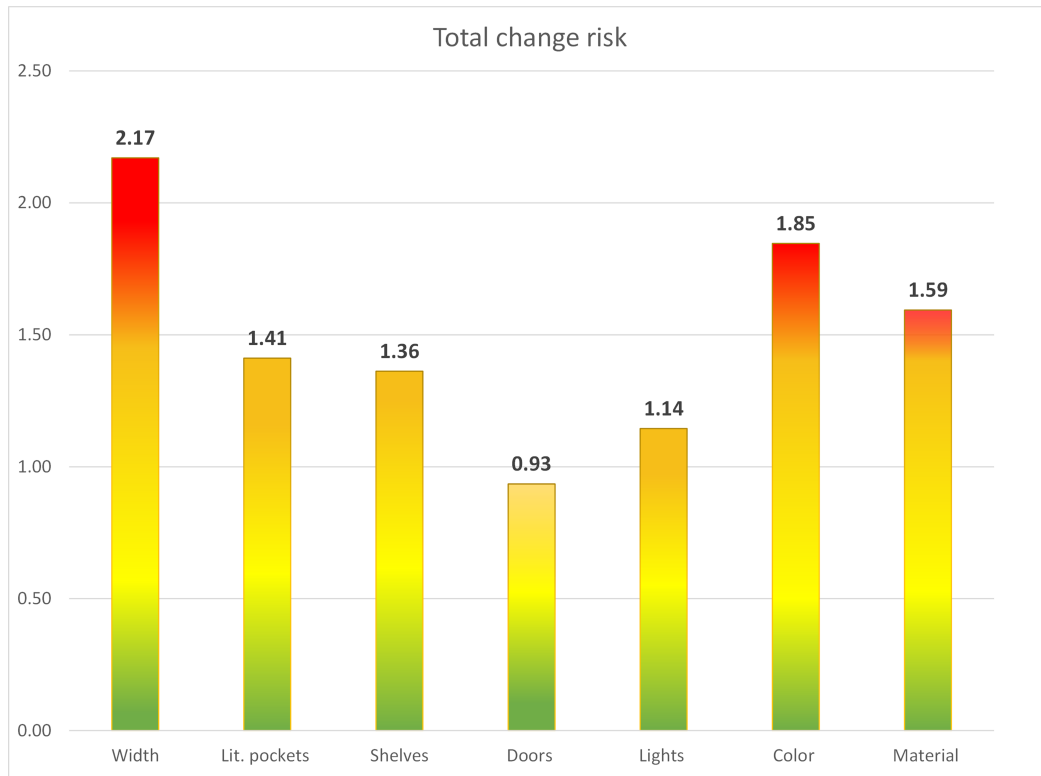


Figure 4.5: Change risk.

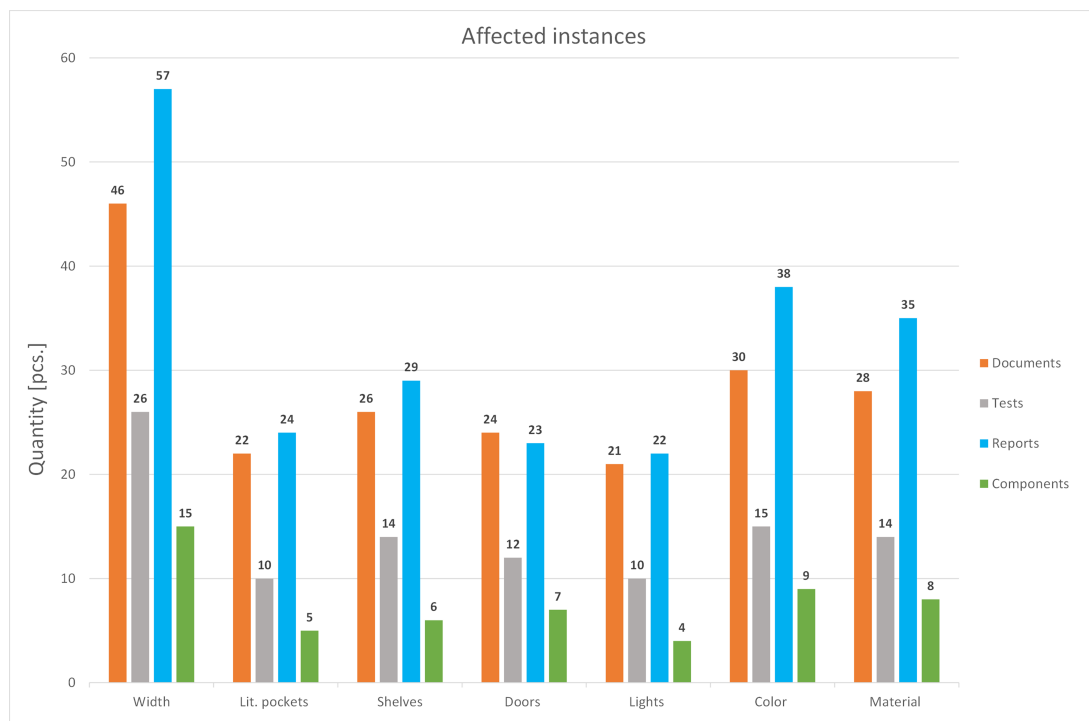


Figure 4.6: Affected instances.

The total number of documents, tests, reports, and components that could be affected by a specific change is shown in fig.4.6. Such data visualization is a justifica-

tion of change option risk as it presents a direct connection between the number of impacted instances and total change risk. It pinpoints which documents or processes could have space for improvement. This issue can be considered as a future research area. In this report, it will support the comparison with solutions developed further in this study.

4.2 Clustering results

The clustering algorithm delivered new clustered DSMs and lists of components included in clusters. Ten results were analyzed and three architectures were chosen. The criteria for down selection were the size of clusters, maximizing the number of interactions within clusters, and minimizing the amount of one-component clusters. Those requirements were fulfilled by architectures completed in runs 1, 4, and 8. Finally, clustered DSM from run 8 was chosen as a foundation for further product modularization. It consisted of 6 modules, only two of them were one-component modules and those were including integrative components, extracted from the clustering method before. Color and material were kept within one cluster since they were highly interdependent. Components related to stowage doors were combined into one cluster. Structure assembly was included in one module together with components acting as structure equipment kit. The new DSM and components lists are shown in fig.4.7 and fig. 4.8.

Clustering combines components with many interactions into groups, however, it also indicates the interfaces between modules. Those interactions outside clusters can be viewed as system engineering "flags" which pinpoint that special attention is required [29]. They are marked with colored boxes and shown in fig.4.9.

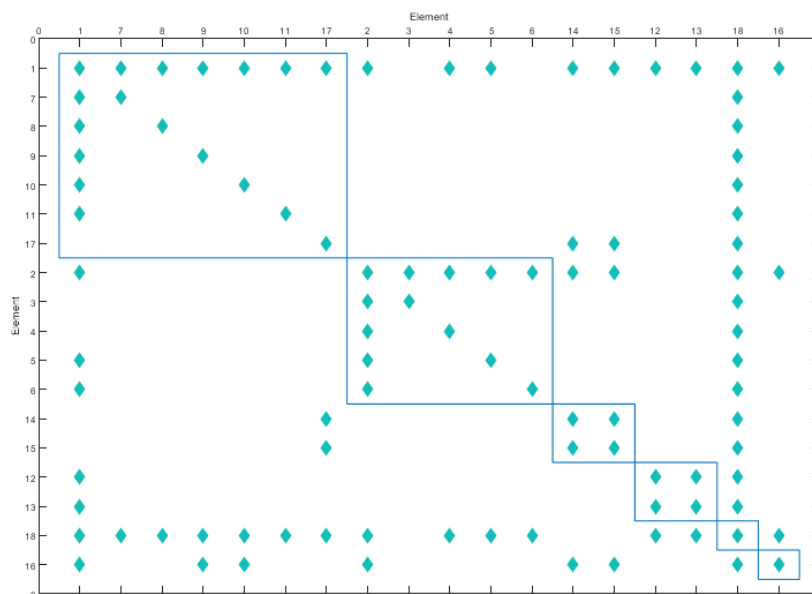


Figure 4.7: Clustered product DSM.

Cluster #1	Cluster #5
Structure assembly (1)	Bolts/rivets/bonding (18)
Bump 2 (7)	
Edge Trim (8)	Cluster #6
Coat hanger (9)	Placards&markings (16)
Light assembly (10)	
Tie rods (11)	
Literature pockets (17)	
Cluster #2	
Door panel assembly (2)	
Door catch/latch (3)	
Door hinges (4)	
Latch strike (5)	
Bump 1 (6)	
Cluster #3	
Color (Finishing) (14)	
Material (15)	
Cluster #4	
Floor attachment (12)	
Installation fasteners (13)	

Figure 4.8: Components list.

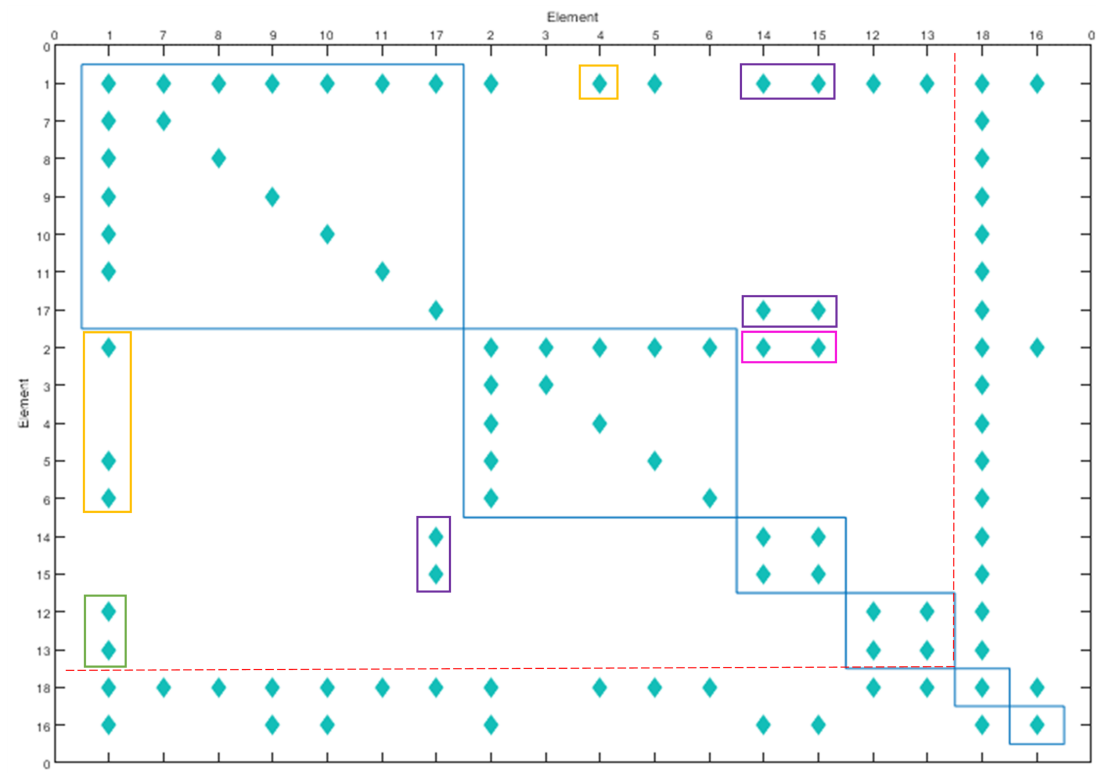


Figure 4.9: Out-of-cluster interfaces.

The red dashed lines separated the extracted components (16, 18). For those two parts, many interactions with other components can be noticed and those were not

investigated in this paper. Bolts/rivets/bonding component (18) as well as placards&markings were spread around the entire product structure. Such components should be either divided further and included in each module which they interact with or they should be recommended for standardization. Interfaces between modules chosen for further investigation and recommended for the redesign were marked with colored boxes and listed below:

- yellow: module 1 and module 2: structure and doors, structure and latch strike, structure and bump 1, door hinges and structure
- green: module 1 and module 4: structure and floor attachments, structure and installation fasteners,
- purple: module 3 and module 1: color& material and structure, color& material and literature pockets
- pink: module 3 and module 2: color& material and door panel

Out of all of those interfaces, two were neglected in further analysis. First was structure and bump 1, due to the fact that this interface was related to the dimensions of respective components and it was already included in the interface between bump 1 and the door panel. Interaction with structure was redundant in that case. The second neglected interface was structure and installation fasteners. This component should be divided further and included inside the corresponding cluster or it should be recommended for standardization.

4.3 New design solutions

Re-design results were summarized in fig.4.10. The table includes product components divided into modules as well as a description of interfaces for each component. High-risk interfaces were marked in two columns. First, ten interfaces were selected within and between modules (all cells marked with symbols). After the interview with the interior engineer, five interfaces were down-selected (marked with a green symbol). They were indicated as possible to redesign in a smart, robust way in order to reduce risk. The design of interfaces which did not undergo the re-design process was determined as sufficient for quick and easy change introduction or it had relatively low change risk compared to other dependencies. In fig.4.10 the baseline design and proposed improvements were described. Additionally, the possible benefits of re-design were summarized together with notes corresponding to interfaces not changed during the process. For each interface the baseline total risk together with risk after improvements were presented. Data for each dependency were populated from fig.4.1 and fig.4.16.

It is worth noting that parts that had interfaces with many other components were not evaluated in this summary. Due to the fact that bolts/rivets/bonding, placards&markings as well as installation fasteners were spread around the entire product, they would require a separate analysis and should be included in the specific modules at the beginning of the product division process. Furthermore, it can be noticed that risk was reduced for components that were not subjected to the redesign process such as edge trim or latch strike. It was due to the fact that those components interfaced with the structure, while the structure's likelihood to change

was reduced, impacting the risk of specific components. This procedure will be explained in detail in section 4.4.

Product components were divided into modules and represented in a modular product structure graph shown in fig. 4.11. Interfaces between modules were marked with blue arrows, while interfaces within modules were marked with dark-blue dashed arrows. All components inside each module are on the same level and they are independent from each other. In module 1 and module 2, there are special components: structure assembly and door panel assembly respectively. Those components act as bus components since they have interfaces with all other components within the module. Components marked in grey represent parts that act as interfaces between two modules and the connection between exact components is marked by the blue arrow. The objective of the redesign process was to reduce the complexity of those dependencies in order to reduce the risk and create a space for robust change introduction. Such product organization allows the reduction of the number of components that need to be changed by simplifying the interactions between them or removing them completely. As a result, fewer part numbers (PN) need to be changed in the PLM system, fewer tests need to be redone as well as fewer technical documents or reports have to be modified and re-released. Consequently, the time and costs of change introduction can be reduced. In comparison to standard product structure, which can be characterized as a multi-level tree, modular product structure emerged as a more suitable approach for constantly changing design.

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Mod. No.	Module	Component	Interface	High risk within module	High risk between modules	Baseline risk	Improved risk	Baseline design	Improvements	Notes/Redesign benefits	
1	Structure equipment kit	Structure assembly	equipment								
		Bump 2	structure	<input checked="" type="checkbox"/>		0.38	0.22	rubber, snap on material, flexible geometry	not required	standard design allows for quick and easy installation	
		Edge Trim	structure	<input checked="" type="checkbox"/>		0.75	0.50	coat hanger installed with screws and nuts on the wall, coat hanger with only one length option	DESIGN: sliding rails with interfaces allowing to accommodate both shelves and coat hangers, extending coat hanger to cover storage width range	shelves interchangeable with coat hanger can be offered as an additional option for customer	
		Coat hanger	structure	<input checked="" type="checkbox"/>		0.50	0.11			allows to have only one top panel,	
		Light assembly	structure	<input checked="" type="checkbox"/>		0.50	0.22	one top panel with cutout for light assembly, additional top panel without cutout	DESIGN: plastic plug is used to simulate the light assembly	the only implication is in the BOM (plug and light assembly have to be both included), however, this is covered by 150% BOM and configuration management module in PLM system	
		Tie rods	structure				0.45	0.28			
2	Doors equipment	Literature pockets	structure	<input checked="" type="checkbox"/>		0.23	0.19	one left panel with inserts and holes for literature pockets installation, additional left panel without inserts and holes	DESIGN: previous holes with inserts in the structure panel	possibility to add components without storage de-installation and PNs change	
		Latch strike	structure	<input checked="" type="checkbox"/>		0.45	0.28	latch strike installed in structure with screws, correct dimension considered	not required	structure designed together with latch strike, identified as an interface within module	
		door catch	door catch		<input checked="" type="checkbox"/>		0.43	0.43	latch strike dimension corresponds to door catch dimension	not required	door catch designed together with latch strike, identified as interface between modules
		Door panel assembly	equipment				0.43	0.43			
		Door catch/latch	latch strike								
		Door hinges	structure	<input checked="" type="checkbox"/>		0.18	0.18	piano hinge installed with screws	not required	robust interface between modules, defined as low risk dependence	
3	Finishing	doors	doors	<input checked="" type="checkbox"/>		0.28	0.28	piano hinge installed with screws	not required	robust interface between modules, defined as low risk dependence	
		Bump 1	doors			0.11	0.11				
		structure	structure			0.38	0.28	structure panel painted, de-installation from aircraft required when color is changed, each panel painted separately		the whole structure can undergo the process, colors and materials have their own PN in separate module, there is no need to change the PN of other modules, a wide range of colors and materials is offered to the customer, easier and cheaper application	
		Color & material	doors	<input checked="" type="checkbox"/>		0.45	0.19	door panel painted, de-installation from aircraft required when color is changed, each door component painted separately	DESIGN: hydrographics and vinyl wrap method		
		lit. pockets	lit. pockets			0.45	0.19	certification of few material combination	DESIGN: certify component in many colors and materials	wide range of materials and colors available as an option to customer	
		Floor attachment	structure	<input checked="" type="checkbox"/>		0.68	0.11	floor attachments installed in the floor panel with screws, floor panel has cutouts to install the floor attachments	DESIGN: QCTL (quick change track lock system) used	no effect on structure when storage width changes	
5	Bolts	Installation fasteners	structure								
6	Placards	Bolts/nuts/bonding	multiple components								
		Placards/markings	multiple components								

Figure 4.10: Re-design summary

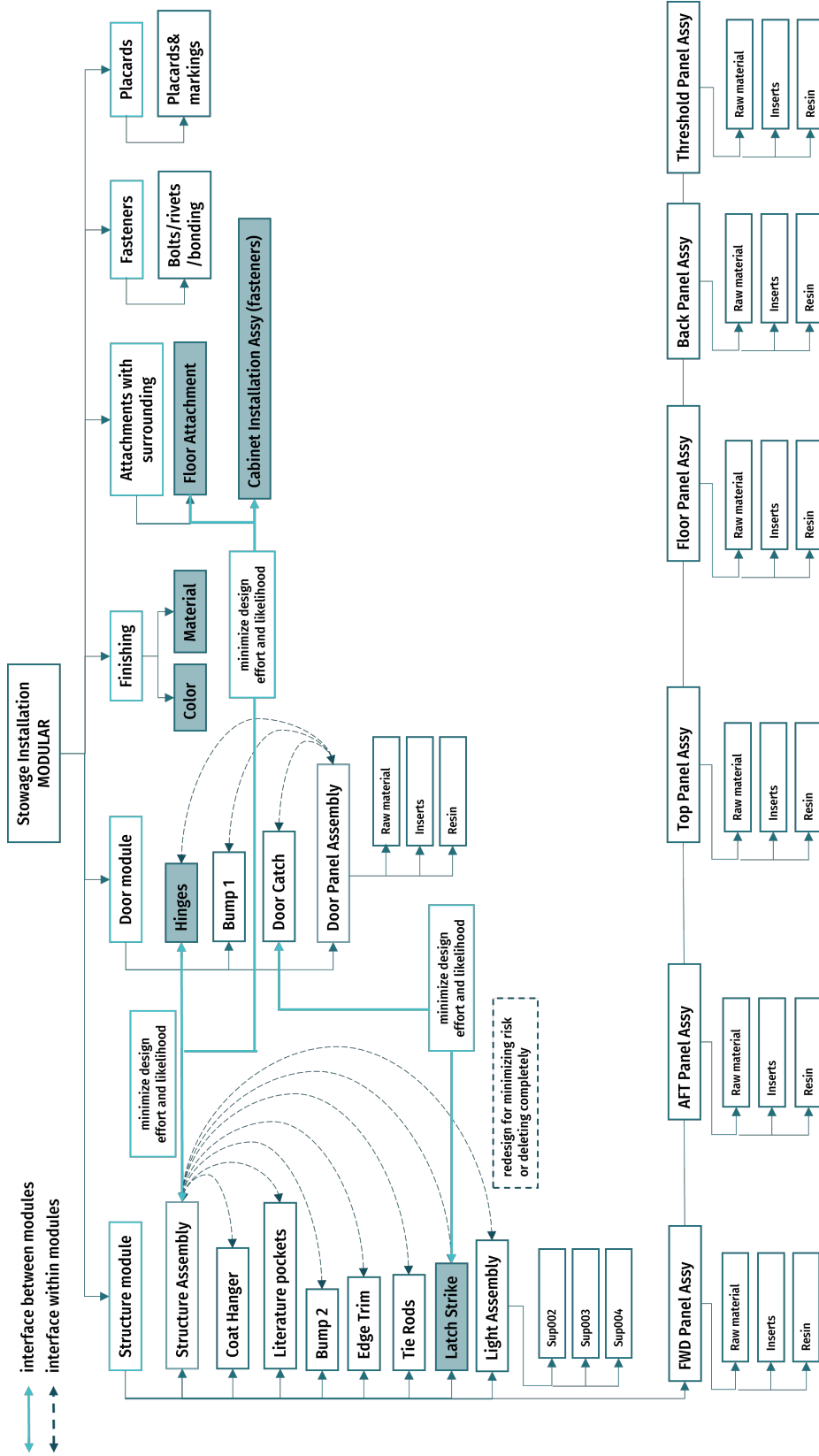


Figure 4.11: Modular stowage product structure - stowage components reorganized into modules, interfaces within modules shown with dashed arrows, components which are the interfaces between modules are marked in grey, and interactions between modules are marked with dashed arrows.

4. Results

New design ideas are shown in the schematic drawings in fig. 4.12, fig. 4.13, fig. 4.14, fig. 4.15.

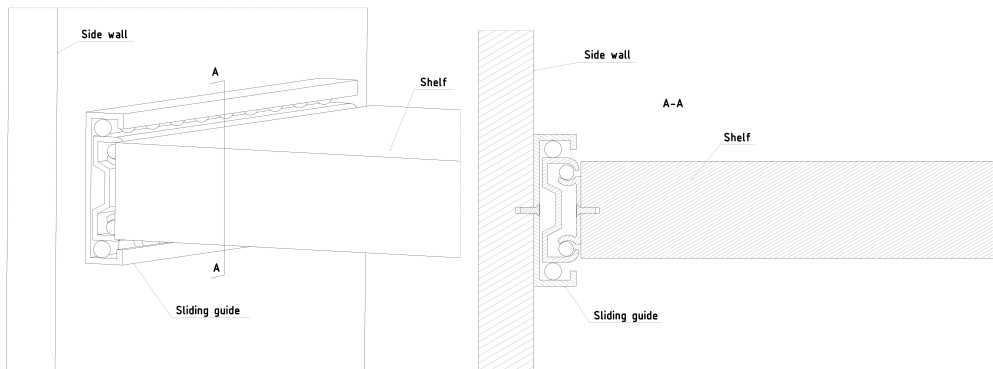


Figure 4.12: Side wall and shelf connection: shelf installed on the side wall through connection with a sliding guide, countersunk screws used in the installation

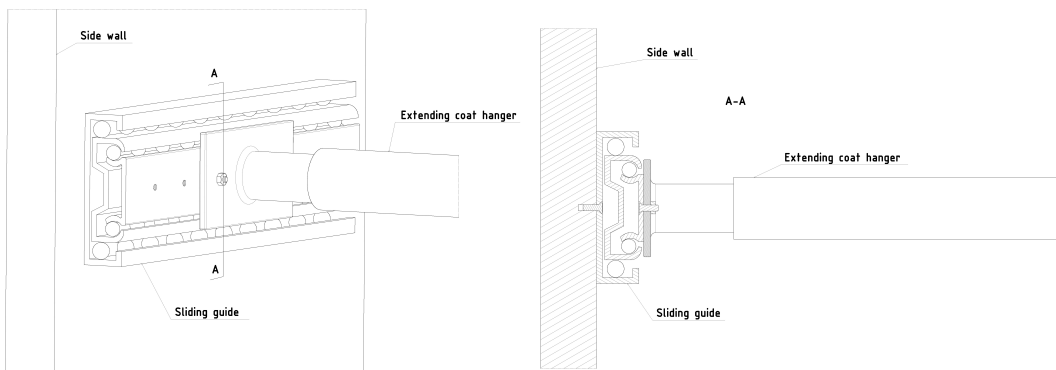


Figure 4.13: Side wall and coat hanger connection: the same sliding guide used for installation of coat hanger, no requirements to change side wall interfaces. Coat hanger designed as extending rod, to cover a wide range of stowage widths.

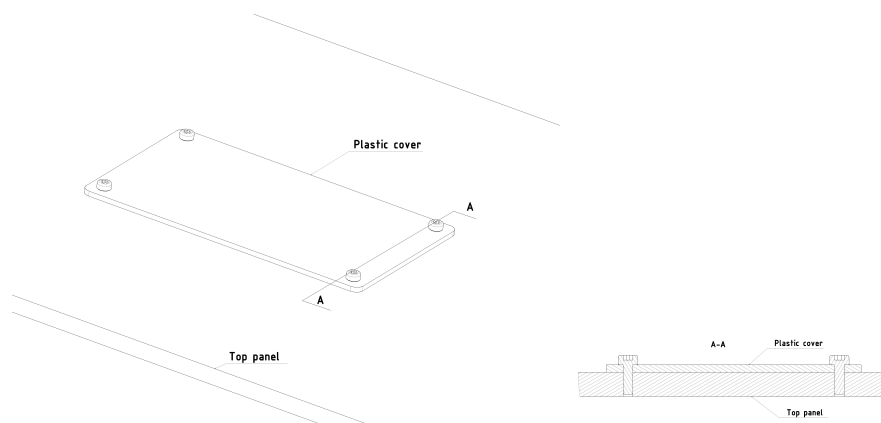


Figure 4.14: Light assembly plug: used to cover the cutout in the top panel, when light assembly option is not selected by the customer.

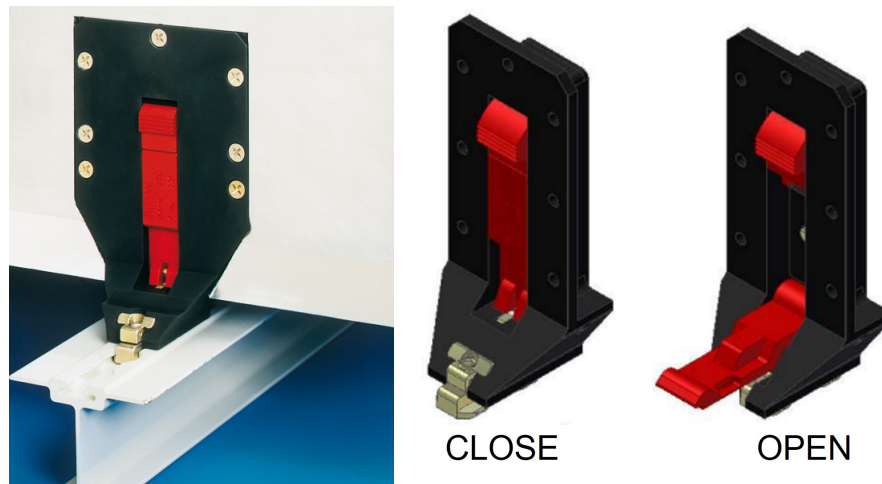


Figure 4.15: Quick Change Track Lock System (QCTL) from Innovint (left), 2023. Retrieved from <https://www.innovint.de/cabin-interior/ancillary-equipment/stowages/> and from VERBINDUNGS-TECHNIKEN-RÜTHER (right), 2021. Retrieved from <https://www.vtr-ruether.de/Produkte/Products/VTR-Produkte/Products/QCTL-QuickChange> (right): floor attachment can be kept in the same position when changing the stowage width.

4.4 Risk analysis for the new design

In order to verify if modular product architecture was, in fact, beneficial for the considered case, change risk analysis was performed again for the new design. Due to limited time, the new risk analysis was executed only in the design domain of the product matrix. Interfaces between product components and documentation, tests, and PLM functions were not re-evaluated in this paper. However, the assessment of design domain interfaces was sufficient to affect the number of documents, tests, and reports impacted by the specific change, which will be discussed later in this section.

Within the design domain, the likelihood and impact of change for interfaces identified in section 4.3 were defined again following the method described in section 3.2. Parameters defining the likelihood of change such as interface complexity and historical data were reduced by one level for interactions affected by the re-design process. Moreover, new risk analysis required redefining the historical data parameter. In the original risk analysis, it represented the number of times that the component changed during its lifecycle in the past. Due to the fact that no historical data for the new product design existed, such a definition was not sufficient anymore. Instead, the historical parameter in the new risk analysis represented a predicted amount of times for component change during its lifecycle. Two components were approximated to change fewer times than for the old design: the coat hanger and structure assembly. The historical parameter for those was reduced by one level. Decreasing this index for structure assembly, had a significant impact on the likelihood value for all components interacting with the structure, according to the likelihood calculation method described in section 3.2.4.1. All the above changes to

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the interface assessment were evaluated and approved by the interior design expert engineer. The results were shown in the updated product risk matrix in fig.4.16. In total 22 interfaces were re-evaluated and the risk reduction is visible in the cells marked with bold frames.

Furthermore, the change option risk analysis was executed again. Two aspects contributed to the reduction in total change risk. Firstly, the decrease of individual interface risk described above. Secondly, some of the components affected before by specific change options could have been excluded from the analysis. Each product component carried a risk which was then added to the total change risk. Extracting some components resulted in a total risk reduction. The comparison between total change risk for baseline and modular design is shown in fig.4.17. A significant drop can be visible for almost all changes. The door change option was not affected, since the interfaces were not re-designed and the same components were affected by such change introduction for both designs.

Despite the fact that the documents, test, and reports domains were not evaluated again, a significant reduction in affected instances was identified, which was summarized in fig. 4.18. It emerged as a result of excluding specific components from change options. Each component, when changed, requires a specific amount of documents and tests to be released, hence when the change does not affect the component, the tests, and documents are not affected either. It can be visible that the "affected instances" graph follows the total change risk graph. For changes where components were removed, the number of documents, tests, and reports decreased as well.

Components	Product risk matrix																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Product components																			
Structure assembly	1		0.28		0.18	0.18		0.06	0.12	0.06	0.11	0.18	0.12	0.15	0.23	0.28	0.23	0.19	0.15
Door panel assembly	2	0.14		0.12	0.18	0.18	0.06								0.19	0.11	0.23		0.30
Door catch/latch	3		0.22																0.22
Door hinges	4		0.28																0.22
Latch strike	5	0.28	0.43																0.28
Bump 1	6	0.22	0.11																0.11
Bump 2	7	0.22																	0.11
Edge Trim	8	0.50																	0.15
Coat hanger	9	0.11																	0.14
Light assembly	10	0.22																	0.33
Tie rods	11	0.28																	0.14
Floor attachment	12	0.11												0.28					0.28
Installation fasteners	13	0.45											0.18						0.15
Color (Finishing)	14															0.28		0.38	0.14
Material	15													0.45				0.38	0.14
Placards&markings	16	0.30	0.14							0.12	0.11			0.23	0.14				0.15
Literature pockets	17													0.19	0.11				0.14
Bolts/rivets/bonding	18	0.47	0.18		0.09	0.13	0.13	0.09	0.13	0.18	0.37	0.25	0.25	0.37			0.23	0.23	

Figure 4.16: Re-evaluated product risk matrix.

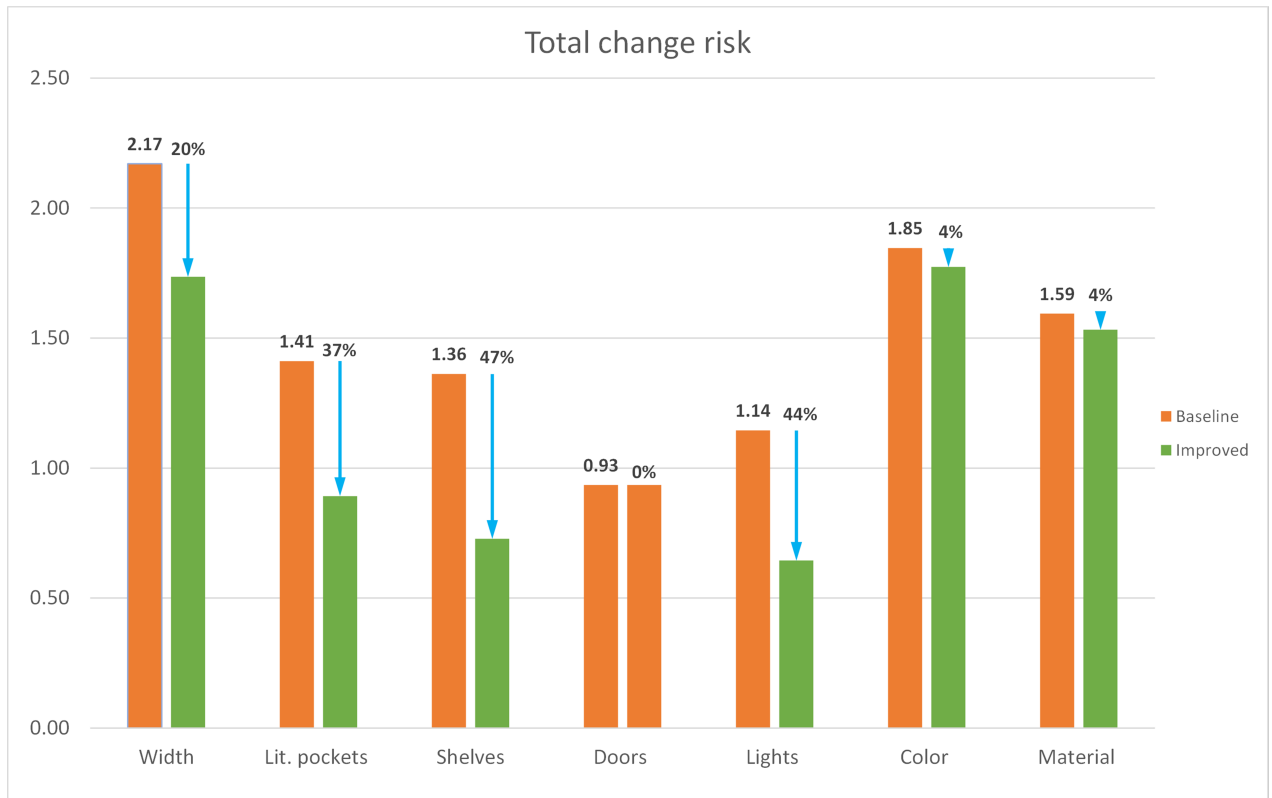


Figure 4.17: Risk reduction for the new design.

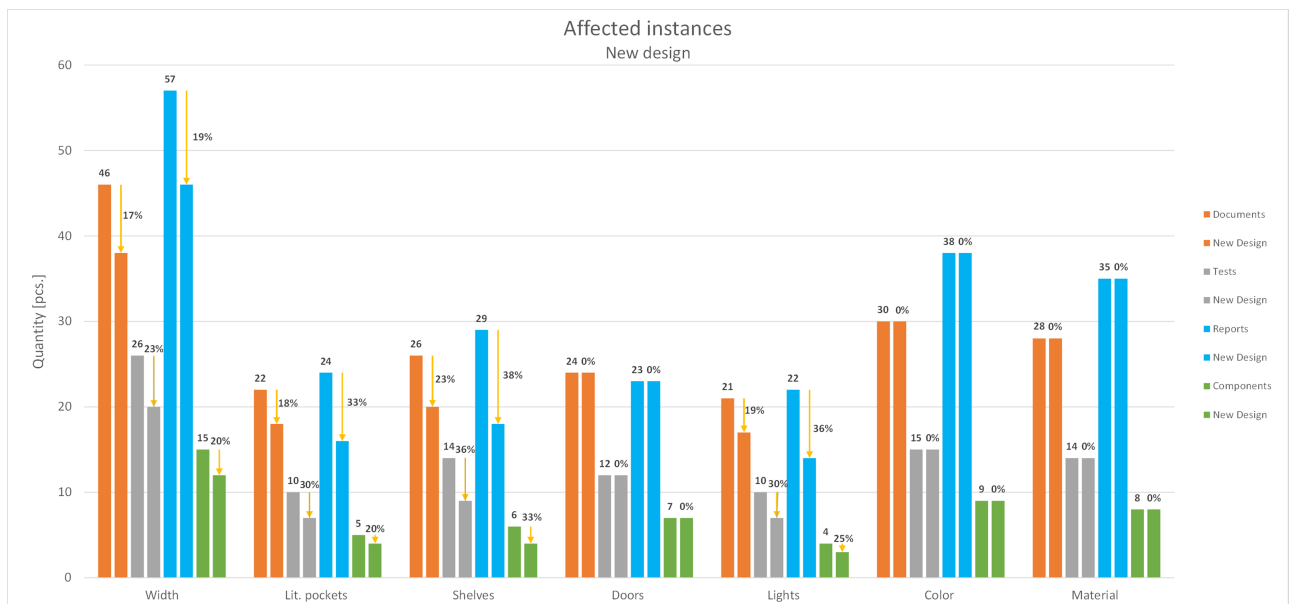


Figure 4.18: Affected instances for the new design

Presented graphs showed that excluding the component from the change option completely was more beneficial for risk reduction, rather than only simplifying interfaces between components. The fewer components that can be affected when change is introduced, the less re-design effort is needed. Simplifying interfaces resulted in a

4. Results

4% reduction of total risk (color and material change option), while designing the components in such a way, that they will not be affected by the modification of surrounding parts, resulted in up to 47% risk decrease.

5

Conclusions

5.1 Validation

At the beginning of the work, the possible issues and high-risk interfaces were discussed with the design engineer, based on his previous experience and general knowledge of the product. The results of the initial change risk analysis were consistent with the predictions he made. Risk reduction shown in section 5 validated the modular design of the product as sufficient for quick change introduction. Further validation of the proposed approach could include calculating the number of documents, tests, and reports affected by the change of real stowage when the aircraft is manufactured and introduced into service.

5.2 Conclusions

This paper presents an application of the change prediction method and clustering technique for an aerospace product. Such an approach facilitates and improves the redesign process, which is essential for quick change introduction. The methodology was developed based on previous work performed in the field of change propagation, change risk assessment as well as modularization. A change risk analysis was outlined, followed by a clustering technique application. The results of those operations served as inputs for redesigning the stowage interfaces and the significant risk decrease confirmed the method's validity. Modular product structure emerged as a suitable architecture for products that require many modifications during their lifecycle.

The work performed presented in this thesis allowed to answer the research questions defined at the beginning.

- What are the issues that the designers are facing when introducing an aircraft cabin interior design change?

Change process analysis helped to answer this question. The most important challenge when introducing change into interior design is the number of documents and tests designers have to plan and prepare in order to certify the aircraft. Detailed information about those numbers was outlined in the results section of the thesis 4.1. Those data could be further used to calculate the exact time and cost needed to complete the design change process. Specific issues related to changing the design of

stowage were identified by finding the high-risk dependencies between components. The structure assembly interfaces yield the most challenging to introduce change. In this thesis, the selected interior component was analyzed, however, the proposed methodology can be used to investigate challenges that could appear for any other interior component or system.

- Can the modular product architecture facilitate the configuration change introduction?

Through the literature study, a thesis formed that modular products are very beneficial for quick change introduction. This research question was created to verify if the predictions made would be valid for the aerospace component. It could have been answered by creating a modular stowage structure using the clustering technique and redesigning the high-risk interfaces in order to uncouple the dependencies between identified modules. Results shown in section 4.4 proved that the modular design can facilitate change introduction. The total change risk was reduced for all proposed change options. Additionally, the new design solutions allowed to reduce the number of documents and tests required to prepare for certification. The new modular product structure 4.11 shows that introducing the change would require less new part numbers creation, hence less time allocated to the PLM system. The modular architecture is beneficial in terms of the cost and time required to complete the design change process.

To summarize the key findings and outline the contribution to the research and company, the following conclusions regarding the proposed approach were drawn:

- Modular design was proven useful for quick change introduction, enabling greater ease in the customization of the product and configuration of the cabin interior.
- The proposed methodology presents the structured redesign process which allows controlling the product from the early development stages.
- The thesis presents means to collect detailed data on the product in an organized way, which allows for a deep understanding of the product on a comprehensive level.
- Utilizing the approach, the potential changes can be predicted and effectively integrated into the design from the beginning. As a result, a broader range of configuration options can be offered to the customers.
- The approach can serve as a tool for the marketing department to estimate the cost of possible configurations and create customer catalogs.
- The modular product structure was proven to have a positive effect on time allocated for PLM system operations - more leveled BOM reduces the number of part numbers required for re-release.
- The approach can help map the product or a system into groups. It can support the management team in making more informed decisions on team division and identifying optimal communication channels.

In order to manage and develop the proposed methodology in the company, some recommendations for the future were listed:

- Such an approach might require a skilled systems engineering team.
- Software for CPM including indirect risk analysis should be deployed to yield a closer approximation to the real-world change risk and improve the inputs for the redesign.
- The special focus should be given to the granularity of the product division and the quality of data gathered as inputs. Those are essential to achieve accurate results both in change risk analysis and clustering.

Further validation of the proposed method is recommended and could be realized through a case study on a prototype of the stowage. Applying this methodology to other interior components can support creating more detailed guidelines for product division and structure the analysis further. Although the redesign process may require increased effort and time allocation when applied to other interior elements, this thesis presents evidence that such a process can be executed fast and efficiently. To summarize, the presented approach was proven beneficial for design change introduction and should be considered as a standard process developed and practiced in the company.

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