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Impact assessment of design guidelines in the conceptual development of aircraft product architectures

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Abstract

The optimization of the assembly phase, in complex products, is a challenging phase and it need to be handled in the early phase of product development (i.e., conceptual design). Several methods have been developed to assess the assemblability of product at the conceptual design phase, however, the most critical aspect concerns the possibility to derive design guidelines starting from the results of assemblability analysis. In this context, the present work aims at defining a methodology able to retrieve design for assembly and installation guidelines starting from the analysis of a given product architecture at the conceptual design phase (loop-back of the design for assembly method). The developed method makes use of matrices and vectors to provide a list of design actions that affect the product assemblability including a ranking of their impacts on the final design. The methodology was used to retrieve and select design guidelines in the context of aircraft manufacturing. The case study (cabin equipping of commercial aircraft) provides interesting results in the identification and implementation of design guidelines to improve the aircraft architecture at the conceptual level.

Keywords: Conceptual design; Product architecture; Design for Assembly; Aircraft; Knowledge formalization; Design Guidelines

1. Introduction

The product development process (PDP) is mainly characterized by four phases: (i) planning and task clarification, (ii) conceptual design, (iii) embodiment design, and (iv) detail design [1]. The PDP is primarily focused at the design process itself without considering interaction between designers and other departments, such as the manufacturing department. Evolution of this framework has been proposed by Boothroyd et al., in which interactions among departments are supported since the initial phase of the design process [2]. This paradigm, called concurrent engineering (CE) aims at optimizing the design process by considering all product aspects from the beginning, breaking barriers between different departments [3]. Many methods are counted as part of the new PDP, such as Design for X (DfX) methods [4][5], where the “X” is replaced with the optimization target (e.g., assembly, manufacturing, etc.). The design for manufacturing and assembly methods (DFMA) is the first family of DfX methods that was developed. DFMA methods aims at optimizing the process and cost of manufacturing activities of subsystems by using the product own proprietary data [6]. In the aerospace field, product assembly is often overlapping with product installation. Assembly is the process by which modules/components are fixed together or with the primary structure to obtain the final product, while installation is the process by which harnesses, cables, pipes, etc. are fixed and connected to link the modules/components [7]. Within the aircraft manufacturing, assembly and installation processes are usually performed at the same time. Always within the aerospace field, few attempts in the development of DFMA methods have been done: Lockett et al., [8] applied DFMA techniques with the help of CAD

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software to identify small changes to improve wiring system installation tasks; Barbosa et al., [9] collected a set of design guidelines that can be applied during the aircraft design to improve the assembly and manufacturing performance, while Butterfield et al., [10] proposed a method to make use of digital manufacturing techniques with the aim to evaluate the assembly process of an aircraft fuselage in the final assembly line. However, the adoption of DFMA methods is limited and few issues were highlighted within the literature. The first one is the elevate number of information required to implement DFMA methods that are mainly available at late design phases. The second one is the presence of constraints such as safety or weight limitations which are currently not addressed within the available DFMA methods. To cope these issues, few research works were developed working at the conceptual level, when only general information are available such as product requirements, functions, etc. [11][12]. Among design methods and tools applicable at the conceptual level, Domeshek et al., [13] developed a tool that, by collecting previous airplane design, can be interrogated to provide useful information during the conceptual design phase. Other methods allow to create schemes to represent the collected information [14][15], describing how product functions are allocated to the physical components which is known as product architecture [16]. The improvement of the product architecture can positively impact the assembly phase [17], especially when modularity is aimed. Indeed, the creation of a modular product leads to advantages such as reduction of interface complexity between product parts, easier product maintenance, reduced development costs, creation of product family and many others [18][19][20]. The idea of modularity is relatively new for the aeronautical sector and some researchers were focused at modularity to improve assemblability of aircraft sub-parts [21][22][23]. Product modularization could be also beneficial in terms of aircraft design for assembly as described by Bouissiere et al., in the Conceptual Design for Assembly (CDfA) methodology [24]. However, even if the proposed approach is a powerful tool to assess aircraft product architectures using information available at the conceptual design phase, it fails in providing useful indications (i.e., design guidelines) to reduce the product architectures' complexity.

The present paper moves towards two goals that are closing the current limitation observed by the literature analysis: i) it allows to derive a list of design guidelines starting from the CDfA methodology, and ii) it allows to choose the most impacting design guidelines oriented to fit for assembly performances and optimized architectures. The method makes use of the CDfA method (parameters, criteria, and evaluation score) to derive a list of design rules. Afterwards, by the definition of a *Design Correlation Matrix (DCM)*, each design rule is evaluated in relation the specific model (the CDfA methodology), providing an impact assessment tool to identify the design rule which affect the most module assembly in a given architecture. The impact assessment method was tested on a specific case study: the cabin modules assembly of a civil aircraft. Results highlight that the impact assessment method allows to identify the most impactful design guideline which can be selected as first in the re-design process of an aircraft product architecture. The paper is structured as follow: after this Introduction (1), the proposed method is presented in Material and Method (2) along with a short description of the CDfA approach. Then, the Case Study (3) of a cabin interior installation is described, and Result and Discussion (3) argued. Finally, Conclusion (5) are presented.

2. Material and Method

The Conceptual Design for Assembly (CDfA) methodology proposes a framework and a mathematical model to assess the assemblability of complex product architectures (i.e., fit for assembly) with conceptual design data [24]. The method can be applied on product architecture modules and/or interfaces, obtaining one single score for each element analyzed. Starting from the functional representation of the product, functional modules and interfaces are graphically represented with the functional scheme [25]. Then, from the functional scheme, a simplified digital mock up is obtained by using conceptual design information. The simplified digital mock up is mainly composed by basic geometrical figures (i.e., cylinders for connections/interfaces, boxes for modules, etc.). The core of the methodology is the hierarchical structure created to translate the simplified digital mock up information from graphical to numerical, allowing to perform mathematical computations. The structure is composed by *attributes*, *domains,* and *levels*. An *attribute* is a key feature that influences assembly operations, and it is referred to a specific aspect related to the assembly operation. A *domain* is a cluster of one or more attributes that address the same assembly aspect and provides the same meaning for each designer/engineer. Finally, a *level* is defined as a group of domains. Levels are used to divide the main problem (i.e., overall product architecture) into sub-groups of smaller complexities (i.e., a given compartment or a given area). To move from one level to another one is necessary to define a product invariant. A product invariant is a design feature that does not change and cannot be changed within the product under study. The hierarchical structure is presented in Fig. 1.

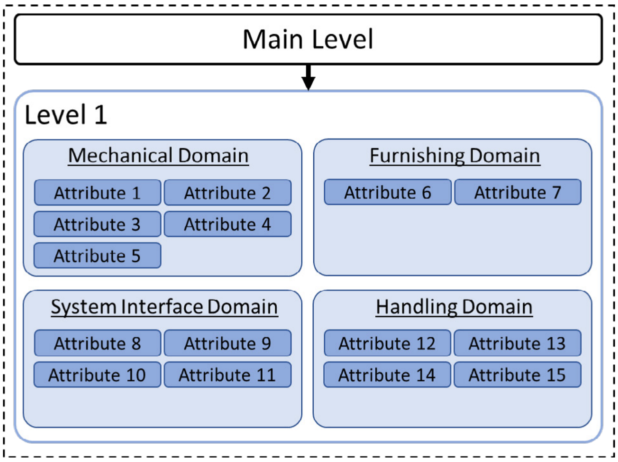
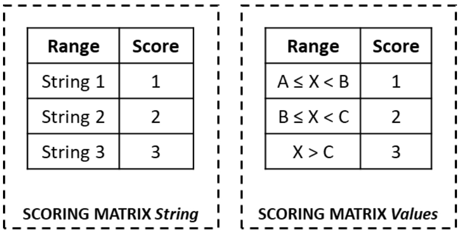


Fig. 1 - CDfA hierarchical structure

Since attributes represent different heterogeneous information, they need to be normalized before being combined into a single score. To do so, information inside attributes is normalized using scoring matrices [26]. A *Scoring Matrix* is the final results of a knowledge-based approach, where tacit implicit knowledge from manufacturing and assembly department is translated into explicit knowledge which can be used by engineers and designers. A scoring matrix is a table that allows to normalize information for each attribute (i.e., from string or number to a value), and it represents the current technological level of the company (Fig. 2).



Range	Score
String 1	1
String 2	2
String 3	3

SCORING MATRIX *String*

Range	Score
A ≤ X < B	1
B ≤ X < C	2
X > C	3

SCORING MATRIX *Values*

Fig. 2 – Examples of scoring matrices

Once all attributes are normalized by the use of the scoring matrices, the normalized values are collected using mathematical operators. For the sake of brevity, the overall CDfA approach is not discussed here. Further information can be found in previous works of the same authors [24][25][26]. By using the given framework (CDFA methodology), and the scoring matrix (knowledge database), a final score for each interface and for each module is provided showing the most critical item to install (module) or the most critical connection (interface). Although the mentioned scores are very useful to assess and to understand the assembly complexity and where the designers should focus on, the CDfA method does not strictly provide any design suggestions about how to improve the product architecture. With the aim to progress on this field, here below (Fig. 2) is presented the impact assessment workflow which aims at defining design rules and identifying the most impacting one to implement. The method is based on four steps: (i) derive *Design Guidelines (DG)*, (ii) derive *Design Correlation Matrix (DCM)*, (iii) retrieve *Elements Vector (EV)*, and (iv) compute *Design Guideline score (DG_score)*.

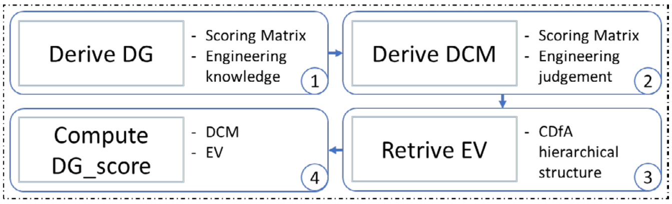


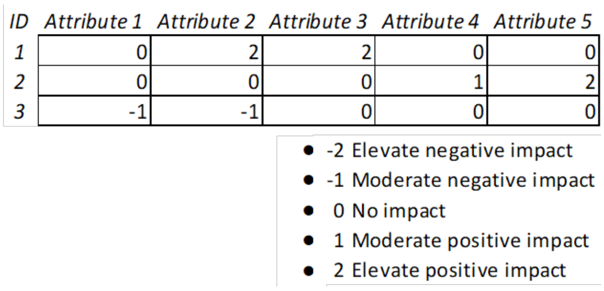
Fig. 3 – Impact assessment workflow

The first step consists of deriving a list of *design guidelines (DG)*. A design guideline is a design action that can be performed to change the overall design of a given architecture (i.e., the position of a module, the shape/geometry of the module, the routing of an interface). A design guideline may improve or reduce the score of a module or an interface in a given architecture, changing the performances of parameters defined in the CDfA model. The framework to collect design guidelines is composed of:

- *ID* – it describes the number of the design guideline;
- *Source* – it represents the source of the design guideline;
- *Domain of interest* – it describes the domain affected by the design guideline;
- *Affected attributes* – it describes the attribute affected by the design guideline;
- *Design guideline* – it explains the design guideline in the form of *verb + object*;
- *Explanation* – it details the design guideline proving more detailed information.

The list design guidelines can be obtained in two different ways: the first one is based on the scoring matrices associated to the CDfA method. Scoring matrices represent the way how implicit knowledge is translated into explicit knowledge. Scoring matrices represent critical aspects observed during the assembly phase providing rationale behind the issues observed in the assembly line. For this reason, the lowest score of the scoring matrix associated to a given attribute represents the best design option to implement. Another method consists of collecting the engineering knowledge and develop new innovative solution using brainstorming sessions. The brainstorming sessions need to be performed with a concurrent approach, in fact different people from different department should be involved in the definition of design guidelines to obtain the highest number of them. This approach allows to achieve completely new solutions from different point of view. Moreover, some of them might not be feasible or implementable yet. The main goal is to wider the solution space previously created with the scoring matrix approach.

Once the list of design guidelines is derived, the *Design Correlation Matrix (DCM)* is created (second step). The *DCM* is a [t x n] matrix where rows (t) represent design guidelines while columns (n) represent the attributes identified with the CDfA methodology. The goal is to determine the impact that each design guideline has on all the attributes included in the model. The impacts of each design guideline to a given attribute ranges from -2 to +2 where negative values mean an increment of the assembly complexity while positive an improvement, for the attribute considered (Fig. 4). It is important to notice that, for the creation of the *DCM* all attributes are considered on the same level. Indeed, no hierarchical structure is created.



ID	*Attribute 1*	*Attribute 2*	*Attribute 3*	*Attribute 4*	*Attribute 5*
1	0	2	2	0	0
2	0	0	0	1	2
3	-1	-1	0	0	0

- -2 Elevate negative impact
- -1 Moderate negative impact
- 0 No impact
- 1 Moderate positive impact
- 2 Elevate positive impact

Fig. 4 - Design Correlation Matrix [t x n]

The third step focuses on the analysis of the CDfA hierarchical structure to obtain the normalized attributes' scores of each element, and thus, to create the *Element Vector (EV)*. The *Element Vector* is a vector [1, 2, …, n] composed by *n* items, where *n* is the overall number of attributes used in the CDfA methodology (Fig. 5). Each item contains the attributes' score associated to the element analyzed (e.g., score of the attribute 1 for the Toilet B, score of the attribute 2 for the Toilet B, etc.). The Element Vector may be identified for all elements assessed in the CDfA method (i.e., modules or interfaces) but, in general, only the Element Vector of the most critical component is derived.

	Attribute 1	*Attribute 2*	...	*Attribute n*
Element	4	2	...	2

Fig. 5 - Element Vector [1, 2, …, n]

The final step (fourth step) combines the DCM and EV derived in the previous step to obtain a final score - *Design Guideline score (DG_score)*. The *DG_score* is calculated by performing the multiplication reported in the equation 1:

$$DG\_score = DCM * EV^{T} \quad (1)$$

The *DG_score* is a vector [1, 2, …, t] representing the impact of each design guideline on the analysed component (Fig. 6).

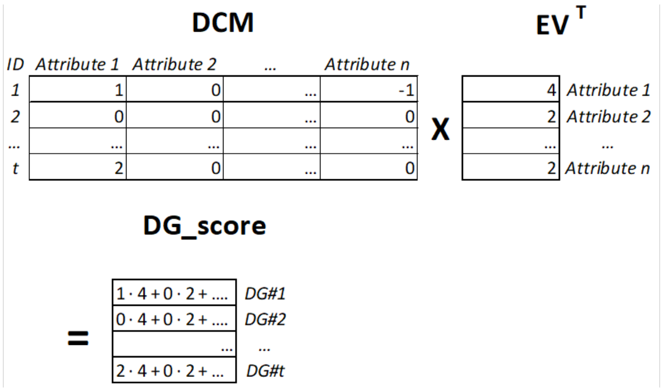


Fig. 6 – *DG_score* vector assessment

Finally, by selecting the item with the maximum value of the *DG_score* vector, the most impacting design guideline is obtained. The identified design guideline represents the solution that has the highest positive impact on the overall architecture. If it is implementable (i.e., it exists the technology and knowledge to perform the given design option) then it should be considered, otherwise the second or the third highest values of the *DG_score* vector should be selected. Once the chosen design guideline is implemented to provide a design alternative, a new run of the CDfA analysis shall be performed and check if the previous most critical element changed its score. Indeed, the proposed workflow together with CDfA method shall be applied in an iterative manner to reduce the product architecture score by reducing the assembly complexity of the new most critical element.

3. Case Study

The proposed workflow was tested on the CDfA analysis performed on the Cabin modules of the aircraft Airbus A330 (Fig. 5). The hierarchical structure created to perform the analysis is composed by only one level due to the characteristic of the system of interest (cabin interior equipping) that does not require a further discretization in additional levels. In the first level, four different domains were identified: i) mechanical domain in which five attributes are clustered, ii) furnishing domain containing two attributes, iii) system interface domain where five attributes are collected and, iv) handling domain with four attributes. The analysis was performed to assess the complexity related to the installation of modules inside the cabin. A module is an element that by means of tools need to be fixed inside the cabin and linked with mechanical and system interfaces. For instance, hat racks, toilets, seats, and galley are considered cabin modules.

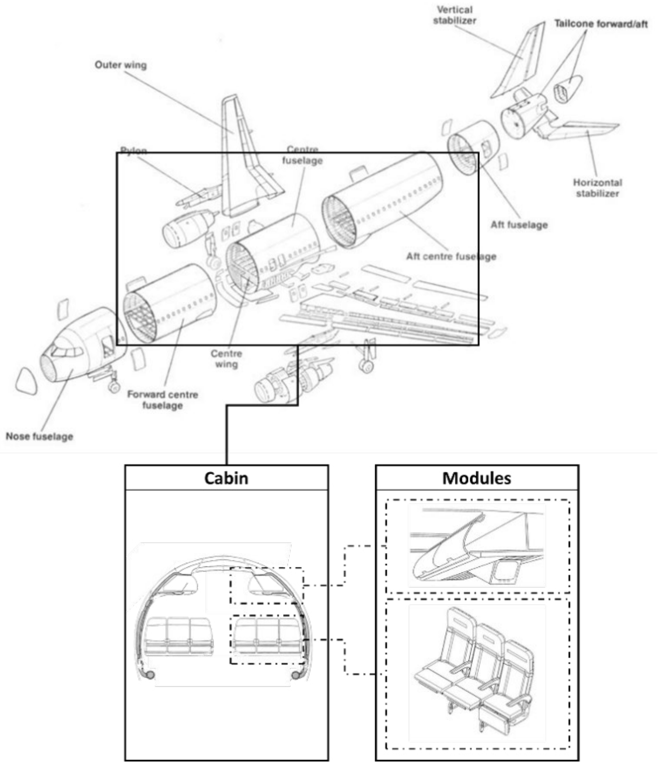


Fig. 7 - Cabin A330

The CDfA analysis showed that the most critical module to install in the module *Galley A* with a score of 4,7 (in a ranking from 1 to 5). Complexity in the installation for the *Galley A* lies in the fact that each domain presents an elevate score. Indeed, scores associated to each attribute are high. To reduce *Galley A* score, the impact assessment method proposed here above was applied. First, a list of design guidelines (DG) was obtained. The list is composed of 24 design guidelines of which 15 derived from Scoring Matrices and 9 from engineering knowledge. Then, the *DCM* was obtained indicating the impact of each design option identified. An example of the *DCM* for the first three *DGs* is reported in Fig. 8. The example reports only the first five attributes (A1, A2, A3, A4, and A5) referred to the mechanical domain.

DCM

DG	**Attributes**				
ID	**A1**	**A2**	**A3**	**A4**	**A5**
1	0	2	2	0	0
2	0	0	0	1	2
3	-1	-1	0	0	0

Fig. 8 – Example of *DCM* for the first three *DGs*

It is worth noting that the five attributes belonging to the mechanical domain address the number of mechanical interfaces, the standardization and principles of mechanical connections, aesthetic features and process issues. The impact derivation was performed organizing two 1-hour meetings with architecture engineers' experts. During the first meeting, the design guidelines identified from the Scoring Matrices were analyzed and the impact recorded. In the second meeting only design guidelines derived from engineering expertise were considered. An interesting result was obtained: impacts associated to design options derived from scoring matrices had only positive value (0, 1, 2) while the ones derived from engineering expertise had both positive and negative values. Next, the *EV* of the most critical module (i.e., *Galley A*) was obtained. A simple example for the first five attributes (A1, A2, A3, A4, and A5) is reported in Fig. 8.

EV

Module	**Attributes**				
Galley A	**A1**	**A2**	**A3**	**A4**	**A5**
	3,5	1,0	3,7	5,0	5,0

Fig. 9 - *Galley A* Element Vector

Finally, the multiplication between the transposed vector *EV* and *DCM* was performed, obtaining the *DG_score* vector for the *Galley A*. The first three items of the vector are presented in Fig. 10.

$$\overset{\textbf{DCM}}{\begin{bmatrix} 0 & 2 & 2 & 0 & 0 \\ 2 & 0 & 0 & 1 & 2 \\ -1 & -1 & 0 & 0 & 0 \end{bmatrix}} \mathbf{X} \overset{\textbf{EV}^{\mathbf{T}}}{\begin{bmatrix} 3{,}5 \\ 1{,}0 \\ 3{,}7 \\ 5{,}0 \\ 5{,}0 \end{bmatrix}} = \overset{\textbf{DG\_score}}{\begin{array}{|r|l} \hline 9{,}4 & \mathit{DG\#1} \\ \hline 22{,}0 & \mathit{DG\#2} \\ \hline -4{,}5 & \mathit{DG\#3} \\ \hline \end{array}}$$

Fig. 10 - *DG_score vector* assessment for *Galley A* example

The maximum value of the *DG_score* vector is "22" and corresponds to the DG#2 that is "*modify design principles to avoid the rigging process*". Since the DG #2 requires the use of a non-available technology (not mature enough), it could not be applied. Then, the DG #1, which is "*Bundle different system interfaces connecting two modules*" was analyzed and, indeed, implemented. Once the design guideline was implemented, a new run of the CDfA methodology was done and results collected. From the new analysis it appeared that the *Galley A* reduced its value from 4,7 to 3,2, reducing its initial score of 1,5 points. In the new product architecture, the most critical module is the module *Toilet R* with a score of 4,5. The overall process can be repeated to identify the most suitable solution the reduce the *Toiler R* score.

4. Results and Discussion

The derivation of the *DG_score* vector allowed to obtain impacts for all the derived design guidelines. From the *DG_score* vector, the most impacting design guideline is the DG#2, with an impact of 22,0. Although it is the most impacting solution, it could not be applied due to technological reasons (technology readiness). Indeed, the second guideline suggest modifying interfaces *Design Principles* to simplify the installation process avoiding the need of rigging. This solution can be implemented using a technology not implemented yet inside the manufacturing plant. Then, the second most impacting design guideline is the DG#1 with an impact of 9,4. The suggestion was to bundle different system interfaces connecting two modules to reduce the number of operations required to install them. This design guideline was implemented to improve the assemblability of the *Galley A*. An interesting result is shown in Fig. 10; in fact, the DG#3 presents a negative score. The negative score means that this design rule should not be implemented otherwise an increase in the assembly complexity of the module *Galley A* will be obtained. However, the DG#3 should not be deleted from the list of design guidelines, because it may provide a positive impact for other modules, since the EV will change. The proposed method allows to derive design guidelines and identify the most impacting one to reduce the assembly complexity of the element analyzed (i.e., modules or interface). During the derivation of the design guidelines' list, it is necessary to consider all elements in the product architecture. This aspect leads to the possibility that not all design guidelines may be applicable to a particular module. For instance, a design guideline that suggests to "*Reduce number of electrical interfaces*" is not applicable to modules without electrical interfaces. Moreover, some design guidelines may be not applicable due to technological reasons (i.e., the technology proposed has not been released yet), or economic issues, meaning the cost of modification is too high to justify the reduction of the assembly complexity (i.e., plant re-arrangement or new equipment). Thus, when the *DG_score* vector is obtained, it is necessary to check which design guideline is suggested, and, if possible, implement it. Another result has been obtained during the definition of the *DCM* for the A330 case study. Design options derived from scoring matrices have only positive impacts (0, 1 and 2), while the ones obtained from engineering knowledge can have both positive and negative values. The reason lies in the meaning of scoring matrices: they represent the technological level of the industry and the lower is the score, the better is the attribute. Indeed, all design options suggest actions to reduce the score of a given attribute, without considering other interactions. For example, for the attribute "*Number of mechanical interfaces*", the lower is the number of mechanical interfaces, the better is the score obtained from the scoring matrix. Thus, the design guideline associated to this attribute will suggest reducing the number of mechanical interfaces to have a positive impact on the specific attribute, without affecting other attributes. The creation of the DCM is a crucial aspect of the proposed approach. In fact, if impacts are not assessed correctly, the computed *DG_score* vector will lead to inconsistent results. The assessment process should be performed with a concurrent approach: experts from different areas (i.e., manufacturing, architecture, R&D, etc.) need to cooperate in the definition of the *DCM*, to be sure that the impact associated to each design guideline is reasonable.

5. Conclusion

It is possible to assess the assemblability of complex product architecture using the CDfA methodology. This methodology consists of defining a hierarchical structure to formalize the product architecture using conceptual design information. The method provides a numerical information regarding the assembly complexities of modules and/or interfaces composing the product architecture. However, it does not provide clear guidelines to how the product architecture may be modified in order to reduce the complexities. The impact assessment process described in the paper aims at the definition and selection of the most impacting design guideline, to reach an optimized product architecture with fit for assembly performances. The process workflow is based on four steps that, together with results obtained by the CDfA analysis, allows to obtain a vector, called *DG_score* vector expressing the impact of each design guideline on a given element (i.e., module, interface). The method was tested on the Cabin of the Airbus A330 to derive modules assembly complexities. Results showed that by implementing the most impacting design guidelines identified by the *DG_score* vector to the *Galley A* (the most critical module in the cabin), its CDfA score was reduced from 4,7 to 3,2. Although the approach is of great support to guide designers through the modification of the product, the method presents few important drawbacks. The first is that it is time-consuming, in fact the definition of the design guidelines, together with impact assessment, is a complex process that requires a multidisciplinary team to avoid mistakes. Furthermore, the approach is highly linked to engineer judgement. If mistakes are made in the creation of the *DCM* the overall approach may lead to inconsistent results. Finally, it is strictly linked to the CDfA methodology. It will not work outside the CDfA methodology and cannot be applied with other methods. Future works will focus on the improvement of the design guidelines' list formulation providing methodology to speed up the overall process, and on the creation of the *DCM* by reducing the human effort with the integration of mathematical algorithm based on artificial intelligence (e.g., Bayesian networks, data analysis, etc.).

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