CDFA method: a way to assess assembly and installation performance of aircraft system architectures at the conceptual design

Original
CDFA method: a way to assess assembly and installation performance of aircraft system architectures at the conceptual design / Formentini, G.; Bouissiere, F.; Cuiller, C.; Dereux, P. -E.; Favi, C.. - In: RESEARCH IN ENGINEERING DESIGN. - ISSN 0934-9839. - 33:1(2022), pp. 22-52. [10.1007/s00163-021-00378-5]

Publisher:
Springer Science and Business Media Deutschland GmbH

Published
DOI:10.1007/s00163-021-00378-5

Authors

Giovanni Formentini[a], Francois Bouissiere[b], Claude Cuiller[b], Pierre-Eric Dereux[b], Claudio Favi[a]

[a] University of Parma, Parco Area delle Scienze 181/A, 43124, Parma, Italy

[b] Airbus S.A.S., 1 Rond-Point Maurice Bellonte, 31700, Blagnac, France

Corresponding author: Giovanni Formentini, giovanni.formentini@unipr.it, +39 0521 90 6344, Parco Area delle Scienze 181/A, 43124, Parma, Italy

Title

CDFA method: a way to assess assembly and installation performance of aircraft system architectures at the conceptual design.

Abstract

This paper describes an engineering design methodology called Conceptual Design for Assembly (CDfA) in the context of aircraft development, to assess aircraft systems installation during conceptual phase, in relation to industrial performance objectives. The methodology is based on a given framework (hierarchical structure) which includes a set of attributes, collected in recognized domains that characterize the aircraft systems installation. The framework of the Conceptual Design for Assembly methodology enables to analyze product architectures at different levels of granularity, splitting the global analysis into sub-problems (problem discretization) with the aim to help architects and designers to identify product architecture weaknesses in terms of fit for assembly performances. The Conceptual Design for Assembly methodology was applied on a complex system (the nose-fuselage of a commercial aircraft) presenting a high number of criticalities both for the product and its assembly operations. Results identified the architectural components leading to the less efficient assembly operations, and the rationales enabling to elaborate alternative architectures for an improved product industrial efficiency.

Keywords

product development; architectural design; design methodology; conceptual design; aircraft design, design for manufacturing and assembly, fit for assembly.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

1. Introduction

The global demand for commercial aircraft significantly increased in the last decades, and despite the recent COVID-19 pandemic situation, this trend is confirmed. In this context, aircraft manufacturers are called to improve the industrial performances keeping under control industrial investments (Maropoulos et al. 2014; Yancey 2016), safety requirements (certification) (Hickie 2006) and production lead time (Brusoni and Prencipe 2011). With this aim, product engineering and manufacturing engineering need to be integrated at the earliest design phase to design product architecture meeting both product and industrial performances.

Among all the design phases described in the *Product Development Process* (PDP), the conceptual design phase is aiming at identifying the most suitable product architecture, providing the highest degrees of freedom. In this phase, any architectural change has no cost effect on the product until decision is made on the product architecture. In literature, many methods have been presented to consider the assembly aspects during the PDP, they are known as "Design for Assembly" (DFA) and/or Design for Manufacturing and Assembly (DFMA). However, DFA and DFMA methods are mainly applicable at late design phase (i.e., embodiment design and detail design) when detailed information is available. The value brought by the development of DFA/DFMA methods at the conceptual design phase relies on the early consideration of the industrial dimension which is currently the main gap observed within the literature analysis.

The methodology described in this paper, called *Conceptual Design for Assembly (CDfA)*, translates product architecture data into a set of numerical values associated to fit for assembly assessment criteria (attributes), which are then integrated into a single value for a given assembly/manufacturing aspect (domain) and enabling product architectures comparison. The methodology is an applied research in the engineering design context starting from aeronautical industry needs and requirements. The term *Conceptual Design for Assembly* is already known and used within the engineering literature (Lombeyda and Regli 1999; Stone et al. 2004). However, concepts and frameworks presented in the mentioned works discuss the topic from a different research angle (i.e., software solution for a collaborative CAD-based design environment, or integration of conceptual and detail information for the assessment of assembly performance by using time-based method). In the present work, the CDfA methodology covers novel aspects in this field: (i) it collects assembly/manufacturing knowledge switching from tacit implicit knowledge (unstructured information) to explicit knowledge (scoring matrices with numerical data), (ii) it avoids the use of detailed design information (i.e., the assembly time) in favour of design data available at the conceptual design phase, (iii) it creates a mathematical model and a framework able to consider the overall aircraft assembly problem by using sub-problems that are limited in terms of complexity (problem discretization), and (iv) it provides information to the designer regarding weaknesses of the product architecture in terms of assembly operations efficiency. In addition, by analysing the results of this methodology, it is possible to use the numerical values to elaborate architectural design guidelines. These guidelines can be used to derive optimized product architecture able to minimize the assembly and installation complexity. The optimization process usually starts from a given architecture and the context in which the CDfA methodology is used is the re-design phase rather than a novel design/idea. The use of functional model leads the system engineers/architects to change the way the module is built as well as its position, consequently a functional model is necessary to find alternative design solutions and alternative architectures. The CDfA methodology is considered a decision-making tool developed to assess the performance of an aircraft product architecture in relation to the assembly/installation phase. It is worth to noting that, due to the specific context, usually alternative product architectures are developed within the same manufacturing/production framework due to many reasons: (i) the high cost of changes related to the production sites, (ii) the adaptation and validation of test procedure and equipment, and (iii) the reluctance of changes about consolidated activities and technologies which guarantee high standard in terms of safety and quality (one of the most important pillars to develop an aircraft). All these aspects contribute to the reactivity of the manufacturing/production sites to implement disruptive concepts and ideas even if the CDfA methodology does not prevent the possibility to assess high-innovative architectures.

The paper is structured as follow: after the literature analysis related to the topic of this paper (section 2), the *Conceptual Design for Assembly Methodology* is presented (section 3). The *Case Study* provides an application of the methodology on the nose-fuselage of a civil aircraft (section 4). Then *Results* obtained by the application of the method are presented (section 5). Finally, *Conclusion* discusses limitations and future developments of the presented approach (section 6).

2. Literature background

The *Product Development Process* (PDP) is articulated in several phases in which different disciplines are collaborating. The main work on the formalization of the PDP is proposed by Pahl et al. (2007) where four (4) phases necessary to design a product are identified: i) Planning and task clarification, (ii) Conceptual design, (iii) Embodiment design, and (iv) Detail design. The PDP proposed by Pahl et al. (2007) considers only the design process itself without considering interactions between designers and other departments, such as the manufacturing department. Boothroyd et al. (2011) proposed a *New Product Development Process* (nPDP) in which interactions among departments are considered since the initial phase of the design process. This new paradigm has led to the birth of the *Concurrent Engineering* (CE), whose purpose is an optimization of the design process by considering all product aspects from the beginning, breaking barriers between different departments (Lyu and Chang 2010). CE product development leads to many advantages such as reduced lead times (K. C. Tseng and Abdalla 2006), even if it requires a higher effort to manage the elevate number of information and stakeholders involved at the same time (Jun et al. 2006).

Several methods are counted as part of the nPDP, such as *Design for X* (DfX) methods (Huang et al. 1999; Kuo et al. 2001; Holt and Barnes 2010), where the *x* is replaced with the optimization target (e.g., Assembly, Cost, Maintenance, etc.). The DFMA is the first family of DfX methods that was developed. DFMA methods aim at optimizing the process and cost of manufacturing activities of subsystems by using the product own proprietary data (Coma et al. 2004). Cost and lead time are the main drivers associated with the manufacturing and assembly aspects. This is particularly true for big and complex products such as aircraft, where assembly and installation can impact over the 40% on the final cost (Bullen 1999;). The most-used DFMA methods are: (i) the Boothroyd-Dewhurst (B&D) (Boothroyd et al. 2011), (ii) the Hitachi method (AREM) (Suzuki et al. 2003), and (iii) the Lucas method (Stone et al. 2003).

In the aerospace field, few attempts in the development of DFMA methods have been done. Lockett et al. (2014) applied DFA techniques with the help of CAD software to identify small changes to improve wiring system installation tasks. Barbosa and Carvalho (2014) collects a set of design guidelines applicable during the aircraft design to improve the assembly and manufacturing performance. Moreover, Butterfield et al. (2007) proposed a method to make use of digital manufacturing techniques 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 use the derived 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, reducing the amount of potential architectural alternatives.

While state-of-art DFMA methods require detailed information available at the final stages of product design (El-Nounu et al. 2018), working at the conceptual level forces designers to use partial and high-level information such as product requirements, functions, etc. Starting from the basic approaches (i.e., functional and modular analysis), few attempts were done to adapt DFMA methods for the conceptual design phase providing as outcome the module analysis for assembly time reduction (Stone et al. 2004) as well as the assessment of the product layout with the assembly sequence (Favi and Germani 2012). Most of these works can be considered a baseline for the development of conceptual design for assembly methods related to aerospace products but limitations related to the product complexity and required information details have been observed. Indeed, concerning the aerospace sector, only a limited number of works describing design for assembly methods and tools applicable at the conceptual level was observed. Among all, Domeshek et al. (1994) develop a tool that, by collecting previous airplane design, can be interrogated to provide useful information during the conceptual design phase. Other works moved the research angle from the product to the final assembly line (Butterfield et al. 2007; Mas et al. 2013, 2016; Gómez et al. 2016). The optimization of the final assembly line is an important topic referring to the reduction of manufacturing and assembly costs, but it requires to be integrated with product design to be efficient.

The main challenge working at the conceptual phase is the availability of data which is characterized by high granularity. In this phase, the collected information is represented by schemes that encapsulate functions required by the product. There are many methods in literature to create schemes to represent the collected data. For instance, the product functional representation is one of those and it is characterized by black boxes connected with basic flows (i.e., energy, material, and signal) (Pahl et al. 2007). Other tools and methods can be used to derive the scheme representing the product functions, such as the Function Means Tree (Hubka and Eder 1989) and the Functional Evolution Process (FEP) (Shimomura et al. 1998). The arrangement of functional elements into physical chunks which become the building blocks for the product or family of products is known as “Product Architecture” (Ulrich 1995). To way to represent the product architecture is not unique. The design structure matrix (DSM) is a powerful tool to describe interactions between product architecture components using a square-matrix (Browning 2016). However, the assessment of product architectures requires mathematical models that need to be validated in each context considering specific constraints. Concerning the optimization of product architecture, the creation of a modular product leads to advantages such as product differentiation (AlGeddawy and ElMaraghy 2013), parallelization in design and testing (Ethiraj and Levinthal 2004), flexible manufacturing and synergic cooperation with suppliers (Jiao et al. 2007), creation of product family (Ma and Kim 2016; Bonvoisin et al. 2016, Ethiraj and Levinthal 2004). The improvement of a given product architecture usually require the analysis of modularity. From the literature, emerged that modular product architecture can positively impact the assembly phase (Stief et al. 2020). While the benefit of modularity is acknowledged for these technical aspects the over-increasing degrees of modularity in design decisions may lead to opposite results (i.e., increment of costs) (Engel and Reich 2015; Engel et al. 2017; Bonvoisin et al. 2016). The concept of modularity was introduced in the aeronautical sector (Monnoyer and Zuliani 2007) creating independent sub-parts or *modules* (Frigant and Talbot 2005; Erens and Verhulst 1997; Miller et al. 2002; Fricke and Schulz 2005; Siddiqi and de Weck 2008; Jung and Simpson 2017). However, the creation of fully modular aircraft is an on-going challenge (Atasoy et al. 2012).

The literature analysis highlighted how the conceptual design phase is the most critical phase to prevent installation and assembly issues. Aerospace industries are facing an integration challenge between product concept and manufacturing (i.e., assembly and installation) since product complexity is increasing, requiring a huge number of operations impacting cost and resources needs. Preliminary studies tried to tackle assembly and manufacturing aspects within the conceptual framework of product development but several limitations were observed such as the problem formalization for product architecture assessment, the mathematical models (framework) to link assembly parameters, as well as the quantitative assessment of assembly issues referring to information available at the conceptual design .

3. Conceptual Design for Assembly Methodology

The proposed methodology, called CDfA (Conceptual Design for Assembly) is divided in three main phases: (i) Product Functional Decomposition, (ii) Architecture Geometrical Definition, and (iii) *Conceptual* Design for Assembly Assessment. Each phase is characterized by different steps and design tools as reported in Fig. 1. The following paragraphs describes in detail each phase of the CDfA methodology.

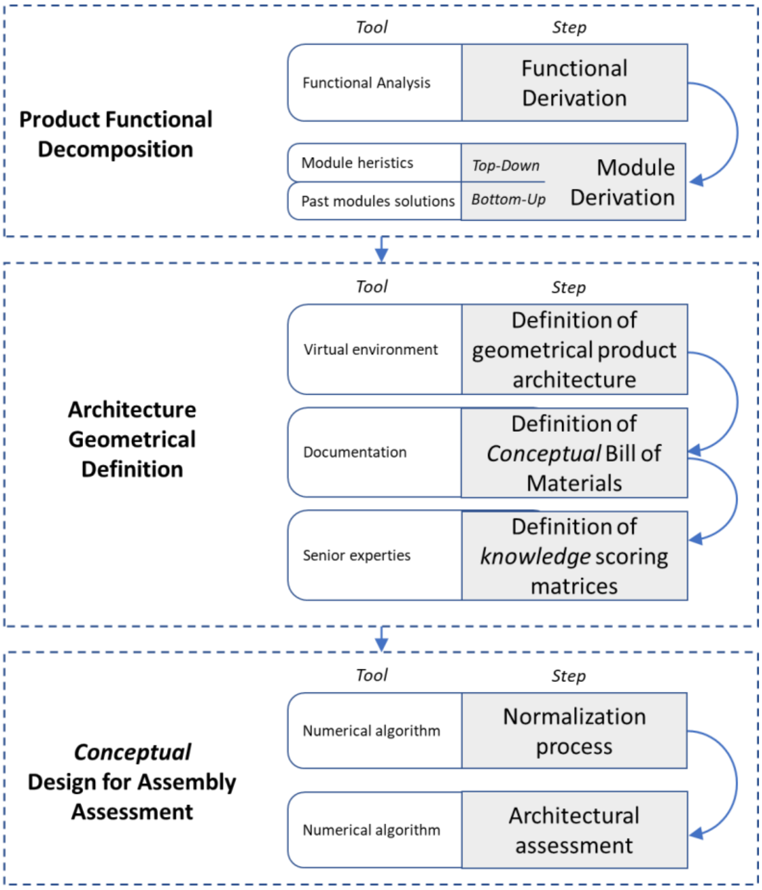

FIG. 1 - CONCEPTUAL DESIGN FOR ASSEMBLY METHODOLOGY

3.1 Phase 1: Product Functional Decomposition

The Product Functional Decomposition is the starting point of the analysis. It enables to identify functional modules and their functional interconnections that will then be used to define the physical modules and their physical interconnections. Modules and their interconnections will then be characterised to perform the assembly assessment. Product functional decomposition is of a great importance in this field which is characterized by consolidated design solutions and technologies. While keeping the compliance with stringent requirements for this type of product, the design of new product architecture at the conceptual design phase (e.g., module layout/arrangement, module position, module integration/decoupling, module assembly/installation, module fixation, interface routing, interface installation, etc.) is allowed. For this reason, this initial phase, even if limited to initial choices about technology and design solution, still provides an important window on how possible changes can be developed at the conceptual level. The Product Functional

Decomposition is performed in two (2) steps: (i) Functional Derivation, and (ii) Module Derivation. Literature approaches have been used with some adjustments (i.e., customization) to proceed with other methodology steps.

3.1.1. Functional Derivation

The functional derivation applies the functional analysis (Pahl et al. 2007) to the product under study to obtain the product functions. The functional analysis consists of defining functions and sub-function (main and auxiliary) through a hierarchical scheme and basic fluxes that link these functions (Kroll 2013). Basic fluxes identified by Pahl et al. (2007) are material, energy, and signal. In the proposed methodology a modified version of the functional analysis proposed by Pahl et al. (2007) is used to characterize the given product (aircraft) with the support of a dedicated tool. Indeed, within the same functional flow (e.g., material flow) different types of fluxes are determined and associated to a given colour (see Table 1). For instance, assuming that two generic functions are connected by a flux of material, it is possible to further specify the type of material (e.g., gas) and the sub-type (e.g., air). A given colour is assigned to the type of material (e.g., green for gas type) and a unique RGB code is assigned to the sub-type (e.g., 7, 255, 62 for the air). The outcome of the modified approach is a graph presenting as many colours as different fluxes available for the whole functions. Moreover, the colour assignment is important to cover the issue related to people with colour vision deficiency (CVD) (Nuñez et al. 2018). Indeed, a general colour was assigned for each type of flow, then a gradation of the general colours is proposed for sub-flows to provide a CVD-safe colour map. Once colours are assigned, they must not be changed to avoid inconsistencies during the application of the CDfA approach on other case-studies. The presented functional derivation enables users to: (i) improve readability of the functional representation, (ii) increase the level of detail of the functional analysis without requiring data from a lower design phase, (iii) provide better understanding of the implication of each requirement, and (iv) facilitate the switch from fluxes (functional representation) to physical interconnections (physical representation). Table 1 shows all basic fluxes identified within an aircraft. These fluxes were defined by the authors following the previous work of Hirtz et al. (2002). These fluxes are then used to derive modules interfaces and subsequently their physical interconnections to create modules.

Table 1 - Basic fluxes for aircraft (extension of the basic fluxes provided by Hirtz et al. 2002)

Aircraft Basic Fluxes								
Basic Flow	***Symbol***	***Type***	***Explanation***	***Example***	***Sub-Type***	***Type Colour***	***Colour***	***RGB***
Material		Human	All or part of a person who physically interacts with the system	Cabin crew entering the cabin	*N.A.*	Black		0 0 0
		Solid	Object with mass and shape which physically interacts with the system	Luggage entering the hat rack	Waste	Brown		205 133 63
					Objects/Parts			171 85 24
		Liquid	Fluid which physically interacts with the system	Fuel that flows in pipes	Liquid waste	Blue		0 191 255
					Fuel			30 144 255
					Oil			72 61 139
					Water			230 230 250
		Gas	Gas that physically interacts with the system	Air entering the fans and ducts	Air	Green		7 255 62
					Gas mixture			63 243 76
					O2			177 247 171
Energy		Human	Work performed by a person on the system	Energy generated by the pilot to move the cloche	*N.A.*	Black		0 0 0
		Acoustic	Work performed to produce and trasmitt sound	Energy generated by turboprop motion converted into noise	*N.A.*	Orange		255 127 80
		Chemical	Work resulting from chemical reactions	Energy produced by aircraft batteries	*N.A.*	Green		124 252 0
		Electrical	Work resulting from motion of electrons	Energy transmitted by aircraft harnesses	*N.A.*	Yellow		255 255 0
		Hydraulic	Work performed by moving fluids	Energy used to actuate the landing gear	*N.A.*	Blue		167 167 255
		Mechanical	Work performed by a mechanical system	Energy generated by a mechanical connection to fix the seat on the cabin	*N.A.*	Purple		138 43 226
		Pneumatic	Work resulting from the motion of gas	Energy used by the pnemuatic aircraft system	*N.A.*	Brown		165 42 42
		Thermal	Work resulting from a themal system	Energy exchanged in the aircraft cooling system	*N.A.*	Red		255 0 0
Signal		Control	Command sent to an apparatus to regulate it	Pilot that regulates air in the cabin	Sound	Red		250 128 114
					Tactile			220 20 60
					Visual			255 0 0
		Feedback	Information about the state of the system	Indicator of the fuel level in the aircraft	Visual	Purple		238 130 238
					Sound			255 0 255
					Tactile			148 0 211

Among the potential benefits of functional decomposition in terms of product abstraction, functions characterization and fluxes identification, the process is laborious, time-consuming and requires collaborative sessions to be developed. Some functions can only be analysed in the context of a particular solution, limiting the design space as well as the ability of designers to think in abstract terms (Kroll 2013). Moreover, when the level of details in functional decomposition is too deep, it may lead to a lack of freedom for the designer adversely affecting innovation and creative performance (Leenders et al. 2007). Due to the specificity of the aeronautical field and aircraft product development, which is mainly characterized by very stringent regulations about safety requirements, and high cost of changes, the conceptualization of new ideas, carried out through a novel design process, requires a long time to be formalized, discussed, accepted, validated and tested. Within this framework, the criticisms highlighted for the method proposed by Pahl et al. (2007), although partially restrict the potential of this method, do not negatively affect the development of the CDfA methodology which focuses on the assessment of product architectures in terms of manufacturing and assembly. Besides, functional representation is a powerful tool to develop new module concepts and proceed towards the design of new architectures.

3.1.2. Module Derivation

Once the functional scheme is obtained, it is necessary to derive modules. The derivation of modules requires first to move from functions to interfaces. Interfaces represent how functions physically interact with the system of interest. Interfaces are derived considering the basic flows that interact with the system, and their type. The colour is inherited by the basic flux colour type (i.e., general colour) while, at this stage, the arrow's type becomes meaningless. Thus, for the presented CDfA methodology, all interfaces are represented with solid arrows. It is worth noting that, while the functional representation identifies all the interactions that are present in the system of interest, some of them might not need an interface to connect with the system. For instance, the cabin crew interacts with the system to store luggage within the cabin (usually called hat-rack), and, in this case, the interface necessary to connect these two modules is the human interface. Since the purpose of the CDfA methodology is to analyse product assembly and system installation, the human interface is meaningless because the action to store luggage within the cabin is performed by the human. Following this principle, for aircraft systems only four interfaces are derived starting from the identified fluxes: i) electrical, ii) mechanical, iii) fluid, and iv) air. Table 2 reports the four interfaces considered for the aircraft systems and the related matching with the basic flow types.

TABLE 2 – INTERFACES

Aircraft Interfaces				
Basic Flow	***Type***	***Interface***	***Colour***	***RGB***
Material	Human	*N.A.*	*N.A.*	*N.A.*
	Solid	*N.A.*	*N.A.*	*N.A.*
	Liquid	Fluid		230 230 250
	Gas	Air		7 255 62
	Human	*N.A.*	*N.A.*	*N.A.*
	Acoustic Chemical Electrical Hydraulic Thermal Pneumatic	Electrical		255 255 0
	Mechanical	Mechanical		138 43 226
Signal	Control Feedback	Electrical		255 255 0

Once interfaces are defined, it is possible to proceed with the creation of modules. Modularisation aims at clustering the functions into modules (product decomposition into building blocks) with specified interfaces (Ericsson and Erixon 1999). Module derivation from functional analysis is a key step at the conceptual design stage, whether novel design or redesign. It provides an engineering view of how the sub-functions work together to achieve the desired functional requirements, independently of how the function is performed. The engineering definition of modules in aircraft systems presents many concerns related to the huge number of constraints that need to be satisfied (the presence of redundant elements placed in different areas for safety reasons). The method proposed by Stone et al. (2004) is adopted within this methodology with the aim to consider all the constraints required for the development of modules. This method is based on three heuristics (dominant flow, branching flow, and transmission/conversion) and it allows to identify product modules by grouping sub-functions together. The list of modules retrieved by the adoption of this method can be used for concept generation and module instantiation. Among the different methods developed for module derivation (i.e., module heuristics, design structure matrix - DSM, and modular function deployment - MFD), the module heuristics is the most suitable for the scope of this work, since it shows important features which fit with the type of product under analysis and the level of confidence required to develop the modules in such a product. Module heuristics can capture flows describing the underlying physics of the product and it is more flexible than other methods that require a matrix or mathematical description (Borjesson 2010). The method presents a high repeatability on a given function structure diagram which is the result of the previous phase (functional derivation) as demonstrated by Hölttä-Otto (2005). The module heuristics is well supported by empirical research on hundreds of real products; however, it requires an engineering judgement (theoretical foundation is less scientific than the other methods) to be operated and it does not guarantee that the identified modules represent the optimum clusters. Nevertheless, it provides a consistent and repeatable product structure breakdown. The application of the module heuristics suffers of software integration/implementation which would be beneficial for large projects as in the case of aircraft. This drawback is counterbalanced by flexibility, indeed it is worth nothing that, to increase the level of confidence in the definition of suitable modules in such a critical product, a mapping with existing modules for a given product is possible. In this case, the module heuristics method (top-down approach) is coupled with the analysis of available product structure (bottom-up approach) with the aim to match the existing modules with the ones retrieved by module heuristics. If the goal of the CDfA assessment is the optimization of a given architecture, this task is necessary and it will lead to two results: (i) keep the level of confidence about modules derivation in relation to aircraft products that are characterized by many design constraints and, (ii) identify possible alternative solutions for modules definition (i.e., module splitting/merge). On the other hand, if the goal is to assess a new concept (i.e., concepts that are newly developed), module breakdown is fully based on module heuristics (top-down approach) increasing the design solution space but downgrading the level of confidence in module definition. A one-to-one mapping between modules and functions is the easiest solution to consider aspects such as safety or operability requirements. However, this option can bring to product architectures with more modules (more options and a higher level of modularity), giving importance to the role of component interfaces increasing the difficulty of achieving product assemblability (Engel et al. 2017). Hence, having more modules is not always the right way to proceed in this phase and the use of module heuristics allow an engineering assessment of feasible modules based on initial requirements and given design decisions (e.g., combustion of fuel for power generation). Once modules are defined, it is possible to create the product physical architecture by linking modules with interfaces derived in the previous step (Fig. 2).

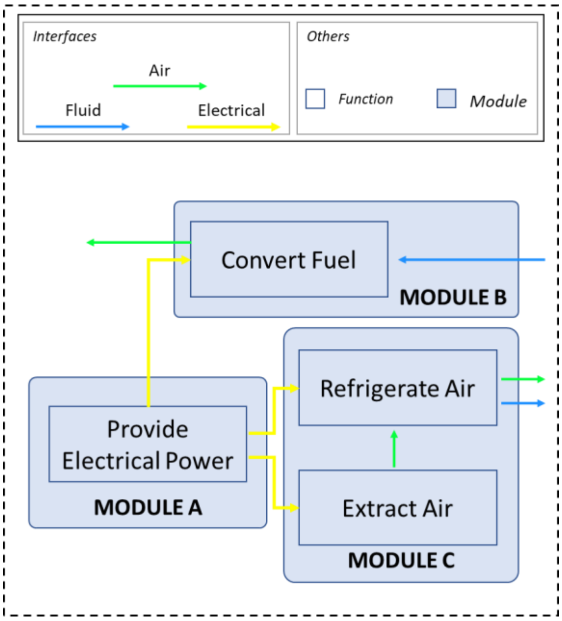

FIG. 2 – EXAMPLE OF MODULE DERIVATION – *LEGENDA BASED ON TABLE 2*

3.2 Architecture Geometrical Definition

The Architecture Geometrical Definition consists in reading the data available in the derived product and translating them into numerical format. This phase is composed of three (3) steps: (i) Definition of geometrical product architecture, (ii) Definition of *Conceptual* Bill of Materials, and (iii) Definition of *knowledge* scoring matrices (knowledge-based).

3.2.1. Definition of geometrical product architecture

The fit for assembly assessment at the conceptual level requires the conversion of conceptual features into parameters that can be visualized and measured. The information derived in the previous steps (i.e., functional modules and functional schemes) are used to create a virtual representation of the product under study. The use of a virtual environment (i.e., CAD tool) enables to represent data available at the conceptual phase into elementary geometries. The *simplified* Digital Mock Up (sDMU) is a graphical and geometrical representation of a specific product architecture showing modules shape and interfaces among modules in a three-dimensional space. The sDMU is composed of 3D geometrical-items such as boxes, cylinders, etc. that describes how modules and interfaces are built and interconnected (Fig. 3). The sDMU provides a visual representation of the product architecture obtained in the previous steps, enriching the product architecture itself with a new set of information. It presents more detailed information such as the distribution of modules inside the system of interest (module position), the overall module shape and volume (module bounding box) and many others. Information represented in the sDMU is enclosed in the functional scheme, for example by knowing how many functions and the type of functions collected in a functional module then module position, module bounding box, length of interfaces, etc. can be estimated to create the sDMU. The level of detail and the granularity of the sDMU evolves during the application of the methodology. If the methodology is used to analyse new products, then the sDMU starts with a low level of detail (i.e., low granularity) and it is enriched with more detailed information when later design phases are approached. On the other hand, if the methodology is based on an existing product of which a CAD file is available, it is possible to simplify the CAD file by neglecting all details and representing modules as boxes with their bounding box and interfaces as cylinders whose diameters reflect the real dimension.

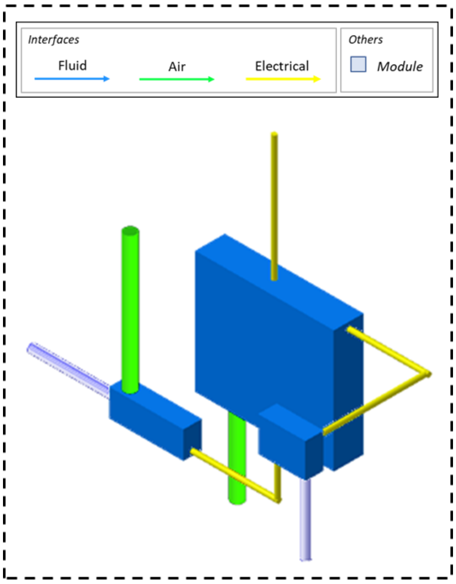

FIG. 3 – EXAMPLE OF A *SIMPLIFIED* DIGITAL MOCK UP – *LEGENDA BASED ON TABLE 2*

The sDMU is providing the minimum set of data enabling to perform the fit for assembly assessment. The required set of data necessary to build a sDMU is reported in (Table 3).

TABLE 3 – REQUIRED DATA PROVIDED BY SDMU

sDMU item	Information collected in sDMU
Module	Position (x, y, z) based on a given reference

Interface	Shape (i.e., rectangular box, cylinder) Bounding Box Colour (i.e., blue) Position (x, y, z) based on a module in/out reference Path Overall length Shape (i.e., cylinder) Size (i.e., diameter) Colour (based on interface type)

3.2.2. Definition of *Conceptual* Bill of Materials

The *conceptual* Bill of Materials (cBoM) is a document aiming at capturing the functional and geometrical data of the previous steps to enable computation of the fit for assembly scoring. The cBoM presents a table-form in which each row represents an interface between modules and each column represent an attribute that is characterizing a particular interface. The cBoM is characterized by a hierarchical structure, subdivided into levels (layers), domains, and attributes. The hierarchical structure is the methodology framework that allows to combine attributes for a given problem (i.e., the overall assembly or a sub-assembly). The cBoM structure enables a decomposition of the given problem in sub-problems allowing to incorporate aspects from different level of granularity that otherwise might be discharged. The proposed framework is a description of the product enabling to identify the impact of each attribute on the assembly process. The cBoM is collecting product data through fixed information which characterizes a specific level. Information that must be enclosed in the *fixed information* part are collected in Table 4.

TABLE 4 - FIXED INFORMATION FOR THE CBOM DOCUMENT

Title	Type	Description
Name	*string*	it is the name associated to the element under study. It can be chosen arbitrarily by the user
ID	*integer*	it describes the ID of the element under study. It can be generated according to a specific rule, or it can be chosen arbitrarily by the user
Interface Type	*string*	it identifies the type of interface; it is compliant with interfaces identified in the functional scheme. It can be defined by the user following the interface type reported in table 2
Module IN	*string/integer*	it represents the module where the interface starts
Module OUT	*string/integer*	it represents the module where the interface ends

If necessary, other information can be added within this framework, depending on the level (layers) and the type of product under study.

Definition of Levels (layers)

A level is defined as a group of data which is modelling the main feature characterized a specific sub-problem of the overall product assembly. Different levels can be defined according to the available information. To switch from a level to another one is necessary to identify the product *invariant*. A product *invariant* is a design feature that does not change and cannot be changed within the product under study. The definition of the *invariant* allows to specify information with respect to it. For each defined level, the following actions are necessary: (i) to identify possible invariants that link two neighbouring levels, and (ii) to express the relation that exists between two neighbouring levels using invariants.

For example, if the “space distribution” (i.e., product areas) in a product is fixed and cannot be changed; then the “space distribution” can be considered as an *invariant*. The identified invariant allows to split the global analysis into sub-problems that are limited in terms of complexity (problem discretization).

Attributes and Domain definition

Attributes and Domains that characterize the main criteria of fit for assembly performances are defined on a knowledge basis, with a concurrent engineering approach (i.e., involvement of manufacturing department, architecture designers, operators, etc.). A mathematical model is then created to operate on these criteria providing the fit for assembly assessment.

Attributes Class definition

An attribute (A) is a key feature that influences assembly operations. Giving a generic attribute A [1 to x; $x \in N>0$], the attribute A describes a specific aspect related to the assembly operation. To define an *attribute*, it is necessary to indicate: (i) the name of the attribute, (ii) the dimension (i.e., the unit measure or the quantity), and (iii) the level in which it is available. The definition of an *attribute* can be set after a deep study of the product under development. A list of key attributes reflecting the assembly complexity can be obtained knowing the design phase in which the methodology is applied (e.g., conceptual phase, detail phase, etc.). Attributes might be of interest or not, according to the level in which they are placed.

Domain Class definition

A domain (D) is a cluster of one or more attributes (A) that address the same assembly aspect and provides the same meaning for each designer/engineer. Giving a generic domain D [1 to t; $t \leq x$; $t \in N>0$], the domain D is a vector characterized by *n* attributes [$n \geq 1$; $n \in N>0$]. For each level of the cBoM framework, domains can have a different number of attributes. By clustering attributes into domains, and placing domains into levels, the hierarchical structure is obtained (Fig. 4).

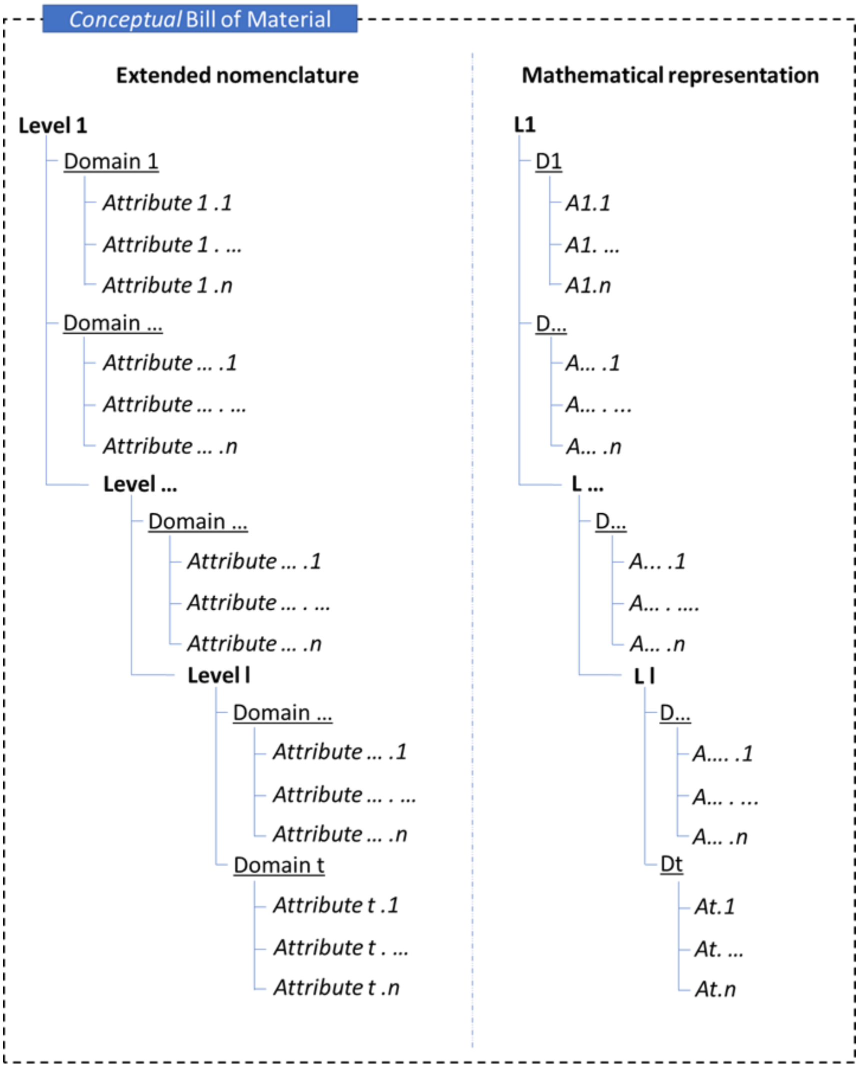

FIG. 4 - CBOM FRAMEWORK (HIERARCHICAL STRUCTURE)

3.2.3. Definition of knowledge scoring matrices

The formalization of the knowledge is a great challenge and the research field associated to it is called Knowledge Engineering (KE). Relevant knowledge might appear in different forms (e.g., technical drawings, spreadsheets, etc.) and in unstructured manners but the main challenge is how to deal with it in terms of collections, formalization, and utilization (Staab et al. 2001; Ahmed 2005; Reed et al. 2011). The approach proposed within this methodology to formalize the knowledge focuses on two aspects: knowledge acquisition and ontology definition (Guarino 1995). The knowledge acquisition relies on a knowledge-based *concurrent* approach (Favi et al. 2019). The method enables to retrieve the *knowledge* through the definition of scoring matrices. The structure and the vocabulary (i.e., ontology) of the knowledge must follow three principles: (i) role-limiting, (ii) knowledge typing and (iii) reusability (Musen and Schreiber 1995). The ontology proposed within this methodology is based on the definition of *knowledge* scoring matrix (kSM). The *knowledge* scoring matrix is table of Y_f rows, where each row corresponds to a score (i.e., from 1 to m). The kSM form is different according to the information it processes. For example, if the kSM translates *strings* information (i.e., $Y \in \mathbf{\Sigma}$ with $\mathbf{\Sigma}$ be the set of alpha-numerical strings without the null element), then to each string a score is associated (Fig. 5 - sx). On the other hand, if the kSM translates *numerical* data (i.e., $Y \in \mathbf{R}$ with $\mathbf{R}$ be the set of real numbers), then to a given range of values a score is associated (Fig. 5 - dx). By following this approach, a scale from 1 to 5 (Likert scale) has been used, since considered the most suitable for the specific problem.

Attribute A *(generic)*		
String		**Score**
Y_0	=	1
Y_1	=	2
…	=	…
Y_f	=	*f*

$Y \in \Sigma$

Attribute A *(generic)*			
Numeric range			**Score**
Y_0	< X <=	Y_1	1
Y_1	< X <=	Y_2	2
…	< X <=	…	…
Y_{f-1}	X >	Y_f	*f*

$Y \in \mathbf{R}$

FIG. 5 – kMS DEFINITION FOR STRING (SX) AND NUMERIC DATA (DX)

The kSM is necessary to translate the collected information into dimensionless values and perform mathematical computations. The kSM shall be created for each attribute in the cBoM and is composed of: (i) name of the attribute, (ii) numerical range or string, and (iii) score. It is important to notice the maximum score available for all the *knowledge* scoring matrix must be the same. A good practice during the creation of *knowledge* scoring matrices is to express the rationale behind each score and to annotate it together with the kSM. In fact, the kSM represents the current industrial capabilities associated to the product technological level. The kSMs are updated every time an improvement of the assembly and/or manufacturing plant is performed.

3.3 Conceptual Design for Assembly Assessment

The architectural analysis is divided into two phases: (i) Normalization process, and (ii) Architectural assessment.

3.3.1. Normalization process

The normalization process consists in transforming the data inside each attribute into dimensionless value switching from heterogeneous data (i.e., string, number, etc.) to homogeneous data (i.e., dimensionless scores) to perform mathematical operations. The Normalization process requires two inputs: (i) the *knowledge* scoring matrices, and (ii) data for each attribute. For example, if the *interface 1* presents a generic value for the attribute “length” (i.e., 3,5 [m]) then the normalization process will translate the value into a dimensionless score according to the *knowledge* scoring matrix associated to the attribute “length” (i.e., 1). Once the normalization process is completed for all attributes, all data in the cBoM are normalized and dimensionless, enabling to proceed further with the architecture assessment. The normalization process can be performed by using a spreadsheet to avoid a prone-to-error task.

3.3.2. Architectural assessment

The product architecture is analysed by using the cBoM framework. The analysis starts from the lowest level (i.e., Level *l* reported in Fig. 6), by considering the first ID (i.e., i1.*l*.1 where *l* indicates the digits representing Level *l*). The function $g(\cdot)$ is a mathematical operator which is applied inside each domain to collect scores of each attribute associated to the same ID. The choice of mathematical operator used to collect scores is addressed later within section “Mathematical Operators”.

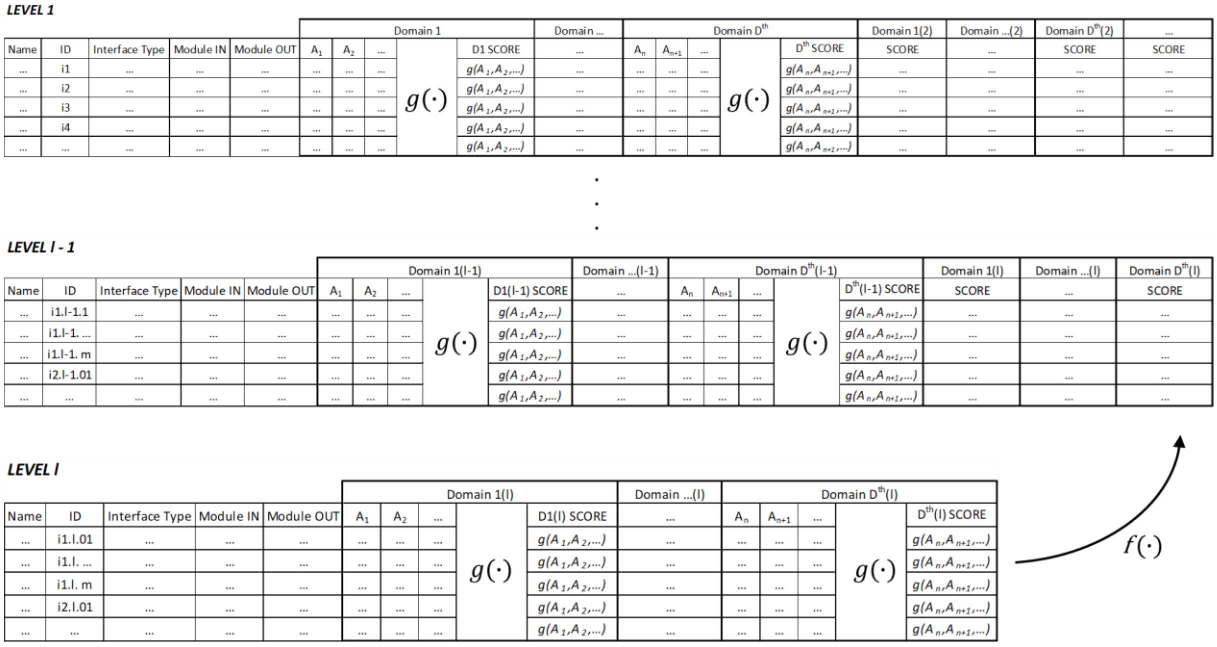

FIG. 6 – MATHEMATICAL MODEL USED COLLECT INFORMATION INSIDE A LEVEL AND TO SWITCH FROM ONE LEVEL TO ANOTHER ONE

This process is repeated for each ID. The output of the first computation (Level *l*) is a single score for a given ID representing the information for a specific domain. When all IDs of level *l* have a single score associated for each domain (i.e., domain SCORE), then the IDs which have the same first digits are collected with the function $f(\cdot)$ which is a mathematical operator (e.g., i1.*l-1*.1; i1.*l-1*.2, etc.), defined according to the level invariant. The output of function $f(\cdot)$ is a single score for interface that has the ID of the upper level. Indeed, the domain of the upper level (i.e., Level *l-1*) is automatically filled by the lower level (i.e., Level *l*). The output of this process is represented in (Fig. 6). The process is repeated for all levels, clustering the results of all interfaces, with the aim to obtain a single score for each domain. Interfaces and scores are collected in the final domain called “Main Level” which presents scores for all domains defined in the cBoM and all interfaces of the product under study.

The aim of the architecture assessment is to obtain a single score for each *Interface* that characterises the assembly complexity of all product interfaces. Thus, it is required to further collect scores inside the Main Level with the mathematical operator $h(\cdot)$. Once the function $h(\cdot)$ is applied, one single score for each *Interface* is obtained (Fig. 7). This is the final results of the CDfA assessment.

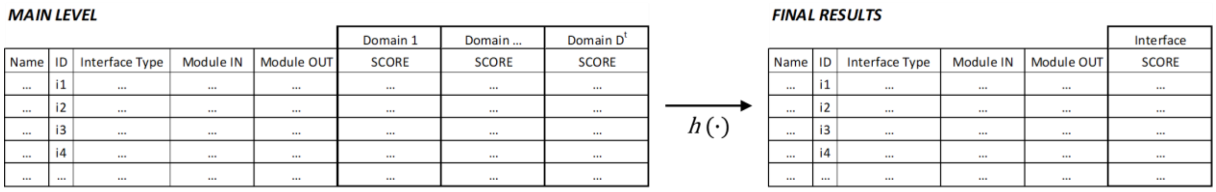

FIG. 7 - OUTPUT OF THE CDFA ASSESSMENT (FINAL RESULTS)

The scores describe the interfaces assembly complexity considering all the parameters involved in the assembly and installation processes. Scores can be sorted out from lowest to highest to identify elements (interfaces and modules) that are the most complex to install inside the aircraft and that required to be redesigned.

Mathematical Operators

The process of translating data from one level to another one is achieved through mathematical operators. A mathematical operator is a function – y = f(x1, x2, …, xn) – that combines inputs (x_1, x_2, …, x_n) to obtain one single output (y). For the proposed methodology, the mathematical operators available in literature can be divided into two groups: weighted operators and weight-less operators. The former enables to apply weight on the input data. In this group there are Multi-Attribute-Decision-Making (MADM) methods (i.e., Technique for Order of Preference by Similarity to Ideal Solution - TOPSIS) (Hwang and Yoon 1981). On the other hand, the mean operator, the root mean square (RMS), and the average square are some of the available weight-less operators. The choice of the mathematical operator is driven by: (i) the invariant chosen in the analysis, (ii) the uncertainty whose is affecting the input data, and (iii) the importance given to outliner/inliner data. The mean operator is used to collect data that do not contain discrepancy, for instance domains' scores are collected using the mean operator since, through the data normalization and score collection, domains' scores do not contain discrepancy. On the other hand, the RMS is used to collect scores when data might have discrepancy due to: i) errors in the data collection process, ii) the creation of clusters of information which are not strictly related (e.g., *total length of harness* and *number of connections* belong to the same domain, but these attributes are not directly affecting each other). Thus, RMS is usually adopted to cluster scores of different attributes within a domain.

4. Case Study

The proposed methodology was applied to assess the fit for assembly performances of one of the most challenging system of a civil aircraft: the nose-fuselage (Fig. 8). Within the nose-fuselage many modules and connections are present (e.g., electrical cables, air ducts, hydraulic pipes, etc.) and they need to be installed and assembled within very confined areas. Moreover, the nose-fuselage architecture is constrained by several aspects, for instance the need to install elements inside an already-given structure (i.e., aircraft skeleton), the requirements to have elements redundancy for safety purposes, etc.

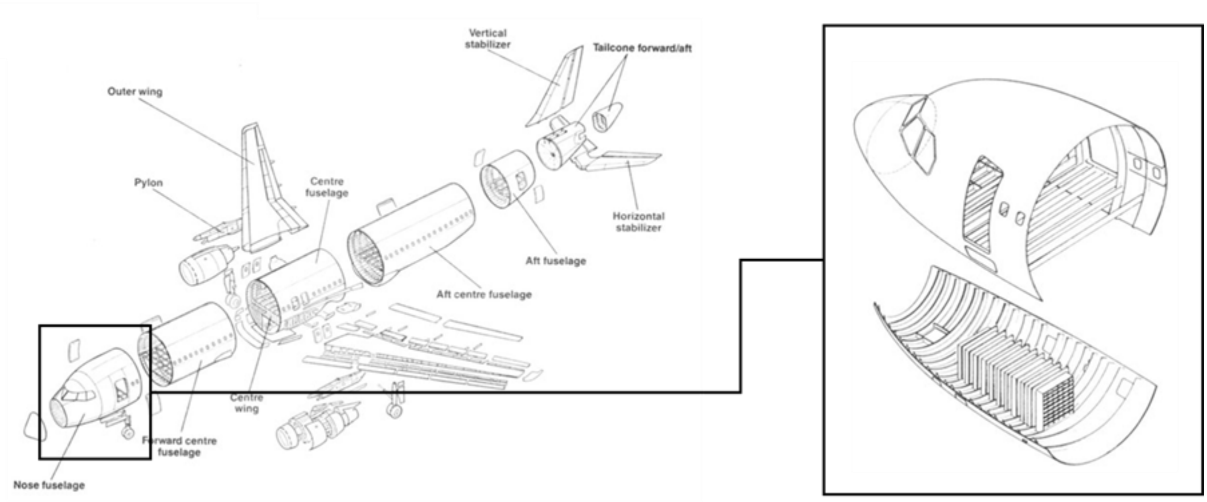

FIG. 8 – CIVIL AIRCRAFT NOSE-FUSELAGE EXAMPLE

The goal of the presented case study is to numerically assess the nose-fuselage architecture with the aim to identify interfaces considered critical for the installation process, providing a list of the most critical items to install. The ranking can be considered as a very helpful tool to guide the re-design phase, providing hot-spots and rationales to identify and subsequently avoid critical assembly tasks. This information will then be used for design improvements which is outside the scope of this work.

4.1 Nose-Fuselage Functional Decomposition

The Nose-Fuselage Functional Decomposition is composed of: (1) Functional Derivation, and (2) Module Derivation. The Functional Analysis was performed to derive all the nose-fuselage functions and interfaces among them. Functions were derived according to Pahl et al. (2007) using information available in literature (e.g., equipment functions, connection among equipment, etc.). The functional scheme was obtained considering a civil aircraft already available from the market. In fact, it is necessary to start from design actions already available to be able to derive a full functional scheme. Functions were derived using several documents among which technical documents describing systems used in aircraft, technical drawing of the nose-fuselage, use and maintenance manual, accident and malfunctions reports, etc. The analysis of these documents allowed to obtain information regarding systems inside the aircraft, how they interact and how they are subdivided. The general function "Fly, manage flight and allow passengers entrance and carry" was considered, and then it was subdivided into more specific functions with a hierarchical structure. Four hierarchical levels were obtained. Fig. 9 shows an extract of the second level (the overall functional scheme is not provided due to space limitation and confidentiality).

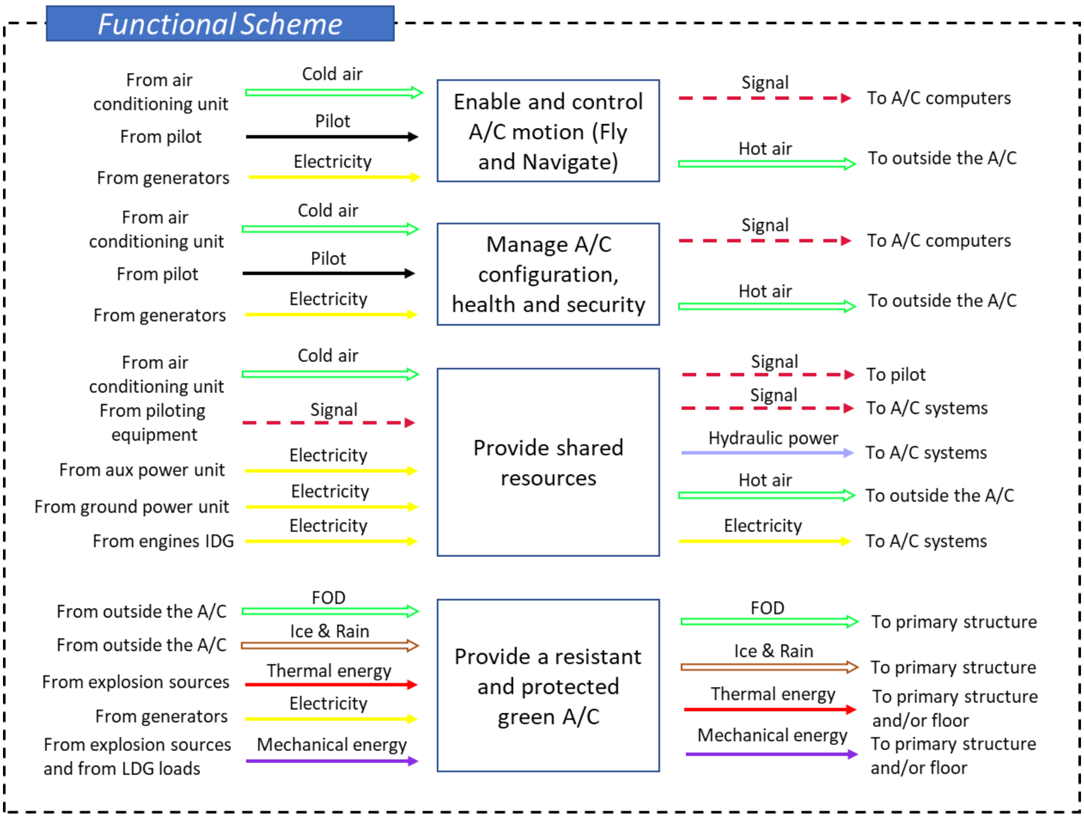

FIG. 9 – EXTRACT OF FUNCTIONAL SCHEME (2ND LEVEL) - LEGENDA BASED ON TABLE 2

Once the functional scheme was obtained, a top-down approach based on module heuristics (Stone et al. 2004) was coupled with a bottom-up approach to derive modules. From basic fluxes identified in the functional scheme, it was necessary to switch to interfaces. To reduce the overall analysis perimeter, only *electrical* and *air* interfaces were considered within this work since from engineering experience they were considered the most complex to install (Hermansson et al. 2013). In this specific case, since it is based on a real product and the scope of the analysis is the evaluation of a given product architecture through the mean of the CDfA, the module heuristics was coupled with the analysis of available product structure (overlapping existing modules with the ones retrieved by module heuristics). It is worth to notice that in the product architecture development of aircraft systems, the optimization phase is mainly characterized by the module re-arrangement which means the possibility to split/merge modules, module reallocation, interface routing, re-architecture of interconnection among modules. Thus, the list of modules is mainly driven by the available solutions and modules derivation using module heuristics is an exercise done to investigate possible alternatives (slit/merge modules) for module definition based on functional decomposition. An extract of the derived modules is shown in Fig. 10

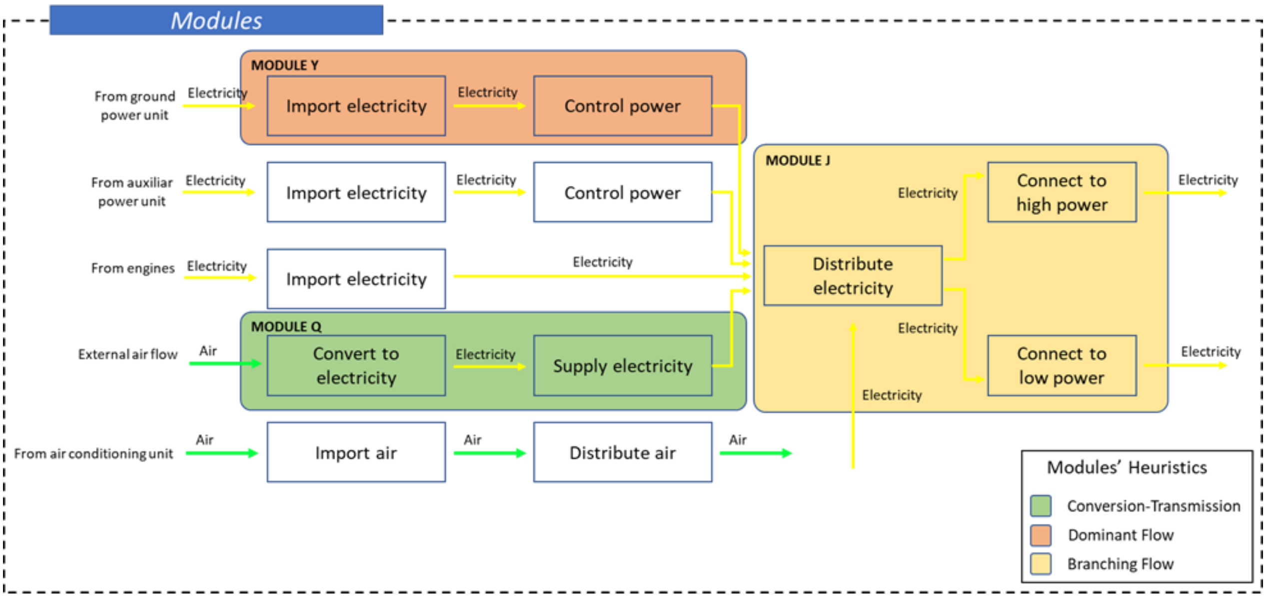

FIG. 10 – EXTRACT OF MODULES DERIVATION

4.2 Nose-Fuselage Architecture Geometrical Definition

The *simplified* Digital Mock Up was created following the conceptual modules, and architectural data were created making use of existing product definition information, in particular: (i) the bounding box of each module, (ii) the length of connections (interfaces) among modules, (iii) the modules and connections position, and (iv) the connections diameters. Rectangular boxes were used to model modules while cylinders for interfaces. Interfaces colours are based on Table 2. For the case study in exam, since 3D models were already available, with the help of *virtual reality* technologies it was possible to draw interfaces, modules connections and bounding boxes easily and in a straight-forward manner. The sDMU obtained is presented in Fig. 11.

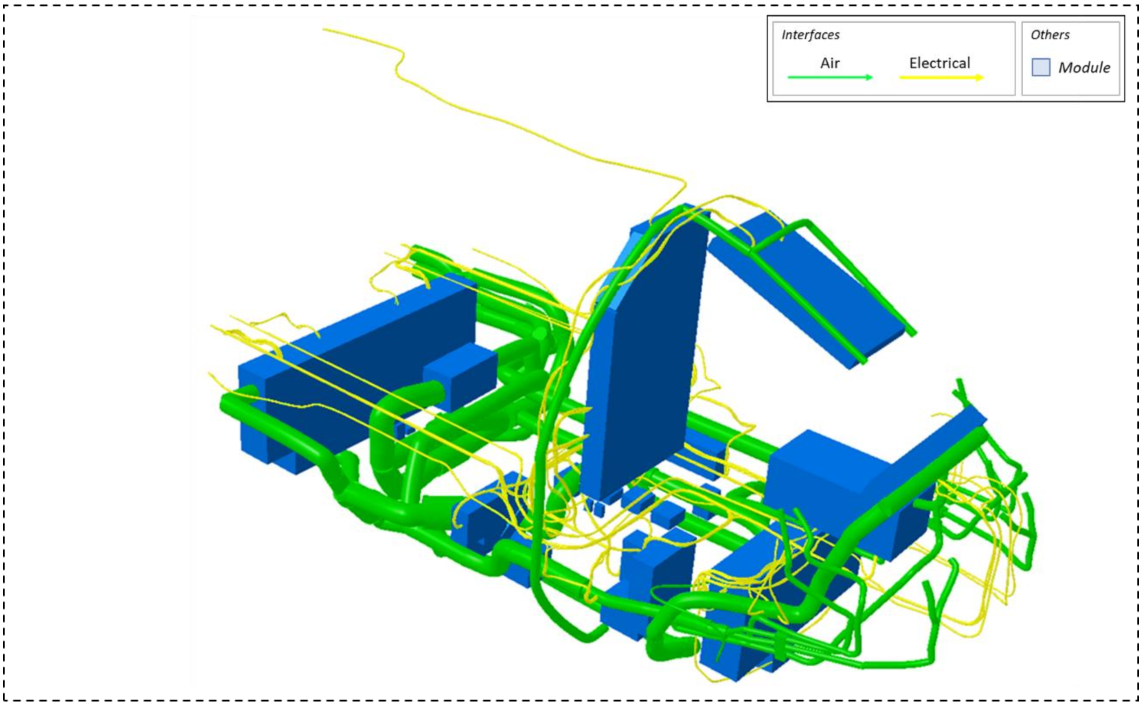

FIG. 11 - *SIMPLIFIED* DIGITAL MOCK UP – LEGENDA BASED ON TABLE 2

Then the *conceptual* Bill of Materials was derived. For the product under study, it is composed of three (3) levels (layers) of data: Level 1, Level 2, and Level 3. The Level 1 is composed by only one domain called “Interface Domain” which includes attributes referring to the overall interfaces among modules. To switch from the Level 1 to the Level 2 the invariant *working area* was defined. Working areas are pre-defined areas identifiable in the nose-fuselage. These areas cannot be changed due to structural reasons (i.e., design of beams, skin and floor). The invariant *working area* is used also to define attributes’ scores inside knowledge scoring matrices. Each attribute has a different score according to the working area in which is defined (Table 5). For instance, in the working area “Right Bay” the attribute “Zone” for the value “Middle” has a score of 4, while for the working area “Cockpit” the same attribute with the same value (i.e., Middle) has a score of 1.

TABLE 5 - EXTRACT OF KSM FOR ATTRIBUTE “ZONE” (II LEVEL)

Invariant (Working Area)	Zone	Score
Right Bay	Upper	5
Right Bay	Middle	4
Right Bay	Lower	4
Cockpit	Upper	3
Cockpit	Middle	1
Cockpit	Lower	3

The Level 2 is composed by two domains called “Ergonomic Domain” and “Assembly Domain”. The first one includes four attributes referring to ergonomic aspects of the installation process, while the second one presents two attributes representing complexity of the installation process itself (see Table 7).

To switch from the Level 2 to the Level 3 the invariant *interface* was defined. Interfaces are defined from the functional analysis and cannot be changed without changing the product. The invariant *interface* was used to define attributes' scores inside knowledge scoring matrices (Table 6).

TABLE 6 - EXTRACT OF KSM FOR ATTRIBUTE "LENGTH" (III LEVEL)

Invariant (Interface)	Length	Score
Air	0 <x <= 2	1
Air	2 < x < 5	2
Electrical	0 < x <= 5	1
Electrical	5 < x < 10	2

The Level 3 presents one domain called "Component Domain" which includes attributes referring to physical elements composing the interface. All Attributes and Domains used for the analysis are summarized in Table 7.

TABLE 7 - ATTRIBUTES AND DOMAINS IDENTIFIED FOR THE NOSE-FUSELAGE

Domain	Interface type	Attribute	Explanation
Interface domain	Air	Total Length of Ducts	Overall air interface length
	Air	Branches	Number of times air interface branches out
	Elec	Total Length of Harness	Overall electrical interface length
	Elec	Number of Connections	Number of connections electrical interface collects
	Elec	Number of Straight Nodes	Number of times electrical interface branches out
Ergonomic domain	Air/Elect	Access	Access used to bring the interface inside the working area
	Air/Elect	Zone	Zone in which interface is installed
	Air/Elect	Working Space Size	Available space during the installation operations
Assembly domain	Air/Elect	Variety of Tools	Number of tools necessary to perform the assembly
	Air/Elect	Process	Complexity of the installation process
Component domain	Air	Air Bends	Number of air ducts elbow
	Air	Air Shape	Shape of the air duct
	Air	Air Weight	Weight of the air duct
	Air	Air Piece Length	Length of the air duct
	Elect	Electrical Weight	Weight of the electrical cable
	Elect	Electrical Piece Length	Length of the electrical cable
	Air/Elect	Fragility	Breakability of the duct/cable material

After the definition of the cBoM structure, the *knowledge* scoring matrices for each attribute were defined according to the ontology developed. Four meetings were organized: (i) an initial in person meeting, (ii) two follow-up *web* meetings and (iii) a final in person review meeting. Industry departments involved in the meetings are collected in Table 8.

TABLE 8 - MEETINGS PARTICIPANTS

Department	Participants	Meeting First	Second	Third	Fourth
Product Architecture & Design	Aircraft Architect	X		X	X
Product Architecture & Design	DMU operators	X		X	X
Product Architecture & Design	System installation designers	X		X	X
Manufacturing & Assembly	Industrial architect	X	X		X
Manufacturing & Assembly	Industrial routing designers	X	X		X
Manufacturing & Assembly	Manufacturing operators (blue-collar)	X	X		X
Manufacturing & Assembly	Ergonomic expert	X	X		X

During the initial meeting (first meeting), the methodology was presented. Then, in the first *web* meeting (second meeting) a survey was submitted to the manufacturing department to collect expertise from assembly operations and related tasks. Then, results of the survey were analysed to obtain the first draft of the kSMs. The second *web* meeting (third meeting) was organized with the Product Architecture & Design department to show the kSMs obtained and few modifications were suggested. In the final meeting, the latest version of kSMs was presented and finalized. An extract of the kSMs obtained is presented in (Fig. 12).

kSM extract

INTERFACE DOMAIN				RATIONALE
Total Length of Harness			Score	Electrical interfaces connecting modules with a distance higher than 5,6m are complex to install due to: (i) alignment errors, (ii) interface management. Interfaces shorter than 1,4m do not present
	X<=	1,4	1	
1,4	< X <=	2,8	2	
2,8	< X <=	4,2	3	
4,2	< X <=	5,6	4	
	X >	5,6	5	

ERGONOMIC DOMAIN			RATIONALE
Working Space Size		Score	Inside the Nose-Fuselage five different Working Spaces are identified according to: number of adjacent modules, number of operators working in the same area, module bounding box
Very Big	=	1	
Big	=	2	
Normal	=	3	
Small	=	4	
Very Small	=	5	

FIG. 12 – DERIVED KNOWLEDGE SCORING MATRIX FOR TWO DIFFERENT ATTRIBUTES (TOTAL LENGTH OF HARNESS AND WORKING SPACE SIZE)

4.3 *Conceptual* Design for Assembly Assessment

To perform the final step, which is the *Conceptual* Design for Assembly Assessment, it was necessary to: i) normalize all information collected in the cBoM using the derived *knowledge* scoring matrices, and ii) provide the mathematical algorithm to collect the normalized date inside the cBoM to obtain a Final Global score for each interface. The mathematical algorithm was defined using three different operators: i) Root Mean Square operator - RMS, ii) Mean operator and iii) TOPSIS method. The RMS was chosen to collect attributes' scores for each domain. The reason lies in the need to consider possible errors, in fact initial data present different roots (i.e., some data are measured, others are derived by engineering knowledge) and they might present some evaluation errors. The use of RMS allowed to obtain a more conservative result with respect to other mathematical operators.

The Mean operator was chosen to collect score at each level (i.e., from Level 3 to Level 2, from Level 2 to Level 1). In fact, data are initially collected in the cBoM, then, using the *knowledge* scoring matrices, they are normalized (i.e., data are translated into scores) and collected per domain. After the normalization process and the domains' collection, scores have all the same roots and no further source of error need to be considered. Finally, the TOPSIS was used to obtained one single score (i.e., Final Global score) for each interface from domains' scores. The TOPSIS method was chosen since it allows to apply weights on each domain to tune the overall assessment. In fact, due to the nature of the methodology itself, in the model definition some attributes and domains might be underestimated or overestimated in terms of assembly complexity. This may lead to some shortfalls that can be recovered afterward making use of weights. Indeed, weights can be used to increase/decrease the importance on the Final Global score of each domain. However, for the specific case-study, no weights were added since results showed to be in line with engineering judgment. The overall *Conceptual* Bill of Material, where operators are stated explicitly is shown Fig. 13, while Fig. 14 shows an extract of the result of the *Conceptual* Design for Assembly Assessment phase, where the five most critical interfaces (i.e., most complex to install) are displayed and highlighted in the sDMU.

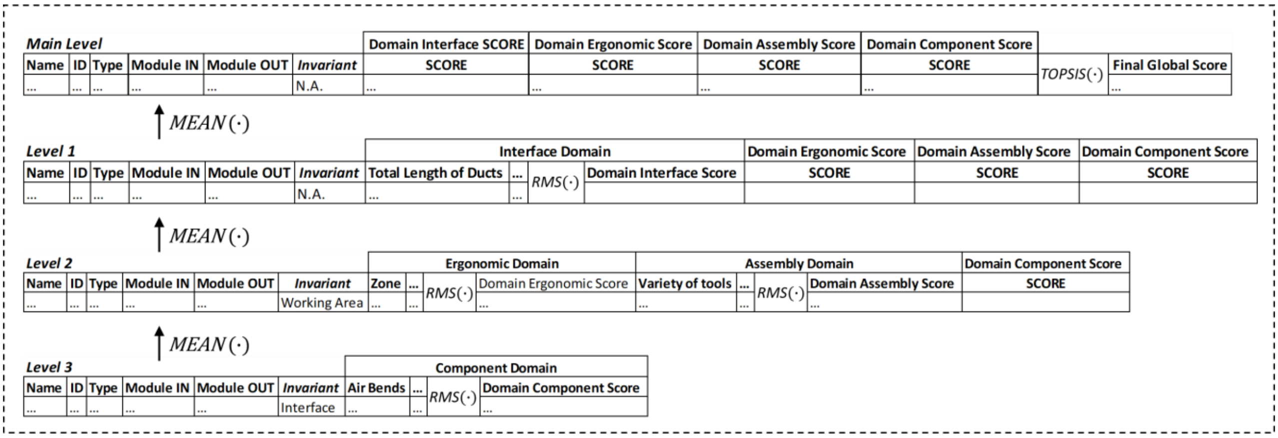

FIG. 13 - CBOM MATHEMATICAL ALGORITHM

Final Results

Name	Module IN	Module OUT	Score
E45	Module N	Module S	0,83
E17	Module L	Module N	0,82
E5	Module I	Module M	0,79
E8	Module I	Module P	0,78
E19	Module L	Module P	0,78

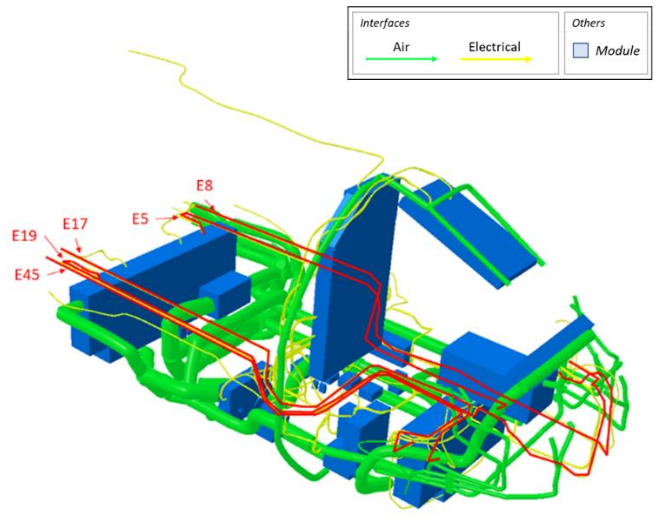

FIG. 14 - 5 FINAL RESULT OF THE NOSE FUSELAGE WITH CRITICAL INTERFACES – LEGENDA BASED ON TABLE 2

5. Results

CDfA results provide an estimation of the complexity to install connections (interfaces) and associated modules inside the nose-fuselage. Final Global scores range from 0 to 1 due to the application of the TOPSIS method. Interfaces with highest score represent the most complex to install. As general outcome, results show that electrical interfaces are the most critical for the installation process. The hierarchical structure (framework) of the CDfA methodology enables to understand where criticalities lie. An example is reported below for the interface E45 which has the highest score among all interfaces as reported in Fig. 14. Indeed, Interface E45 connects Module N to Module S and presents an overall score of 0,83 and it is the most critical to install. Moving to the global scoring a more accurate understanding of the E45 connection assembly complexity is obtained (Table 9**Errore. L'origine riferimento non è stata trovata.**).

TABLE 9 - E45 MAIN LEVEL RESULTS

Name	Type	Module IN	Module OUT	Interface Domain	Ergonomic Domain	Assembly Domain	Component Domain
E45	Electrical	Module N	Module S	4,12	3,66	3,54	4,12

Among all, the highest score is associated to Interface Domain (4,12) and Component Domain (4,12). Analysing results for the Interface Domain, the attributes *Total Length of Harness* and *Number of Connections* present a score of 5 (Table 10**Errore. L'origine riferimento non è stata trovata.**). Thus, alternative modifications might be implemented to reduce the Interface Domain score: i) reduce the overall length of the connection by moving modules closer, ii) merge modules together to minimize the connection (i.e. build a new module which encompasses the two modules or fit altogether the two modules outside the aircraft and bring them inside as a single module) and, iii) make use of dedicated plate in order to install all connectors at the same time.

TABLE 10 - E45 DOMAINS RESULTS

				Interface Domain		
Name	Type	Module IN	Module OUT	Total Lenght of Harness	Number of connections	Number of Straight Nodes
E45	Elect	Module N	Module S	5	5	1

				Ergonomic Domain			Assembly Domain	
Name	Type	Module IN	Module OUT	Access	Zone	Working Space Size	Variety of Tools	Process
E45.1	Elect	Module N	Module S	4	3	1	3	4
E45.2	Elect	Module N	Module S	4	5	1	3	4
E45.3	Elect	Module N	Module S	4	5	1	3	4
E45.4	Elect	Module N	Module S	1	3	4	3	4

				Component Domain		
Name	Type	Module IN	Module OUT	Electrical Weight	Electrical Piece Length	Fragility
E45.1.01	Elect	Module N	Module S	5	2	5
E45.2.01	Elect	Module N	Module S	5	2	5
E45.3.01	Elect	Module N	Module S	5	2	5
E45.4.01	Elect	Module N	Module S	5	2	5

Moving to the Component Domain, attributes *Electrical Weight* and *Fragility* presents a score of 5. These scores are shared by all electrical interfaces. The reason behind this result lies on the fact that electrical connections, in the current architecture, are not divided into pieces like air interfaces, in fact same data is repeated for each interface sub-section (Table 11**Errore. L'origine riferimento non è stata trovata.**). Indeed, electrical harnesses are heavy and difficult to handle. Moreover, these harnesses are fragile mainly due to their lack of rigidity and they require special caution during installation operations. This aspect is represented by *Fragility* score (i.e., 5). Thus, to improve the installation aspects of E45 and all other electrical interfaces, electrical harnesses shall be split into sub-harnesses and installed separately. However, the analysis performed does not consider the possibility to have shared interfaces, meaning interfaces sharing the same harness for a given length (or pre-bundled harnesses), which is typically the case for electrical harnesses.

TABLE 11 - EXTRACT OF WEIGHT AND FRAGILITY ATTRIBUTES FOR DIFFERENT INTERFACES (E5, E8, E17, E19, AND E45)

				Electrical Weight		Electrical Piece Length		Fragility	
Name	**Type**	**Module IN**	**Module OUT**	*Original*	*Normalized*	*Original*	*Normalized*	*Original*	*Normalized*
E5.1.01	Electrical	Module I	Module M	24,0	5	8,6	2	High	5
E5.2.01	Electrical	Module I	Module M	24,0	5	8,6	2	High	5
E5.3.01	Electrical	Module I	Module M	24,0	5	8,6	2	High	5
E8.1.01	Electrical	Module I	Module P	21,1	5	7,5	2	High	5
E8.2.01	Electrical	Module I	Module P	21,1	5	7,5	2	High	5
E8.3.01	Electrical	Module I	Module P	21,1	5	7,5	2	High	5
E17.1.01	Electrical	Module L	Module N	24,2	5	8,7	2	High	5
E17.2.01	Electrical	Module L	Module N	24,2	5	8,7	2	High	5
E17.3.01	Electrical	Module L	Module N	24,2	5	8,7	2	High	5
E19.1.01	Electrical	Module L	Module P	22,3	5	7,9	2	High	5
E19.2.01	Electrical	Module L	Module P	22,3	5	7,9	2	High	5
E19.3.01	Electrical	Module L	Module P	22,3	5	7,9	2	High	5
E45.1.01	Electrical	Module N	Module S	22,7	5	8,1	2	High	5
E45.2.01	Electrical	Module N	Module S	22,7	5	8,1	2	High	5
E45.3.01	Electrical	Module N	Module S	22,7	5	8,1	2	High	5
E45.4.01	Electrical	Module N	Module S	22,7	5	8,1	2	High	5

The process can be repeated for the remaining domains (*Ergonomic Domain* and *Assembly Domain*) to identify potential improvements. The procedure is applicable to each interface for identifying criticalities during the installation phases. It is worth noting that the method does not consider the assembly sequence of the product (i.e., system dynamicity), thus some interfaces might be critical at the end of the installation process, but they might not be at an early stage of the process. Again, the hierarchical structure (framework) of the cBoM proposed within the CDfA methodology provides guidelines to the designers for analysing the product architecture and performing modification to improve the installation phase. In fact, by analysing the cBoM it is possible to highlight product issues related to the assembly phase.

6. Conclusion

Although DFA methods can reduce the assembly complexity of products, they are applicable only at late design phase, limiting their benefits. The *Conceptual* Design for Assembly method (CDfA) presented in this paper enables to assess assembly complexity of aircraft system architectures. The CDfA methodology and its general framework can be also adopted in the analysis of assembly performances of different products characterized by a high level of complexity (e.g., automotive, machinery and equipment industry, etc.). The method starts from the Functional Derivation of the product and, through the definition of levels, attributes, and domains creates the hierarchical structure of the *conceptual* Bill of Materials (cBoM). Then, using specific mathematical operators, a single score for each interface is obtained. The highest score identifies the most complex interface to install. The method was applied to the nose-fuselage of a civil aircraft to assess the fit for assembly performance of the component represented with modules, electrical and air connections.

The novelty of the method is highlighted in the following points: (i) collecting and analysing data switching from tacit implicit knowledge to explicit knowledge (*knowledge* scoring matrices), (ii) create a mathematical model and a framework able to consider the global context of an aircraft assembly by using sub-problems that are limited in terms of complexity (problem discretization), and (iii) providing rationales to the designer regarding weakness of the product architecture in terms of assembly operations efficiency. Moreover, the method allows to perform comparisons of different system products architecture (e.g., nose-fuselage, cabin, etc.) to understand which is better in terms of assemblability and to identify design actions aiming at improving system installation. The method does not directly provide redesign actions or solutions to designers, but it helps to spot product architecture issues.

However, the method presents some limitations: (i) it does not offer a quick analysis of the modification that could be implemented to reduce the score: the solution space remains too wide to ease the down-selection of the most appropriate solution, (i) it does not consider in the analysis the dynamic sequence of the operations, and (iii) it does not consider interfaces of the same type which are shared.

Future works will focus on two aspects: on one hand, the improvement of the CDfA method trying to overcome current limitations. For instance, since the current approach is not able to consider shared interfaces (i.e., one interface which is shared between more than one module), it will be necessary to strength the method to assess and identify this design solution. Moreover, an added value will be provided by the implementation of the methodology in commercial CAD systems to automatize the architecture scoring from the data acquisition phase to the scoring visualization. Nevertheless, it will be necessary to add a cost analysis, in fact modularization might not be always the best solutions since the interface cost might be too elevate to provide a real benefit (Engel and Reich 2015). On the other hand, research will focus on the developing of design assistance for exploring the solution space to improve the global product architecture scoring by implementing design guidelines. Regarding this aspect, an attempt has been done by the same authors to use the result of the CDfA method to drive the re-design of the cabin of an aircraft (Formentini et al. 2020, Formentini et al. 2021). However, the proposed research is still on-going. Further research and testing are required to obtain valuable re-design suggestions.

References

Ahmed S (2005) Encouraging reuse of design knowledge: a method to index knowledge. Design Studies 26(6) 565-592

AlGeddawy T, ElMaraghy H (2013) Reactive design methodology for product family platforms, modularity and parts integration. CIRP Journal of Manufacturing Science and technology 6(1) 34-43

Barbosa GF, Carvalho J (2014) Guideline tool based on design for manufacturing and assembly (DFMA) methodology for application on design and manufacturing of aircrafts. Journal of the Brazilian Society of Mechanical Sciences and Engineering 36(3) 605-614

Bonvoisin J, Halstenberg F, Buchert T, Stark R (2016) A systematic literature review on modular product design. Journal of Engineering Design 27(7) 488-514

Boothroyd G, Dewhurst P, Knight WA (2011) Product design for manufacture and assembly. CRC Press

Browning TR (2015) Design structure matrix extensions and innovations: a survey and new opportunities. IEEE Transactions on Engineering Management 63(1) 27-52

Brusoni S, Prencipe A (2011) Patterns of modularization: The dynamics of product architecture in complex systems. European Management Review 8(2) 67-80.

Bullen GN (1999) Assembly Automation and Implementation Issues. SAE Technical Paper 1999-01-2267

Butterfield J, Crosby S, Curran R et al (2007) Optimization of aircraft fuselage assembly process using digital manufacturing. ASME Journal of Computing and Information Science in Engineering 7(3) 269–275

Coma O, Mascle C, Balazinski M (2004) Application of a fuzzy decision support system in a design for assembly methodology. International Journal of Computer Integrated Manufacturing 17(1) 83-94

Domeshek EA, Herndon MF, Bennett AW, Kolodner JL (1994) A case-based design aid for conceptual design of aircraft subsystems. In Proceedings of the Tenth Conference on Artificial Intelligence for Applications pp. 63-69 IEEE

El-Nounu A, Popov A, Ratchev S (2018) Redesign methodology for mechanical assembly. Research in engineering design 29(1) 107-122

Erens F, Verhulst K (1997) Architectures for product families. Computers in industry 33(2-3) 165-178

Ethiraj SK, Levinthal D (2004) Modularity and innovation in complex systems. Management science 50(2) 159-173

Farid AM (2008) Facilitating ease of system reconfiguration through measures of manufacturing modularity. Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture 222(10) 1275-1288

Favi C, Formentini G, Bouissiere F, Cuiller C, Dereux PE, Malchair C (2019) Design for Assembly in the Conceptual Development of Aircraft Systems. In International Conference on Design, Simulation, Manufacturing: The Innovation Exchange (pp. 268-278) Springer Cham

Favi C, Germani M (2012) A method to optimize assemblability of industrial product in early design phase: from product architecture to assembly sequence. International Journal on Interactive Design and Manufacturing 6(3) 155-169

Fricke E, Schulz AP (2005) Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. Systems Engineering 8(4)

Frigant V, Talbot D (2005) Technological determinism and modularity: Lessons from a comparison between aircraft and auto industries in Europe. Industry and Innovation 12:337–355. https://doi.org/10.1080/13662710500195934

Gómez A, Ríos J, Mas F, Vizán A (2016) Method and software application to assist in the conceptual design of aircraft final assembly lines. Journal of Manufacturing Systems 40:37–53. https://doi.org/10.1016/j.jmsy.2016.04.002

Guarino N (1995) Formal ontology, conceptual analysis and knowledge representation. International Journal of Human - Computer Studies 43:625–640. https://doi.org/10.1006/ijhc.1995.1066

Hermansson T, Bohlin R, Carlson JS, Söderberg R (2013) Automatic assembly path planning for wiring harness installations. Journal of Manufacturing Systems 32:417–422. https://doi.org/10.1016/j.jmsy.2013.04.006

Hickie D (2006) Knowledge and competitiveness in the aerospace industry: The cases of Toulouse, Seattle and north-west England. European Planning Studies 14:697–716

Hirtz J, Stone RB, McAdams DA, et al (2002) A functional basis for engineering design: Reconciling and evolving previous efforts. Research in Engineering Design - Theory, Applications, and Concurrent Engineering 13:65–82. https://doi.org/10.1007/s00163-001-0008-3

Holt R, Barnes C (2010) Towards an integrated approach to “design for X”: An agenda for decision-based DFX research. Research in Engineering Design 21:123–136. https://doi.org/10.1007/s00163-009-0081-6

Hölttä K, Suh ES, de Weck O (2005) TRADEOFF BETWEEN MODULARITY AND PERFORMANCE FOR ENGINEERED SYSTEMS AND PRODUCTS

Huang GQ, Lee SW, Mak KL (1999) Web-based product and process data modelling in concurrent “design for X.” Robotics and Computer-Integrated Manufacturing 15:53–63. https://doi.org/10.1016/S0736-5845(98)00028-3

Jiao J, Simpson TW, Siddique Z (2007) Product family design and platform-based product development: A state-of-the-art review. Journal of Intelligent Manufacturing 18:5–29. https://doi.org/10.1007/s10845-007-0003-2

Jonas H, Gumpinger T, Krause D (2009) FLEXGALLEY – INNOVATIVE APPROACH FOR A MODULAR DESIGN OF AN AIRCRAFT-GALLEY

Jun HB, Park JY, Suh HW (2006) Lead time estimation method for complex product development process. Concurrent Engineering Research and Applications 14:313–328. https://doi.org/10.1177/1063293X06073302

Jung S, Simpson TW (2017) New modularity indices for modularity assessment and clustering of product architecture. Journal of Engineering Design 28:1–22. https://doi.org/10.1080/09544828.2016.1252835

Kuo TC, Huang SH, Zhang HC (2001) Design for manufacture and design for “X”: Concepts, applications, and perspectives. Computers and Industrial Engineering 41:241–260. https://doi.org/10.1016/S0360-8352(01)00045-6

Lockett H;, Fletcher S, Luquet N (2014a) Applying Design for Assembly Principles in Computer Aided Design to Make Small Changes that Improve the Efficiency of Manual Aircraft Systems Installations. SAE International Journal of Aerospace 7:284–291. https://doi.org/10.4271/2014-01-2266

Lyu J, Chang LY (2010) A reference model for collaborative design in mould industry. Production Planning and Control 21:428–436. https://doi.org/10.1080/09537280903363217

Ma J, Kim HM (2016) Product family architecture design with predictive, data-driven product family design method. Research in Engineering Design 27:5–21. https://doi.org/10.1007/s00163-015-0201-4

Maropoulos PG, Muelaner JE, Summers MD, Martin OC (2014) A new paradigm in large-scale assembly-research priorities in measurement assisted assembly. International Journal of Advanced Manufacturing Technology 70:621–633. https://doi.org/10.1007/s00170-013-5283-4

Mas F, Ríos J, Gómez A, Hernández JC (2016) Knowledge-based application to define aircraft final assembly lines at the industrialisation conceptual design phase. International Journal of Computer Integrated Manufacturing 29:677–691. https://doi.org/10.1080/0951192X.2015.1068453

Mas F, Ríos J, Menéndez JL, Gómez A (2013) A process-oriented approach to modeling the conceptual design of aircraft assembly lines. International Journal of Advanced Manufacturing Technology 67:771–784. https://doi.org/10.1007/s00170-012-4521-5

Miller J, Guerrero J, Goldstein D, Robinson T (2002) Spaceframe: Modular Spacecraft Building Blocks for Plug And Play Spacecraft. Small Satellite Conference

Monnoyer MC, Zuliani JM (2007) The decentralisation of airbus pruduction and services. Service Industries Journal 27:251–262. https://doi.org/10.1080/02642060701207056

Musen MA, Schreiber AT (1995) Architectures for intelligent systems based on reusable components. Artificial Intelligence In Medicine 7:189–199

Pahl G, Beitz W, Feldhusen J, Grote KH (2007) Engineering design: A systematic approach. Springer London

Reed N, Scanlan J, Wills G, Halliday ST (2011) Knowledge use in an advanced manufacturing environment. Design Studies 32:292–312. https://doi.org/10.1016/j.destud.2010.10.002

Shimomura Y, Yoshioka M, Takeda H, et al (1998) Representation of design object based on the functional evolution process model. Journal of Mechanical Design, Transactions of the ASME 120:221–229. https://doi.org/10.1115/1.2826962

Siddiqi A, de Weck OL (2008) Modeling methods and conceptual design principles for reconfigurable systems. Journal of Mechanical Design, Transactions of the ASME 130:1011021–10110215. https://doi.org/10.1115/1.2965598

Staab S, Studer R, Schnurr HP, Sure Y (2001) Knowledge processes and ontologies. IEEE Intelligent Systems and Their Applications 16:26–34. https://doi.org/10.1109/5254.912382

Stief P, Dantan JY, Etienne A, et al (2020) Product design improvement by a new similarity-index-based approach in the context of reconfigurable assembly processes. Journal of Engineering Design 31:349–377. https://doi.org/10.1080/09544828.2020.1748181

Stone RB, McAdams DA, Kayyalethekkel VJ (2004) A product architecture-based conceptual DFA technique. Design Studies 25:301–325. https://doi.org/10.1016/j.destud.2003.09.001

Suzuki T, Ohashi T, Asano M (2003) Assembly reliability evaluation method (AREM). CIRP Annals - Manufacturing Technology 52:9–12. https://doi.org/10.1016/S0007-8506(07)60518-6

Ulrich K (1995) The role of product architecture in the manufacturing firm. Research Policy 24:419–440. https://doi.org/10.1016/0048-7333(94)00775-3

Yancey RN (2016) Challenges, Opportunities, and Perspectives on Lightweight Composite Structures: Aerospace Versus Automotive. In: Lightweight Composite Structures in Transport: Design, Manufacturing, Analysis and Performance. Elsevier Inc., pp 35–52

Santiago V. Lombeyda, William C. Regli, Conceptual design for assembly (1999). Proceedings of the 1999 ASME Design Engineering Technical Conferences September 12-15, Las Vegas, Nevada

Engel A, Browning TR, Reich Y (2017) Designing products for adaptability: insights from four industrial cases. Decision Sciences, 48(5), 875-917

Engel A, Reich Y (2015) Advancing architecture options theory: six industrial case studies. Systems Engineering, 18(4), 396-414.

Kroll E (2013) Design theory and conceptual design: contrasting functional decomposition and morphology with parameter analysis. Res Eng Design 24:165–183 DOI 10.1007/s00163-012-0149-6

Ericsson A, Erixon G (1999) Controlling Design Variants: Modular Product-Platforms. Society of Manufact. Engineers, Dearborn Michigan

Hölttä-Otto K Modular Product Platform Design (2005). Doctoral Dissertation, Dept. of Mechanical Engineering, Helsinki University of Technology, Espoo.

Nuñez JR, Anderton CR, Renslow RS (2018) Optimizing colormaps with consideration for color vision deficiency to enable accurate interpretation of scientific data. PLoS ONE 13(7): e0199239. https://doi.org/10.1371/journal. pone.0199239

Hwang CL, Yoon K (1981) Methods for multiple attribute decision making. In Multiple attribute decision making (pp. 58-191). Springer, Berlin, Heidelberg.

Borjesson FA (2010) systematic qualitative comparison of five approaches to modularity. In: DS 60: Proceedings of DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia.

Atasoy B, Salani M, Bierlaire M, Leonardi C (2012) Impact analysis of a flexible air transportation system.

Hubka V, Eder WE (1989) Principles of Engineering Design. Springer.

Formentini G, Cuiller C, Dereux PE, Bouissiere F, Favi C (2021) Impact assessment of design guidelines in the conceptual development of aircraft product architectures. Procedia CIRP, 100, 223-228.

Formentini G, Favi C, Bouissiere F, Cuiller C, Dereux PE, Guillaume R, Malchair C (2020) Extrapolation of design guidelines during the conceptual design phase: a method to support product architecture design. In Proceedings of the Design Society: DESIGN Conference (Vol. 1, pp. 857-866). Cambridge University Press.