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Integrating Variety, Assembly, and Lightweight Design in Product Architecture of Cabin Monument

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Abstract

In aircraft cabin design, particularly in the design of aircraft monuments such as galleys, there are specific conflicting objectives that needs to be balanced. The key objectives are to meet customer requirements, optimise assembly processes for increased production and achieve lightweight design for efficient operations. The paper presents a methodical approach that integrates variety, assembly efficiency and lightweight design considerations into the early stages of product architecture design. Using the after monument of the Airbus A320 family as an example, the paper proposes specific module drivers such as 'common unit', 'different specification' and 'load path compatible modules' to guide the design process. These module drivers aim to harmonise the different objectives of stakeholders, including aircraft manufacturers, cabin manufacturers and airlines. The method is illustrated using a geometric representation of product architecture alternatives optimised for each of the variety, assembly and lightweighting objectives. Overall, the paper contributes to the advancement of a stakeholder-oriented modularisation approach and provides a starting point for future developments. It highlights the importance of defining module drivers and visualising the trade-offs to achieve a balanced product architecture in the aviation industry.

Keywords: Aviation; Modularisation; Lightweight; Variety; Assembly

1. Introduction

When developing product families, engineers and designers are often faced with the challenge of balancing multiple and sometimes conflicting objectives. One area where this challenge is critical is the aviation industry. More specifically, cabin design, as it combines customer requirements with technical aspects. Here, aircraft monuments such as galleys bring together different requirements that need to be harmonised.

Today, the aircraft manufacturer has a full order book and is trying to ramp up production [1]. To achieve this, the assembly processes must be optimised and require efficient and standardised workflows to cope with high throughput times [2]. The cabin is made up of many individual parts, which can cause intermittent delays when assembled. The challenge for the cabin manufacturer is to reduce the complexity of its products in order to bring cost-effective, flexibly configurable products to the market [3]. The airline that will later operate the aircraft is particularly interested in lightweight cabins to ensure efficient operations [4], but also in the ability to flexibly retrofit cabins over a long aircraft life cycle [5]. Three stakeholders with different challenges and objectives are therefore involved in the product life cycle of cabin monuments in aircraft.

The extent to which these challenges come into play is already outlined in the early development phase as part of the product architecture design. It affects how well different requirements can be implemented in a product family. Insufficient variety-orientation in the design of the product architecture is perceived as an ongoing cost driver, especially by monument manufacturers. Variety-induced complexity

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causes costs, e.g. due to a variety of processes, costly warehousing or additional maintenance and development costs for numerous variant components [6]. A product architecture that is not optimised for assembly becomes a cost driver for the aircraft manufacturer due to long or error-prone assembly processes. Failure to consider lightweighting targets will in turn result in ongoing costs to the aircraft owner during operation. The difficulty in the product development process, however, is that the product architecture must be defined in the early concept phase [7], long before manufacturing or assembly processes are defined, materials selected or wall thicknesses calculated. On the other hand, the design of the product architecture limits the possibilities for design optimisation by defining interfaces and module boundaries and assigning functions to modules.

The second challenge is that these three objectives are partly contradictory. For example, a variant-oriented product architecture can be achieved by designing small, standardised modules, while an assembly-oriented product architecture focuses on standardised interfaces and few assembly processes, i.e. large modules. Lightweight design, on the other hand, emphasises functional integration and the reduction of interfaces. Figure 1 illustrates this challenge in the form of an objectives triangle, with coloured zones indicating the qualitative importance of each objective.

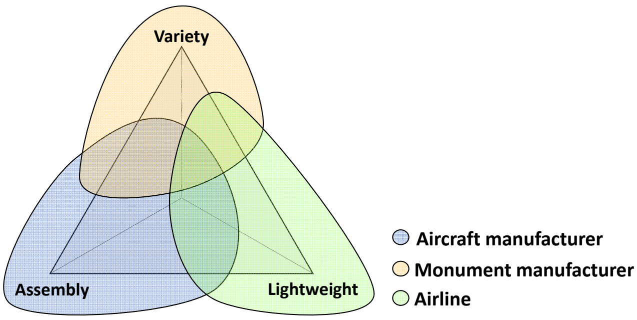

Fig. 1. Objectives triangle of variety, assembly and lightweight.

Accordingly, in addition to lightweight design, the airline also wants its many individual requirements to be implemented well and cost-effectively; the lack of an assembly-oriented design of a monument is only of secondary importance to it if the costs of purchase or retrofitting are high. In addition to assembly-oriented design, the aircraft manufacturer is also interested in reducing the costs associated with variety and the weight of the monuments. The latter is relevant in order to be competitive and to meet aviation standards. For the monument manufacturer, a lack of assembly orientation in the design of the product architecture is also considered to be an ongoing cost driver. However, the components and interfaces involved are different to those of the aircraft manufacturer.

The research question is therefore: How can the partly conflicting goals of variety, assembly and lightweighting be taken into account in the early development of an aircraft galley product architecture?

2. Methods and Materials

2.1. Aircraft Cabin and Monuments

In this paper, the monument at the rear of the Airbus A320 family is used as an illustration (Fig. 2). Customers can choose from three different product families: a full-size galley (G5) and a half-size galley (G4) with space for either three or four trolleys. G4 galleys are complemented by one or two lavatories.

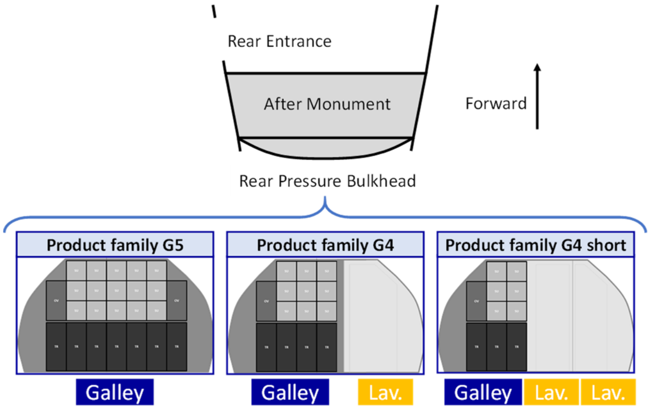

Fig. 2. Monument families at the rear of Airbus A320 family, adapted [8].

The modular design of the multi-variant galley is the focus of this article. The top row of the galley is usually equipped with standard containers or storage compartments closed by a door. In the middle area, the customer can choose from a range of electrical appliances, such as different versions of ovens, beverage makers and refrigerators. The centre compartments can also be used for various storage compartments or fitted with standard containers. In the case of electrical appliances, the compartments need to be fitted with appropriate interface modules, while standard containers require an additional shelf. The lower galley area is usually reserved for different types of trolleys, such as half and full-size trolleys or trash compactors. Various cooling options are also available for trolleys.

Retrofits often involve the installation of new galley equipment or the replacement of galley equipment with standard containers and vice versa. It is also possible to replace full-size galleys with half-size galleys and to change the number of lavatories adjacent to the galley. When major changes are made to the configuration or equipment, a complete replacement of the galley is inevitable, especially in case of adding or changing lavatories. For this purpose, the galley, which is made of laminated sandwich structures, has been provided with defined dismantling lines, so-called split lines. Equipped with two horizontal split lines, the galley is divided into approximately three equal parts, allowing it to be replaced through the rear entrance door when the aircraft fuselage is closed.

2.2. Product Architecture and Modularisation

Product architecture is defined as the allocation of the product functions to its components [9]. As these are usually arranged in the form of a hierarchical product structure, the product architecture is further defined as a representation of the functional structure against the product structure. The product architecture is the result of a modularisation process.

Modules consist of components with certain common characteristics that are treated as a logical unit. Modularity is described as a gradual characteristic of the product structure [10] and can be expressed using the characteristics and properties of commonality, combinability, interface standardisation, function binding, decoupling and oversizing [11]. In addition to technical-functional requirements, product strategic goals for the product should be considered for modularisation [10]. For example, it may be useful to combine into a decoupled module those elements of a product that have a shorter lifetime than the other elements, or those that will be upgraded during the product's lifetime. These reasons for the arrangement and design of modules are called module drivers [12]. All components that can be assigned to the same module driver should ideally be combined in one module. The goals and thus the module drivers for the product structure and its form change over the product life phases [12], whereby the term module is not restricted to physical modules [13]. For example, the modular structure of a product that is assigned to individual design teams during the development phase may not be the same structure that is assigned to different production lines during assembly.

The assignment of module drivers can be represented for each product life-phase, e.g. in a network diagram. The results of the network diagrams are then summarised across the product life-phases in a flowchart representation called a Module Process Chart (MPC) [13]. By summarising the different objectives or module drivers and perspectives on the product architecture in this way, contradictions can be identified and compromises can be made. [14].

Module drivers are therefore an essential concept in the context of modularisation, especially in the case of conflicting objectives. However, as module drivers cannot be formulated in a universal way, but have to be derived specifically depending on the goal of the product design, further and new module drivers can be found in recent studies, e.g. [15]–[17].

2.3. Design for Variety, Assembly and Lightweight

In line with the aim of the article, the topics of 'Design for Variety', 'Design for Assembly' and 'Design for Lightweight' are presented here as a methodological basis. In particular, approaches are sought that already represent a combination of the respective topics or product architecture design. This often takes the form of specific module drivers.

The perception of variety is divided into an internal and an external view. The external view refers to the variety of functions and features of the product family as perceived externally by the customer, while the internal view refers to the number of variant parts and components as perceived internally by the company. The term 'Design for Variety' covers approaches that aim to reduce the external variety to an optimal level, e.g. [18], or those that try to keep the external variety for the customer, but only optimise the technical implementation, e.g. [10], or those that do both, e.g. [19].

The modular structure and the variety of a product are thematically closely related, so there are already established methods that treat these aspects together. One way to make variety visible in product structuring is to visualise it using colours or shading on the product structure. One such geometric representation is the Module Interface Graph (MIG) [10]. Internal variety can also be represented by mathematical models and calculated as a key value for the whole product or counted per component.

With regard to module drivers, technical and functional modularisation is often referred to in order to increase functional integration in the modular structure [13], [15]. This usually requires the use of additional methods. It is therefore not a module driver in the strict sense. Brunoe [16] also mentions 'common unit' and 'different specification' as module drivers in this context. The former refers to the standardisation and reuse of certain modules with the same functionality across the product portfolio. The latter refers to the decoupling of variety-relevant characteristics of products from standardisable modules as far as possible.

‘Design for Assembly’ aims to simplify and optimise assembly processes. Appropriate design guidelines are intended to prevent assembly errors, reduce auxiliary processes such as tool changes, design ergonomic processes and generally reduce assembly times. This can be achieved, for example, by reducing assembly processes through the use of modular structures or by standardising assembly processes for different product variants [20].

Emmaty and Sarmah [21] combine the topics of modularity and assembly by applying the objectives of design for assembly and manufacturing within the framework of product architecture design. These are the reduction of parts and modules and the increase of commonality between the modules. Halfmann et al. [22] analyse structuring measures on the product to show the impact on the assembly process. The approach includes diagrams that integrate a product structure representation into an assembly priority graph. However, both approaches require knowledge of assembly processes and materials for their application. In the early product development phase, especially for new designs, this information is usually not available.

In this context Erixon [12] mentions the drivers 'common unit' and 'process reuse', where assembly processes can also be standardised and reused by reusing parts. This requires greater commonality of components. These module drivers are similar to the assembly guidelines of [20]. Brunoe [16] adds the ‘outsourcing of work content’ as a possible driver to those of [12]. A complementary list of drivers can be found in Halfmann et al. [22], which can mainly be applied using the production process analysis method presented there. ‘Parallel production’ reduces throughput time and can be achieved by modular decoupling. ‘Separate testing’ allows product and process errors to be identified before final assembly. ‘Postponing the generation of variants’, allows processes to remain the same for as long as possible and product design to remain flexible and adaptable for longer.

For 'specific assembly processes' that are clearly associated with particular assembly lines or production machines, assignment to a module can be helpful. Finally, modules can also be adapted to ensure an appropriate scope of work for an 'organisational unit', such as an assembly robot or a work cell.

With regard to ‘Design for Lightweight’, there are a number of design guidelines to consider. Functional integration leads to a reduction in components, which can result in a more compact, vibration resistant and lighter design [23]. In addition, the reduction in components means fewer interfaces, which reduces weight [24]. The best compromise between structural reinforcement and additional weight can be achieved by optimising the topology of the structure [25]. There are two issues to consider, the correct load size and the optimal load path. In determining the optimal load paths, the design must be chosen to ensure that large forces in the design space can be transferred well across product variants.

Gumpinger et al. [26] presented modular lightweight design to address the challenge in aviation of combining a variant modular structure with the requirements of lightweight design. In the methodical approach, a modular product architecture is defined in the concept phase. The defined modules are then optimised for lightweighting during the design phase. Hanna et al. [27] addressed the conflicting requirements in the development of aircraft cabins in an early development phase. On the one hand, there is a high degree of variance due to individual customer preferences dictated by the airlines, and on the other hand, weight reduction through lightweight construction is of paramount importance. However, no specific module drivers resulting from lightweighting could be identified in the reference papers.

In summary, existing work that considers the three goals of variety, assembly and lightweighting in product architecture design only focuses on one of the goals at the same time. This is done either by using special module drivers or by using formal methods, which are only limitedly suitable for the early development phase. Adding missing module drivers for the addressed goals and applying them to the product architecture therefore seems to be a suitable strategy for the early development of galley monuments.

3. Methodological Approach and Results

The methodological approach is to first define the specific module drivers for those goals for which there are no module drivers yet. Then to use these accumulated module drivers to set up alternative product structures. This is done individually for each goal. The product structures can then be harmonised into one consistent structure that represents a compromise between the objectives. This follows in principle the life-phase modularisation approach of [10], [13], but with a difference in the way it is presented.

The use of the network diagram for modular structuring per life phase is difficult to implement for the given cabin monument. An individual and comprehensible labelling of each sandwich panel of the galley, which would be necessary for the application of a network diagram, is difficult to define. The system level of the existing module structure is also too coarse, as the galleys consist of only three large, integrally manufactured modules with various attachments. For this reason, we use a graphical-geometric representation of the product structure for each goal and the associated module drivers.

3.1. Modularisation of the After Monument Product Family

The modularisation of the product families starts with the current situation. Fig. 3 shows the simplified product structure of the after monument product families as they will look after manufacturing, but without the installation elements, i.e. trolleys, standard units and the various galley inserts (GAINs). The illustration is based on a MIG after [10] and uses colouring and line type to show the variety of galley cabinets and built-in elements such as doors and interface rails for the GAINs. However, system connections such as electrical, water supply, waste water, cooling air and exhaust air are not shown for simplicity and because they will not be investigated further at this stage.

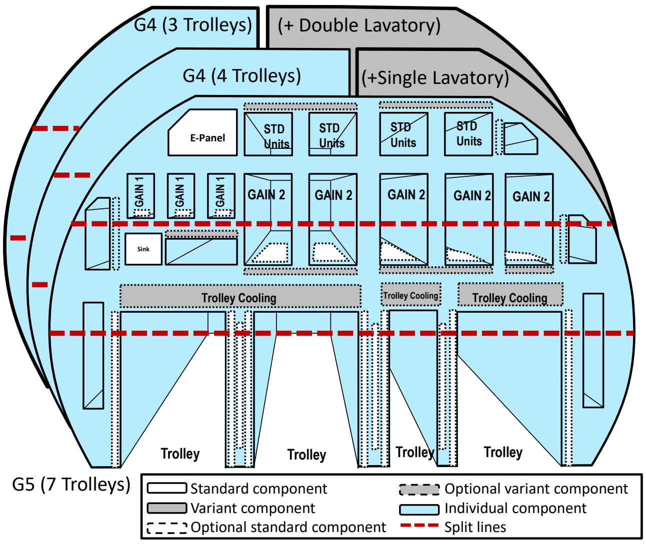

Fig. 3. Product structure and variety of after monument.

If the module drivers 'common unit' and 'different specification' are now applied to this structure to address the goal of variety, a structure as shown in Fig. 4-A is created. The perceived variety from the monument builder's point of view would be significantly reduced compared to the actual state. In Fig. 4-A, the G5 galley is divided into three parts by vertical split lines and is oversized or standardised to allow all customer configurations to be met by combining vertical modules and other optional parts. For example, the trolley cooling components have also been decoupled and the GAIN Size 2 compartments (Fig.3, middle row) oversized to the extent that only an additional horizontal compartment divider or alternatively a GAIN 2 interface element is required to vary the configuration of ovens, refrigerators and standard units. The division into three sections also satisfies the 'future reconfiguration' module driver, as it avoids the need to replace the entire galley in the event of a future retrofit.

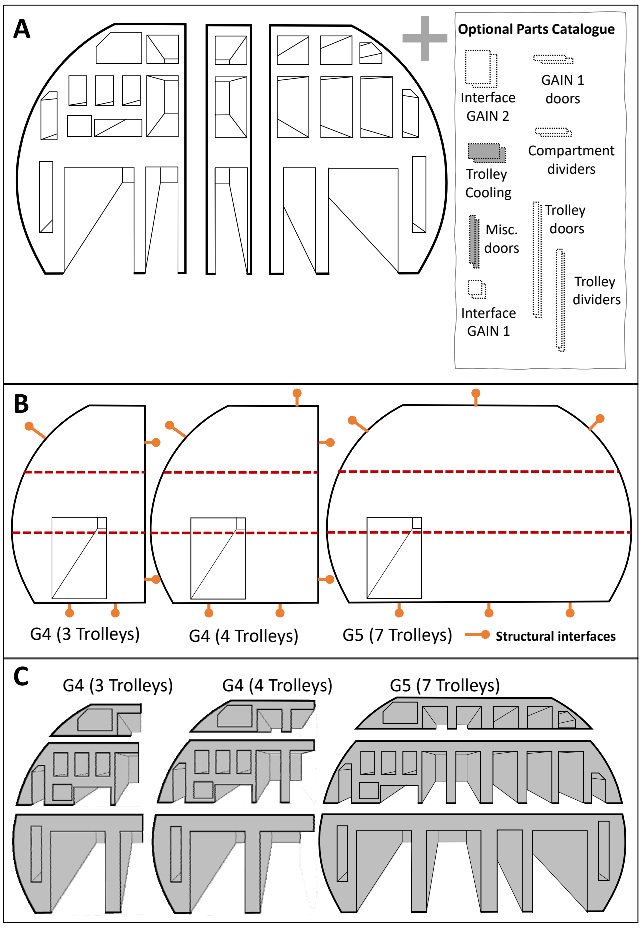

Fig. 4. A) Variety-oriented, B) assembly-oriented and C) lightweight-oriented product structures.

From the perspective of final assembly in the aircraft, the module drivers 'specific assembly processes', 'organisational process unit' and 'disassembly through the door' are relevant. It is therefore advantageous for the galleys to be delivered to the assembly line in a pre-assembled state and to be fitted to the structure via standardised interfaces. Only one installation shaft is required for the system connection. From the aircraft manufacturer's point of view, there are therefore only three galley variants (G4, G4 short and G5), which do not differ in the way they are connected to the structure, but only in the number of structural interfaces (Fig. 4-B). Furthermore, it is best to have two horizontal split lines that divide the galley monuments into three equal parts and allow disassembly through the door.

From a lightweighting perspective, module drivers can be derived from design guidelines. These can be related to the product architecture or to the properties and features of modularisation (commonality, combinability, interface standardisation, function binding, decoupling and oversizing). From the overview of lightweight design guidelines, it can be summarised that the correct load size and load path are crucial for material distribution, and functional integration and avoidance of oversizing are important for reducing interfaces and therefore weight. Using the module driver 'load path compatible module', unnecessary material is avoided and large modules are created. These are cut horizontally between compartments to avoid both interfaces and double floors between modules (Fig. 4-C). However, these split lines are not suitable for disassembly through the door. The 'integral design' module driver aims to avoid oversizing and therefore interfaces by connecting monument modules and additional elements integrally. For example, reconfiguring between ovens and standard units in the GAIN 2 compartments results in a variety of centre compartment modules rather than optional add-ons and oversized compartment modules.

When these drivers are harmonised to form a product structure, a product concept as shown in Fig. 5 is possible. The modules are designed to satisfy the module drivers 'load path compatible modules', 'door disassembly', 'different specification' and 'future reconfiguration'. The assembly of the monument in the aircraft, and therefore the module driver 'organisational process unit', is largely unaffected by the modular structure, as the galley monument can still be delivered pre-assembled to the final assembly line. However, the final allocation of the stabilising walls to the individual modules still requires static calculation. This also means that the number of interfaces between modules cannot yet be determined. The specific compromise between targeted over-dimensioning for the benefit of variety reduction and targeted creation of variance for the benefit of lightweight design requires an iterative development process as well as key figures for evaluating and comparing the respective target values.

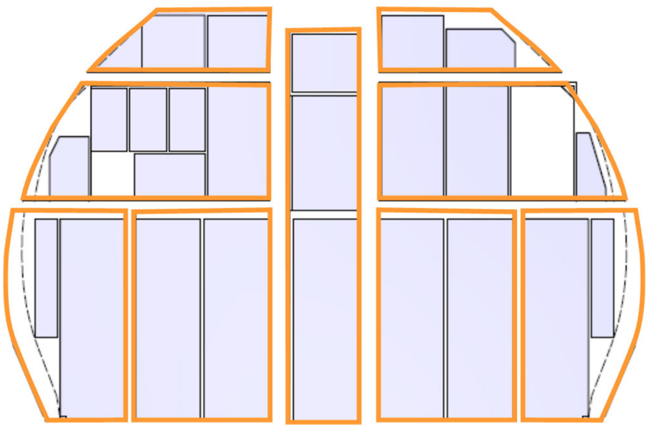

Fig. 5. Harmonized product structure for after monument family

4. Conclusion

To address the research question of how the goals of variety management, ease of assembly and lightweight design can be taken into account in the early development of a product architecture for aircraft galleys, a life-phase modularisation using module drivers is presented. Existing module drivers are applied and specified for the aviation industry, and new module drivers for lightweight design are derived. The visualisation of the product structure alternatives is presented in the form of a geometric representation instead of network and component flow diagrams. The new module drivers and the form of visualisation represent a novelty compared to the state of the art.

Furthermore, the objectives of variety management, ease of assembly and lightweight design also correspond to the primary objectives of the three stakeholders, airline, aircraft manufacturer and monument manufacturer, each of which becomes a key player at different points in the product life phase of the product family. The presented approach thus allows not only a life-phase oriented but also a stakeholder-oriented view on the product architecture.

In future research efforts, however, the approach requires further differentiation both at the level of the conceptual design of the product architecture and in the later steps of balancing and optimising the conflicting objectives. For example, technical-functional modularisation could be used to better address the goals of functional integration and interface design or reduction. This article is therefore a starting point for stakeholder-oriented modularisation, for which a multi-factorial optimisation and evaluation procedure needs to be developed in future research efforts.

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