

# MULTIDISCIPLINARY CONCEPTUAL AND STRUCTURAL DESIGN OF A NEW GENERATION OF AIRCRAFT OVERHEAD STOWAGE COMPARTMENT

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## Abstract

New developments of technical systems are always a very challenging task. This is particularly true for the aviation industries, where extreme lightweight design meets manifold design requirements. Especially the interior structure of an aircraft, which is typically part of a multidisciplinary mechatronical system nowadays, challenges the designer by the multitude of design parameters and influence factors. And on top of it, the cabin has to be ergonomic and comfortable with a striking appearance. These complex requirements do not allow a standard domain-specific design optimization without a basic multidisciplinary design methodology.

This article outlines the systematic approach used to develop a new generation of aircraft overhead stowage compartment. The discussed overhead stowage compartment is movable. The innovative character and the challenge of the presented movable overhead stowage compartment is mainly driven by the removal of the classic housing, a significant stowage enlargement that implies the increase of the payload and demands for a supporting actuator for opening and closing, improved ergonomics in terms of loading and presence in the cabin and a simple structure that meets all mechanical needs at the same time with a reduced mass related to comparable existing solutions. The performed design procedure is based on the state of the art methods of engineering design for mechatronical systems and its main design stages, system design, domain-specific design and system integration. The focus of the present work is on the system design in the early design stage and on the structural design within the domain-specific design. It is presented how the performed systematic approach generates novel design concepts and how a concept develops until the prototype stage. The work outlines the step-by-step development of the multidisciplinary design concept by analyzing, abstracting and solving the design task on the basis of an introduced evaluation scheme. Furthermore, the integration of the structural design in the domain-specific design phase is explicated and the working steps of the structural design are demonstrated by the considered overhead stowage compartment. Finally, the integration of the domain-specific solutions to the overall multidisciplinary solution of the aircraft overhead stowage compartment is described and the results of the successful application of the systematic design approach are presented.

The discussed development project was a cooperation of the Institute of Constructional Lightweight Design at the Johannes Kepler University Linz with partners from aviation industries and ended recently with a patent application. The project was funded by the Austrian Research Promotion Agency (FFG).

## 1. INTRODUCTION

Nowadays lightweight design engineers face an increasing complexity of product development tasks that moreover often unify different engineering domains. In addition a general trend of fast product replacement at the same time with a high level of optimization challenges the modern lightweight design engineer.

As a prime example, aviation industries can be named. From the very beginning, lightweight design was an essential element in the design of aircrafts and it is highly developed with regard to the primary structure. Less attention is generally paid to the aircraft interior. But particularly in this sector products develop quickly and constantly gain complexity. Today, the typical aircraft interior is an interaction of mechanical and electrical components that are governed by a controller, i.e. a mechatronical system according to [1, p.10]. Moreover, the interior of an aircraft is not only challenging due to its

complex technical duties. Amongst these it strongly interacts with passengers and crew members, which demands for ergonomic qualities, comfort and a pleasant appearance. Adding further requirements for manufacturing, maintenance, safety, etc. generates an immense multitude of parameters and factors influencing the design of an aircraft interior system. In contrast, established tools and methods in lightweight design such as numerical topology and shape optimization need defined boundary conditions and constraints in order to fulfill their task. Therefore, a basic methodology is needed that has the capability to handle a large number of multidisciplinary product requirements and includes established design and optimization methods of various domains. This article presents a systematic design approach for multidisciplinary mechatronical systems based on the development of a new generation of aircraft overhead stowage compartments carried out at the Institute of Constructional Lightweight Design together with partners from aviation industries.

## 2. DESIGN METHODOLOGY

The selected design methodology for the presented development of a novel aircraft overhead stowage compartment is the “design methodology for mechatronic systems” according to the VDI-Standard 2206 [1]. This selection appears promising as the overhead stowage compartment represents a mechatronic system. The design methodology according to [1] is introduced by the Verein Deutscher Ingenieure (VDI) as a guideline for the design of products that include interacting elements of different domains. The focus of the methodology is on mechatronic systems that include the domains mechanical, electrical and information engineering. The design methodology is based on three elements:

- a general problem-solving cycle on the micro level
- the V-model as a guideline for the design process
- process modules for recurrent working steps

### 2.1. Problem-solving cycle

The problem-solving cycle is a general procedure to solve a problem and represents the basis of the design methodology. It is used to effectively find decisions for questions arbitrary emerging during the design process. Problem-solving cycles are the basis of many design methodologies (see [1,2,3]). They can vary in their detailed execution but always consist of the general process steps

- 1) problem analysis,
- 2) identification of solution alternatives and
- 3) determination.

These three steps are applied to any problem. For complex problems one cycle in the problem-solving cycle might not achieve a satisfying solution. In this case the cycle is repeated until an adequate solution is obtained.

### 2.2. V-model

The V-model shown in FIGURE 1 serves as a general guideline for the design of mechatronic or other multidisciplinary systems. It represents a procedure on a macroscopic scale that provides a framework to integrate domain-specific design methodologies to design complex multidisciplinary products.

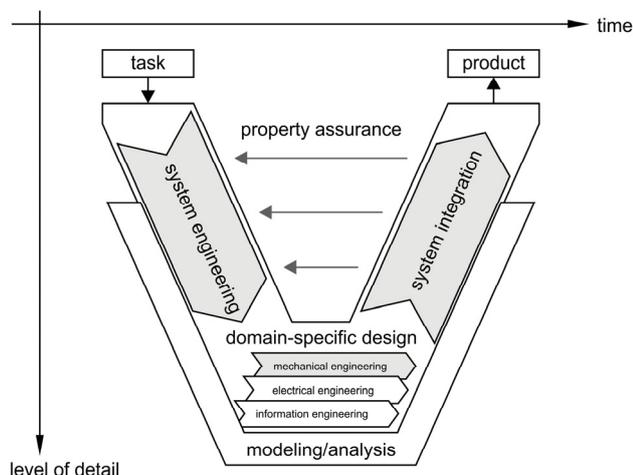


FIGURE 1: V-model acc. to [1, p.29]

The V-model processes a development task from the given requirements until a final product of a certain stage of maturity is achieved. The design phases of the V-model are

- 1) the system engineering, within which the multidisciplinary conceptual design is performed,
- 2) the domain-specific design, within which the design concept is split up into the involved domains and congruently designed and optimized by established methods and tools and
- 3) the system integration, within which the design solutions from the different domains are integrated into the design concept to form the final product.

Applying these process phases to a graph showing the level of design detail over the time leads to the V-shape (see FIGURE 1) of the model and its naming. Furthermore, it highlights the fundamental idea of the methodology to process a development task by quickly establishing a basic concept that is systematically increased in its design detail and after that integrated to the overall product solution. The design phases are constantly monitored by the property assurance. The property assurance guarantees the steady compliance of the design process with the demanded product requirements. Design solutions that do not meet the requirements inevitably result in back steps and demand for the reprocessing of design steps. The modeling and the model analysis represent the continuous analysis of the developed design and design alternatives by the use of models. Within the macroscopic working phases system engineering, domain-specific design and system integration various working steps have to be executed. [1] presents these working steps for the macroscopic working phases system engineering and integration. Guidelines and working steps for the domain-specific design can be found in domain-specific design methodologies. The structural design within the domain mechanical engineering can be processed according to the VDI-Standard 2221 “Systematic approach to the development and design of technical systems and products” [2]. Working steps for the system engineering and the domain-specific structural design are presented and its processing demonstrated in CHAPTER 3.

### 2.3. Process modules

Process modules are a specialization of the general problem-solving cycle predefined to execute certain recurrent working steps of the design process. A large number of process modules for various steps during the design process can be found in the literature. An extensive compilation of process modules and working tools can be found in [4,5]. Furthermore, a comprehensive assembly of process modules and its ability to handle particular working steps is provided by the VDI-Standard 2221 [2].

## 3. DEVELOPMENT OF A NOVEL AIRCRAFT OVERHEAD STOWAGE COMPARTMENT

The discussed development of a new generation of aircraft overhead stowage compartment is processed by the design methodology according to [1], presented in CHAPTER 2. The focus of the present work is on the multidisciplinary conceptual design realized in the system engineering and on the structural design as a part of the

domain-specific design. FIGURE 2 shows the V-model, its design phases and the main working steps as considered in the present development task. The organization charts inside the three main design phases indicate the repeated splitting of the investigated task into smaller sub-tasks that can be solved more easily and hereupon be reintegrated to the main solution. The gray shadings in FIGURE 1 and the green circles in FIGURE 2 indicate the process path presented in the current article. Basically all three phases of the V-model are treated by the general problem-solving cycle consisting of problem analysis, identification of solution alternatives and determination for one solution. The realization of the repeated problem-solving cycle is achieved by processing the working steps presented in FIGURE 2 by suitable process modules and tools.

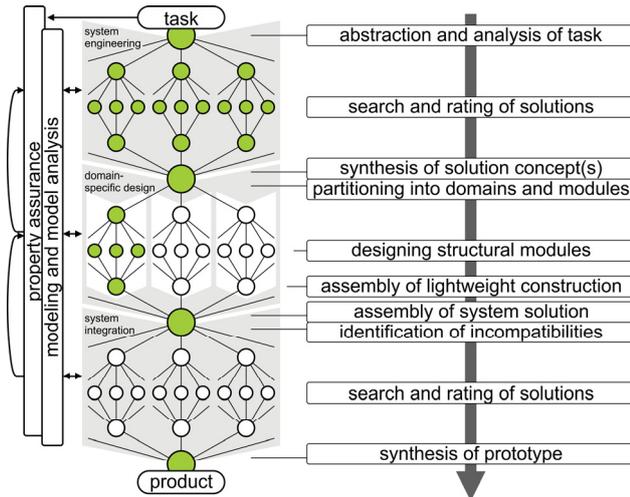


FIGURE 2: Working steps in V-model acc. to [1,2]

How to follow the guideline presented in FIGURE 2 and process the various working steps by the use of process modules and tools is demonstrated in the further chapters. Important to mention is, that the presented processing of the design steps is utile for the discussed development of an overhead stowage compartment but may vary for other design tasks. Furthermore, the design methodology is not a straight forward sequence of working steps as might be suggested. It is a flexible guideline within which the individual working steps and their processing are shifted in its order and repeated as required. Particularly, the constant update of the product requirements, due to the findings during the design process, frequently requires the repetition of design steps.

### 3.1. Development task

The development of an aircraft overhead stowage compartment underlies a large number of various requirements. These are on the one hand driven by safety issues that are mainly met by the regulations of aviation authorities like the European Aviation Safety Agency (EASA) in Europe or the Joint Aviation Authorities (JAA) in the USA. On the other hand the overhead stowage compartment as a part of the cabin has to ensure an ergonomic use, comfort, a generous feeling of space and a striking overall appearance for both passenger and crew. Additionally, the overall overhead stowage system has to be realized at a minimum of mass and an affordable price. Besides the standard requirements, the novel aircraft

overhead stowage compartment has to be innovative in terms of

- its ergonomic use,
- modular composition,
- reduced intersection with the primary structure and
- a significant increase of stowage volume and payload

at the same time with

- an improved feeling of space in the cabin and
- a reduced weight compared to existing products.

These clearly opposing development objectives represent the true challenge of the design task. Especially the need for a supporting actuator for closing the overhead stowage compartment due to the increased payload strongly raises the complexity of the development task and makes it difficult to comply with the given weight objectives.

### 3.2. Multidisciplinary conceptual design

The multidisciplinary conceptual design of the overhead stowage compartment is realized within the system engineering phase of the V-model. FIGURE 2 shows the basic steps as processed. The general working steps are

- 1) the analysis of the task requirements and its abstraction into functions and a system of sub-functions according to the ideas of systems engineering [3]. According to systems engineering every function of a design task can be split up into simpler sub-functions that are easier to solve but altogether realize the required function. This is indicated by the expansion of the organization chart in FIGURE 2.
- 2) the search of solution alternatives for all functions and sub-functions of the generated function structure and its rating based on the product requirements.
- 3) the synthesis of one or more multidisciplinary solution concepts based on the rated solution alternatives. This is indicated by the convergence of the organization chart in FIGURE 2.

Besides these working steps, the property assurance on the one hand provides a product values system, that represents the basis for the rating of the solution alternatives, and on the other hand monitors the compliance of the synthesized solution concepts to the given product requirements.

#### 3.2.1. Analysis of task requirements

The basis for any development process is the specification of a development task by a client. The specification of the discussed development of a novel aircraft overhead stowage compartment is represented by the requirements and product objectives presented in CHAPTER 3.1. For the stowage compartment the certification specification 25 (CS-25) [6] for large aeroplanes, provided by the EASA, and the primary structure of an Airbus A320 are considered. Furthermore, airplane manufacturer requirements have to be fulfilled. These are requirements such as a minimum width of the aisle, a minimum head clearance for people seated or the reachability of the personal service unit (PSU). FIGURE 3 presents a scale model of the A320 fuselage and some of the given geometrical constraints in the cabin.

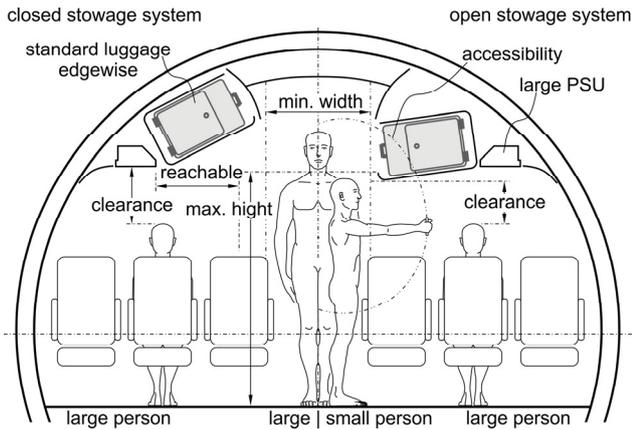


FIGURE 3: Geometric constraints stowage compartment

It is favorable to summarize all given requirements in a clearly defined requirement list [4]. In addition, [4] recommends to expand the requirement list by process tools such as a predefined question list or a life-cycle analysis. Main objective of expanding the requirement list is to capture the given task comprehensively, as it is essential for the design. For the given stowage compartment, the used predefined question list is presented in [4, p.220]. It contains a number of general characteristics a product has to comply during its life, starting with its manufacturing and ending with its recycling or disposal. Associating these characteristics with the given design task ensures that the requirements cover the whole product life or generates missing properties. Additionally, a product life-cycle analysis according to [4, p.219] is applied. The life-cycle analysis operates similar to a predefined question list. Eventually missing design requirements are found by associating the needs of the different phases of product life with the given task. In contrast to a question list, product characteristics are not predefined but have to be generated by the repeated thinking for:

- What happens in this phase of product life?
- Which needs and requirements are to comply?

These process tools highlight hidden product requirements. For the overhead stowage compartment, for example, the following needs of the installation phase are found additionally. All structural elements of the cabin including the stowage compartment

- must pass through the entrances of the aircraft.
- must be manageable by two workmen.
- must compensate manufacturing tolerances.

After the extensive analysis of the needed requirements of the given development task, a product value system is formed. This product value system is formulated by design objectives and represents the basis for decisions in the whole design process. These product design objectives summarize the defined requirements and give a general but very clear and short formulation of the needed design orientation. The above named requirements of the installation phase, for example, are summarized to the design objective “fast assembly” (see FIGURE 4). The selected formulation of the design objectives is the formulation with adjective, specifying the desired development orientation, and objective.

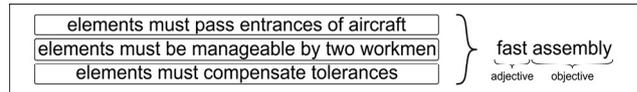


FIGURE 4: Formulation of design objective

Further design objectives defined for the discussed development of an overhead stowage compartment are e.g. maximized stowage volume, minimized mass, simple use, high reliability and maximized passenger safety. These design objectives guide through the whole further design process till the final product. Important to mention, the defined objectives are changeable due to new findings during the product design process. As a basis for design decisions the sole knowledge of the design objectives is not sufficient. Additionally, the design objectives have to be weighted against each other. This is particularly of importance, if two objectives oppose each other. A process tool to achieve the weighting of the design objectives is the comparison in pairs [4]. FIGURE 5 presents a section of the weighting of the design objectives for the considered overhead stowage compartment executed by the process tool comparison in pairs.

		design objective $A_j$						weighting $g_i$ $g = 1 \div 5$	
		max. stowage volume	minimized mass	simple use	high reliability	max. passenger safety	esthetic appearance		
How important is design objective $A_i$ compared to $A_j$ .									
more important... 1									
less important... 0									
design objective $A_i$	max. stowage volume	X	1	0	0	0	...	1	4
	minimized mass	0	X	1	0	0	...	1	5
	simple use	1	0	X	0	0	...	1	4
	high reliability	1	1	1	X	0	...	1	5
	max. passenger safety	1	1	1	1	X	...	1	5
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	esthetic appearance	0	0	0	0	0	...	X	1

FIGURE 5: Weighting of design objectives

The process is simple. Every defined design objective  $A_i$  is opposed to every other  $A_j$ . Is the design objective  $A_i$  more important than  $A_j$ , it is rated with “1”, if not, with “0”. Summing up all ratings of a design objective  $A_i$  (horizontal line) and normalizing the value with the maximum possible number, results in the weighting of the objectives to each other. In the presented weighting of the design objectives (see FIGURE 5) the weighting is normalized to a value between 1 and 5. The generated product value system, consisting of a number of design objectives with a defined weighting, is used to rate and decide in every further design decision in the product development process.

### 3.2.2. Analysis and abstraction of task

After defining the product value system, the actual design process starts. This is done by the analysis of the given development task for its basic objectives in terms of functions. Every product has one or more main functions that are realized by sub-functions [3]. The interaction of

the sub-functions is called functional structure. The number of sub-levels generated in the functional structure is dependent on the complexity of the product function that is to realize. Every additional sub-level of functions simplifies the generated sub-functions but also increases their number. That is to say, many sub-levels in the functional structure simplify the further finding of solutions but increase the effort. The analysis of the discussed aircraft overhead stowage compartment for its functions and their functional structure is carried out by the analysis of existing solutions according to [4,7]. FIGURE 6 demonstrates how four existing overhead stowage compartment concepts are analyzed for their functions and abstracted to general functions on different levels of the function structure.

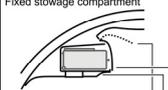
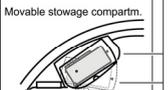
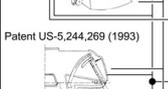
splitting to sub-components	functions	general functions	general main functions
 <p>Fixed storage compartment</p>	<p>control (information engineering)</p> <p>control compartment receive signals distribute signals</p>	<p>save information process information convert information</p>	<p>process information</p>
 <p>Movable storage compartm.</p>	<p>hold luggage isolate luggage resist damage isolate cabin</p>	<p>safe substance</p>	<p>safe substance</p>
 <p>Patent US-5,456,529 (1995)</p>	<p>structure (mechanical engineering)</p> <p>hold compartment resist damage guide compartment hold PSU isolate cabin</p>	<p>transport substance</p>	<p>safe substance</p>
 <p>Patent US-5,244,269 (1993)</p>	<p>actuation (electrical engineering)</p> <p>generate actuation force transform force to movement</p>	<p>convert energy transform energy</p>	<p>safe substance</p>

FIGURE 6: Function analysis of existing solutions

First, the four different concepts are split into the general sub-components control, structure and actuation. Second, all functions provided by the analyzed concepts are listed. Third, the functions are abstracted to general functions according to [7, p.16] and summarized in two levels to the main general function of the product, “safe substance”. The functions are formulated by two words, a substantive and a verb. Benefit of this formulation and the abstraction of the functions is a solution-neutral formulation of the task that enables an open minded search for solutions. The function structure found by linking the functions and sub-functions is presented in FIGURE 7.

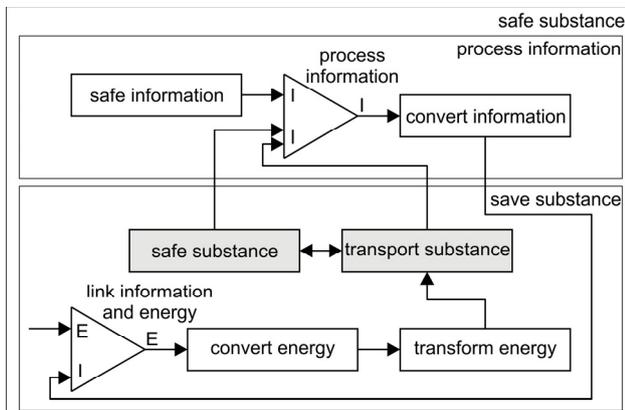


FIGURE 7: Function structure of stowage compartment

The function structure has to realize the required general main functions. The analysis of the functions and its interactions supports the understanding of the overall task. It is possible to find more than one functional structure. For the discussed development task only the functional structure presented in FIGURE 7 is considered.

### 3.2.3. Search and rating of solution alternatives

The working step search and rating of solution alternatives analyzes every single function found on all levels of the function structure. The used process to search and rate solution alternatives is presented in FIGURE 8. This general process is exercised for every found function.

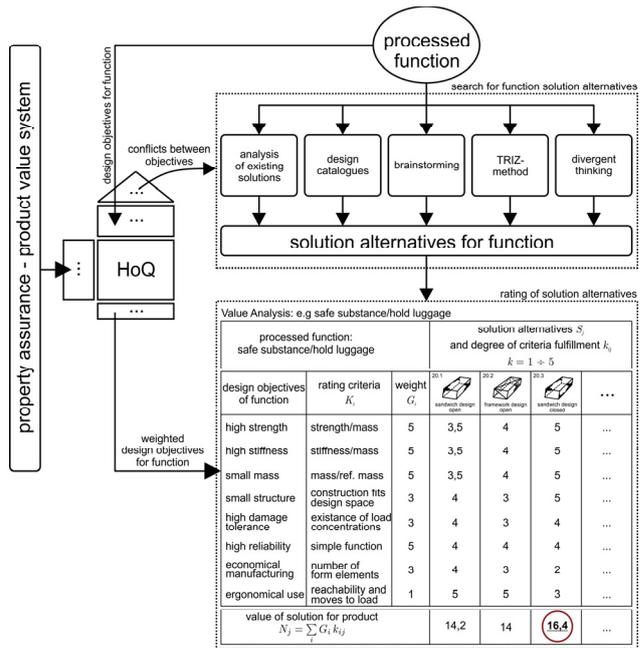


FIGURE 8: Search and rating of function solutions

The process presented in FIGURE 8 is a combination of various process tools. These can be summarized into process tools to

- link the product value system and the design objectives of the processed function,
- search for solution alternatives for the processed function and
- rate the found solution alternatives.

For the discussed development task of an aircraft overhead stowage compartment the process presented in FIGURE 8 is executed as follows:

- 1) Analysis of function requirements and definition of design objectives equally to the procedure presented in CHAPTER 3.2.1.
- 2) Weighting of the design objectives for processed function by comparing them to the product value system represented by weighted product design objectives. This is achieved by the process tool “House of Quality” (HoQ) according to [8]. The HoQ opposes the design objectives of the product to the design objectives of the processed function similar to the comparison in pairs presented in FIGURE 5. Additionally, the compliance matrix (the roof of the house) is generated. The compliance matrix

compares the design objectives of the processed function and highlights conflicts between objectives, i.e. the true challenges in the design task. This information can be used to focus on specific problems in the search for function solutions.

- 3) Searching for solution alternatives for the processed function using
  - a) the investigation tools, analysis of existing solutions, design catalogues and TRIZ-method,
  - b) the intuitive tool brainstorming and
  - c) the discursive tool divergent thinking.
 More detailed information to the application of the used tools can be found in [4,5].
- 4) Rating of found solution alternatives based on the weighted design objectives obtained by the HoQ. The rating is processed by a value analysis according to [9]. The value analysis rates the value of a solution for the product. It is performed by the derivation of rating criteria  $K_i$  for the given function design objectives, analysis and determination of the normalized degree of fulfillment  $k_{ij}$  for each rating criteria  $K_i$  and solution alternative and summation of the product of weighting  $G_i$  and degree of fulfillment  $k_{ij}$  for each solution alternative (see FIGURE 8). The normalization of the degree of fulfillment  $k_{ij}$  is done according to [10] by the definition of a minimum and an optimum fulfillment of the rating criteria  $K_i$ . Further normalization methods see [10, p.42].

The presented procedure generates a large number of rated solution alternatives for the investigated functions. In order to arrange the multitude of solution alternatives clearly, the VDI-2222 Bl.1 [2] presents the solution matrix (also called morphological box) as a useful tool. For the discussed overhead stowage compartment two solution matrices are created. One solution matrix lists the found functions and its solution alternatives from the analysis of existing solutions and a second solution matrix lists the solution alternatives for the generalized functions (see FIGURE 6). FIGURE 9 shows a section of the created solution matrix for the generalized and summarized product functions and FIGURE 10 for the found product functions. All investigated functions are listed on separate horizontal lines together with its solution alternatives.

### 3.2.4. Synthesis of solution concept(s)

The synthesis of one or more solution concepts bases on the basic idea of the value analysis, that combining the most valuable solutions of sub-functions creates the most valuable solution of a main function. For the synthesis of the solution concepts of the overhead stowage compartment therefore the rating of all investigated functions is introduced to the solution matrices presented in FIGURE 9 and FIGURE 10. Consequently the most promising solution concepts can be found by combining the best rated solution alternatives of all functions considering the following aspects [4,5]:

- general design rules
- geometrical compatibility of solutions
- compatibility of solutions
- permanent assurance of properties

Incompatibilities between solution alternatives usually result in more than one concept.

processed general function	solution alternatives $S_j$		
process information	20.1 electronic	20.2 manuel	20.3 combined
save substance	21.1 above PSU	21.2 central	21.3 below seats
convert energy	22.1 box	22.2 net	22.3 hook
...	...	...	...

*Note: Red circles and arrows in the original image highlight a path from 20.3 to 21.3 to 22.3, leading to a 'solution concept' label.*

FIGURE 9: Solution matrix for general functions

The simple combination of a number of function solutions often fulfills the demanded overall product design objectives only poorly. An improvement of a concept can be achieved by the variation of one or more function solution alternatives following the order of the rating.

processed function	solution alternatives $S_j$		
control compartment	10.1 decentralized	10.2 centralized	...
receive signals	11.1 push-button	11.2 inductive/capacitive sensor	11.3 mechanical force
...	...	...	...
hold luggage	20.1 sandwich design open	20.2 framework design open	20.3 sandwich design closed
hold compartment	21.1 framework design	21.2 sandwich desing	21.3 no secondary structure
guide compartment	22.1 rotation	22.2 translation and rotation	22.3 trajectory
...	...	...	...
generate actuation force	30.1 e-motor with gear box	30.2 pneumatic	30.3 hydraulic
move compartment	31.1 lever	31.2 spindle drive	31.3 rope with drum
...	...	...	...

*Note: Red circles and arrows in the original image highlight a path from 10.2 to 11.3 to 20.3 to 21.3 to 22.3 to 30.3 to 31.3, leading to a 'solution concept' label.*

FIGURE 10: Solution matrix for functions

The described process results in five solution concepts for the aircraft overhead stowage compartment. In order to spare resources and time during the domain-specific design phase only one of the five solution concepts is developed further. The selection of the most promising solution concept is again performed by a value analysis. The basis for the valuation of the solution concepts is represented by the product design objectives. The selected solution concept represents the multidisciplinary design concept of the novel aircraft overhead stowage compartment. FIGURE 11 shows a scale sketch of the final design concept.

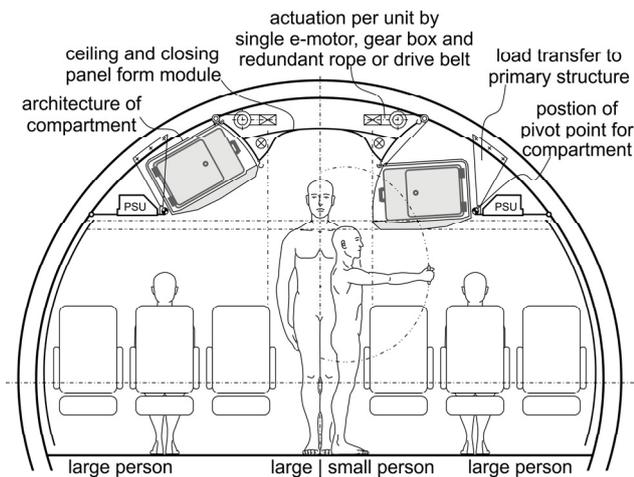


FIGURE 11: Multidisciplinary design concept of the novel overhead stowage compartment

The key elements in the final design concept are e.g.:

- the actuation of the overhead stowage compartment, realized by one single electric motor with gear box and redundant load transmission to the compartment faces via ropes or drive belts that prevents torsional loads on the stowage compartment.
- the realization of the opening/closing-kinematic as a single pivot point positioned at the lower back of the stowage compartment.
- the transfer of the inertial loads resulting from the payload and the compartment structure via pivot point and mechanical stops.
- the prevention of torsional loads in the structure by the mechanical stops.
- the statically determined transmission of loads at the pivot point by an in-plane attachment, a lengthwise profile and a tie-rod that absorbs lengthwise forces
- the use of the lengthwise profile to fasten the PSUs as required.
- the architecture of the stowage compartment consisting of sandwich elements with one side open.
- the monitoring of the loading edge to prevent the damage of payload or the injury of persons while closing the stowage compartment.

Furthermore, a first concept for the system control with input/output signals, actuators and energy sources is created.

### 3.3. Domain-specific structural design

The process of the structural design of the considered aircraft overhead stowage compartment takes place in the domain-specific design phase of the V-model (see FIGURE 1). The basic steps of the domain-specific design phase are shown in FIGURE 2. These are

- 1) the partitioning of the generated multidisciplinary concept into the involved domains and the definition of its interactions [1].
- 2) the generation of a domain-specific layout design and its splitting into modules with defined interactions that can be designed by established domain-specific methods and tools [2,11]. This process of, splitting the design task into smaller tasks called modules that can

be handled more easily, is similar to the procedure in the system engineering phase.

- 3) the design and optimization of all defined modules of the domain-specific layout by established domain-specific methods and tools [1].
- 4) the assembly of the designed modules to the domain-specific design [2,11].

Beginning with the domain-specific concept in working step 2, the domain-specific design can be carried out congruently in the involved domains and enables therefore a significant reduction of development time. Similar to the system design phase, the presented working steps of the domain-specific design phase are continuously monitored by the property assurance to ensure the compliance of the domain-specific design to the given product requirements.

#### 3.3.1. Partitioning into domains and modules

For the domain-specific design process the multidisciplinary concept presented in FIGURE 11 is partitioned into the involved domains mechanical, electrical and information engineering [1]. Within these domains separate domain-specific layout designs are created, considering all requirements and design objectives that are known from the system engineering phase. Interfaces between the domain-specific layouts have to be clearly defined. The advantage of this procedure is the possibility to congruently design the domain-specific layouts and therefore significantly reduce the development time. The further work exclusively deals with the structural design of the lightweight construction within the domain mechanical engineering (see green circles in FIGURE 2). FIGURE 12 presents the layout design of the lightweight construction of the novel aircraft overhead stowage compartment and one of the defined structural modules.

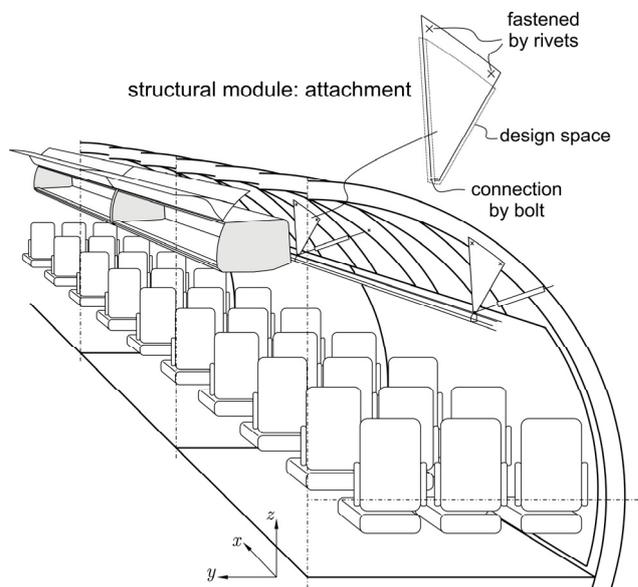


FIGURE 12: Lightweight construction layout

The splitting of the lightweight construction into structural modules bases on the following considerations [2,11]:

- A small number of modules reduces the design effort.

- The module design must be treatable by established and available domain-specific methods and tools.
- The modules must have clear module interfaces.
- The assembled modules have to assure the requested functions of the lightweight construction.

The requirements and design objectives a structural module has to satisfy are found by association of the already existing requirements and design objectives from the system engineering phase. Additional constraints are derived from the layout design of the lightweight construction. Essential requirements for the optimization and dimensioning of a structural module are

- the installation space within which the module can be designed (design space),
- the clearly defined module-to-module interfaces,
- the module and module-to-module interface loads,
- manufacturing constraints,
- recycling or disposal constraints and
- constraints regarding stiffness, strength and failure.

Further constraints can be application-specific. For the design of aircraft interior structures e.g. the very strict fire regulations and the cost intensive approval of new materials and manufacturing processes can be named.

A useful tool to estimate the module-to-module interface loads is the analysis of simplified models by analytical and numerical methods [12].

### 3.3.2. Designing structural modules

The designing of the structure modules bases on the requirements and constraints defined by the layout design of the construction and is usually processed by established and available domain-specific methods and tools. The design approach can vary strongly from application to application. In general, the design of structural modules is processed by

- finding the modules most advantageous topology,
- derivation of a realizable architecture,
- form optimization and
- dimensioning of the structure.

In the present work, the domain-specific optimization and dimensioning of the structural module “attachment” (see FIGURE 12) is outlined exemplarily. The development of the structural architecture of the considered attachment is carried out by topology optimization. The method is based on the finite element method (FEM) and represents unquestionable one of the most established state of the art methods to develop the architecture of a structural module. Essential for the quality of the results received from topology optimization is the knowledge of the applied loads, the boundary conditions, the available design space of the module and the defined optimization objective and its constraints. FIGURE 13 shows the topology optimization result for the discussed attachment generated by the solver OptiStruct provided by the CAE software-suit HyperWorks 12.0 from Altair Inc. Furthermore, FIGURE 13 shows the design space, the boundary conditions and the loads considered for the topology optimization. The defined optimization objective is the minimization of mass constrained by the maximum displacement of the load application point. The loading of the attachment, due to different compartment configurations, is calculated

analytically by a simple beam model of the construction layout (see FIGURE 12).

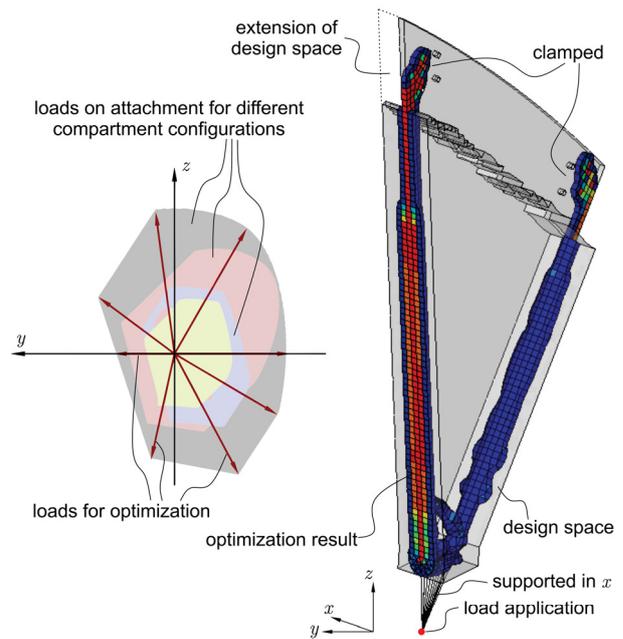


FIGURE 13: Topology optimization of attachment

The module architecture is derived from the result of the topology optimization by considering

- basic types and design principles for lightweight structures as e.g. presented in [13],
- available construction materials and its properties regarding the structural needs as e.g. presented in [14] and
- available manufacturing processes.

FIGURE 14 presents the final attachment design derived from the topology optimization by considering a metallic structure manufactured by milling. The form optimization and dimensioning of the attachment is carried out manually by repeated buckling and stress analyses of the structural loads. Both buckling and stress analysis are carried out by a linear static FEM solver.

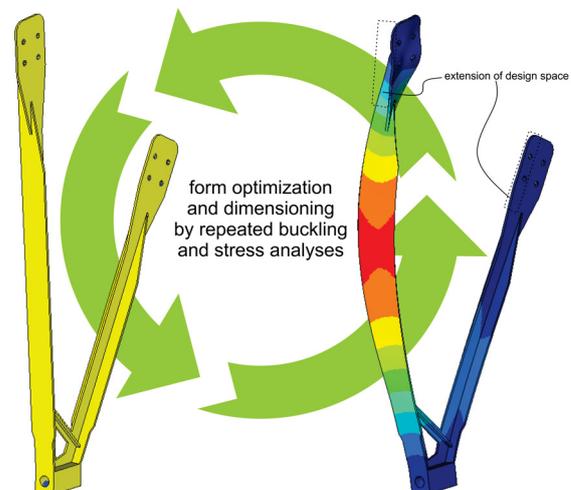


FIGURE 14: Final attachment design

Nowadays the form optimization and the dimensioning of the structure are often carried out by FEM based optimization tools. Nevertheless, it is crucial to the quality of the final design to accurately investigate optimization results by the analysis of the loads and its impact on the processed structure. Findings during this analysis can require changes in the optimization constraints or its objective. Furthermore, it can be necessary to rethink the given design space by returning to the defined construction layout. The buckling analysis of the discussed attachment, for example, ended in an expansion of the defined design space at the interface to the primary structure (see FIGURE 13 and 14). The achieved additional support by the primary structure produces a significant change in the buckling modes of the module structure.

### 3.3.3. Assembly of lightweight construction

The assembly of the optimized and dimensioned structural modules according to the construction layout generates the optimized lightweight construction. During the assembly of the lightweight construction typically the module-to-module intersections are designed in detail and the manufacturing documents are elaborated. Furthermore, it is a crucial checkpoint for the compliance of the developed structure with the product requirements and the feasibility of the whole construction. For the considered overhead stowage compartment, for example, it was necessary to step back to the conceptual design phase due to uncertainties regarding the reliable compensation of geometrical deviations of the installation location and manufacturing tolerances. The task was solved by a significant extension of the discussed attachment. It changed to a central element that guarantees little manufacturing tolerances and reduces the impact of geometrical deviations of the installation location by connecting the pivot point with the closing panel. Consequently the extended attachment got additional functions. These are to serve as a mounting location for the elements of the electrical actuation unit and to insulate the cabin acoustically. Furthermore, the ceiling and closing panel were separated which improves the accessibility of the primary structure for service purposes significantly.

After the redesign of the lightweight construction manufacturing documents are elaborated and statically adequate test bodies are manufactured. The lightweight construction is assembled in a test rack and tested regarding its installation properties, its haptic and appearance and its compliance with the demanded strength and stiffness properties. Particularly the compliance of the construction with the load requirements is crucial for lightweight constructions. Typically the performed structural tests come along with simulations that can be validated by the test results. This enables to do eventually necessary further development of the structure on basis of a validated simulation model. The advantage of reliable simulation results is the reduced number of physical tests necessary to develop a changing structure until it meets all demanded requirements. This reduces costs significantly.

## 3.4. System integration

In the system integration phase of the V-model the developed domain-specific solutions are integrated into the whole multidisciplinary mechatronical system. The basic steps of the system integration phase are presented in FIGURE 2. They are

- 1) the assembly of the domain-specific solutions.
- 2) the identification of incompatibilities between the solutions.
- 3) the search for solutions alternatives for the incompatibilities and the selection of the most advantageous alternative.
- 4) the synthesis of the final multidisciplinary prototype.

Similar to the assembly of the lightweight construction presented in CHAPTER 3.3.3. the continuous assurance of the demanded product properties is crucial for the system integration phase. The focus in this design phase is especially on the main functions the product has to guarantee by the interaction of the included domains. These have to be approved by functional tests. Appearing incompatibilities between domain-specific solutions or the unsatisfactory realization of demanded functions have to be analyzed and solved. Dependent on the nature of the problem, the problem can be solved by adaptations of the domain interfaces or, if necessary, by stepping back to the domain-specific or the conceptual design phase.

The final result of the system integration phase is a physical prototype of the novel aircraft overhead stowage compartment in preproduction maturity, approved to comply with all demanded requirements. Moreover the innovative character of the product is fully met by providing

- an increase of the stowage volume and payload by 33%, compared to the currently typical static A320 overhead stowage compartment,
- a very good accessibility and insight to the stowage compartment,
- an ergonomic loading of the stowage compartment due to the very low loading edge,
- an extremely comfortable electrically driven opening and closing of the stowage compartment,
- a generous feeling of space in the cabin and
- an esthetical appearance of the interior

at the same time with

- reduced intersection points to the primary structure,
- a removed housing,
- a modular construction enabling the adaption of the concept to different types of single-aisle aircrafts and
- a cabin weight similar to the currently typical static A320 overhead stowage compartment and moreover significantly reduced in relation to comparable movable solutions.

## 4. CONCLUSIONS

With respect to the very successful development of a novel aircraft overhead stowage compartment it can be concluded, that the design methodology for mechatronic systems provided by the VDI-2206 [1] is suitable to deal with multidisciplinary mechatronical tasks. The V-model according to the VDI-2206 [1] serves as a framework and guideline in which different engineering domains can be

combined to realize a multidisciplinary development task. In order to process a development task within the V-model according to the VDI-2206 [1] further domain-specific design methodologies and numerous process modules and tools are required. The selection of the domain-specific design methodologies, process modules and tools is free but has to be adapted to the given development task. For the given mechatronical development task of an aircraft overhead stowage compartment the processing of the V-model as presented is applicable. The systematic approach of the design methodology as processed seems to be very useful for a novel development task with many degrees of freedom. For adaptive design purposes the procedure might be too extensive (see also [11, p.15]). Procedures like the abstraction of the task into its real assignment in form of functions help to point out the actual development content. The systematic analysis of the product requirements and its assignment to appearing sub-design tasks supports the overall convergence to the development objectives. Splitting the complex development task into a system of sub-functions facilitates the solving of the overall task. The abstract and open minded generation of solution alternatives for functions provokes reflections of untypical solutions and therefore supports innovation. The possibility to integrate arbitrary available domain-specific design tools facilitates the development process. A constant communication and teamwork between the involved domains is crucial to all phases of product design. A disadvantage of the presented design methodology as processed is its time consuming procedure. Furthermore, it is difficult to realize the full optimization potential of a task within only one cycle in the V-model. Nevertheless, only one cycle in the V-model resulted in a high level of product maturity for the novel aircraft overhead stowage compartment. Moreover the applied procedure generated essential and innovative elements of the design concept by its focus on the actual development content and the solution-neutral and multidisciplinary design process.

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