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# Design for Assembly in the conceptual development of aircraft systems

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**Abstract.** Conceptual design for assembly and installation is a key enabler for the improvement and development of an aircraft and related components. This work attempts to define a design for assembly methodology suitable for the evaluation and architecture design of aircraft systems in the preliminary phases of product development (conceptual design). Three main aspects are covered within this work: (i) the definition of a design framework, (ii) the characterization of suitable parameters driving the assessment and development of product architectures, and (iii) the formalization of internal knowledge for that purpose. The proposed approach has been tested in the assessment and development of an aircraft nose section with positive outcomes in terms of knowledge formalization and robustness of results in relation with the issues retrieved by the analysis of the assembly line. Future works will focus on the methodology optimization including automatic data input and mathematical models refinement.

**Keywords:** conceptual design, design for assembly, knowledge formalization, installation.

## 1 Introduction and context

Aircraft manufacturing is expected to dominate the market over the forecast period. Commercial aircraft led the market, which includes passenger and freighter aircraft. The global demand for commercial aircraft and cargo fleet is expected to grow in line with the annual number of passengers, which is expected to double over the next two decades. In this context, it is required to have an efficient production system which includes manufacturing, assembly and installation processes able to satisfy the market requests (e.g. time to market, lead time for delivery, etc.). Contrary to the automotive industry and other sectors, the development of new manufacturing/assembly facilities equipped with other technologies or a different arrangement of the already-existing ones are hardly achievable due to the extremely high-cost [17,27]. In addition the aerospace industry has strong certification requirements, with consequences on development costs, technology solutions and product development lead time [4].

The first step to face the market challenge is to work at the product (aircraft) architectural level, improving the design concept with the aim to be more efficient during the assembly phase. Conceptual design allows engineers to have higher degrees of freedom designing alternative product architectures oriented to specific target (e.g. assembly) [15,25]. In literature there are plenty of design methodologies oriented to the optimization of specific targets (Design for X - DFX) [5,7,8]. Design for Assembly (DFA) methodologies aiming at minimizing amount of components in complex assembly and at identifying critical tasks in assembly operations [3]. Among DFA methods, the most spread in academia and industry are: Hitachi method [24], Lucas method [11] and Boothroyd and Dewhurst method [2]. However, DFA techniques requires detailed design information and can be applied only during the detail design phase, where most of the choices have been already made [9] and costs engaged. Few attempts have been done to adopt DFA at the conceptual design stage [3,23]. Those methods appear beneficial for this aim although few limitations have been identified: (i) method applicability considering specificities of aircraft systems, (ii) method feasibility considering the product level of complexity and, (iii) method efficiency in terms of quantitative indicators (numerical assessment vs. qualitative analysis).

In recent years, the majority of the work done in this sector focus on the definition of optimized aircraft architectures toward manufacturing and assembly [1,12,13]. In the work of [17] the overall manufacturing cost is condensed by reducing the lead time, using Resource Constrained Shortest Paths (RCSP) optimization applied to production assembly sequences linked to product architecture. Results obtained showed that a co-engineering approach presents many advantages, but it is also time-consuming, and it may require high-skilled operators to run all the necessary analysis. Another attempt has been done by [10] focusing on the relation between aircraft systems and final assembly stage. Unfortunately, the proposed method lacks design information at the right time for the early design and the available data are mostly qualitative than quantitatively. Thus, there is no generalized method for applying the DFA at the conceptual design level.

The goal of this work is to define a design for assembly methodology compliant with the preliminary phases of aircraft systems development (conceptual design). The overall methodology leads to tree main objectives: (i) the definition of a design framework, (ii) the characterization of suitable parameters driving the assessment and development of product architectures, and (iii) the formalization of the required internal knowledge. In particular, the characterization of design parameters together with the formalization of internal knowledge enable to define "scoring matrices" that can be used in the preliminary phases of product development without requiring detailed design information. The mentioned "scoring matrices" are used to translate assembly features in numerical values that are collected and combined through mathematical models defined within the design framework. The main novelty of the proposed approach is the knowledge formalization method for aircraft assembly that allows to characterize installation issues in quantitative manner early in the design phase (conceptual design). Knowledge from manufacturing department, coupled with functional and geometrical information allow to translate different data types (i.e. string, number) in scores that represent the base to apply a design for assembly method. Indeed, from the literature analysis knowledge formalization emerges as a research gap and the characterization of assembly/installation features in numerical scores arises as a potential improvement in this field. This aspect is also recognized as an important progress from the industrial perspective.

The paper is structured as follow: Section 2 presents the overall design for assembly framework, the definition of assembly attributes for conceptual product development and knowledge formalization method. As case study, Airbus A320 nose fuselage is presented in Section 3. Results are discussed in Section 4 and concluding remarks are highlighted in Section 5.

## 2 Materials and methods

### 2.1 Conceptual design for assembly framework

One of the main challenge of the conceptual design phase is the capability to elaborate on early architectural data. To overcome this drawback, the proposed methodology is built upon the use of industrial knowledge avoiding to elaborate specific design data. Therefore, a conceptual design for assembly framework is proposed (**Fig. 1**) using conceptual schemes (e.g. functional analysis and simplified mock-up) as input. Within the framework, a set of scoring matrices is used to translate the manufacturing knowledge into numerical values, and mathematical models allows to obtain two outcomes: (i) an absolute result, and (ii) a comparative analysis of the results.

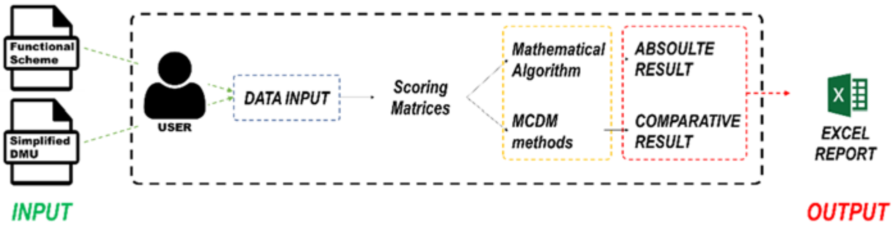


**Fig. 1.** - Methodology framework

The proposed methodology starts with the classical functional analysis [14,15,20]. From the result of the functional analyses it is possible to derive *modules*. A *module* is a physical assembly that is designed according to the module's heuristics [23] applied on the functional analysis.

Once functional modules have been defined, it is necessary to identify *interfaces*. An *interface* describes a functional link between different functional modules. Several interfaces can be identified according to the product under study and using the fluxes defined through module's heuristics [23]. Concerning the aerospace industry, the following interfaces are considered as reference:

*Air* – Interface distributing air fluxes (i.e. air ducts)
*Electrical* – Interface distributing electrical fluxes (i.e. electrical harnesses)
*Liquid* – Interface distributing liquid fluxes (i.e. fluid pipes)
*Mechanical* – Interface providing mechanical connections (i.e. anchor points)

Starting from this functional derivation, a simplified geometrical representation of *Modules* and *Interfaces* is realized using a 3D CAD system. The overall result is a simplify geometry called “simplified Digital Mock-Up” (sDMU). In the sDMU, *Modules* are represented by simple geometries as parallelepipeds, while *Interfaces* are represented by cylinders (**Fig. 2**). *Modules* and *Interfaces* sizes are approximated considering the functions they need to perform. Moreover, the identification of *Modules* and *Interfaces* is coherent between the two representations (using the same color). Functional scheme and sDMU are used as input to start the design analysis.

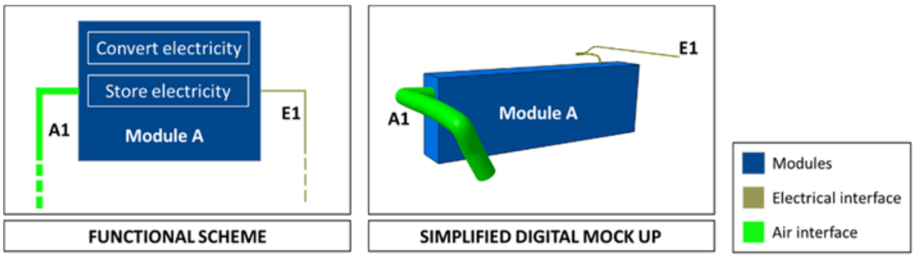


**Fig. 2.** – Example of functional scheme and sDMU

Data from functional scheme and sDMU are allocated within the framework and translated into numerical parameters by the use of *scoring matrices*. Assembly attributes (i.e. working area, modules dimensions, and interface length) are characterized to describe the assembly process of modules/interfaces and they are clustered in specific *domains*. A *domain* is a group of attributes describing specific aspects of the assembly process for components of the product architecture. The concept of domain and attributes is further developed in section 2.2.

Based on the attributes typology (i.e. string, numbers, percentage, etc.) a normalization process is required. Thus, the use of *scoring matrices* allows to have homogeneous data. A *scoring matrix* is defined as a table which translates assembly/installation features in numerical values (numbers in a range between 1 and 5). The matrix is composed of two columns: (i) range of a specific assembly feature, and (ii) score. Further explanations are provided in paragraph 2.3.

Finally, through the application of mathematical algorithms two different results are obtained: (i) an absolute result, and (ii) a comparative result. Absolute result is obtained by applying a Multi-Criteria-Decision-Making Method (MCDM) and it allows to identify criticalities within a specific architecture. Among all, the TOPSIS method has been chosen for its characteristics: (i) simple implementation and, (ii) ability to deal with more parameters without need of modifications [26]. Comparative result is obtained by applying simple mathematical operators (e.g. root mean square) and it allows to evaluate improvements among different product architectures. By doing so, it is possible to generate product architecture focusing on the reduction of installation issues highlighted in a given architecture.

## 2.2 Assembly attributes and domains

The definition of *domains* is a central aspect of this methodology, in fact they represent the starting point to perform the characterization of scoring matrices. A *domain* is a container of several attributes which are clustered based on common assembly features. Three *domains* have been identified considering the specificity of this sector: (i) Components domain – it describes physical aspects of interfaces that need to be brought inside the product and installed, (ii) Assembly domain – it describes the complexity of assembly operations referred to interfaces and, (iii) Ergonomic domain – it describes relation between the area in which operators perform the actions and human factors (**Fig. 3**).

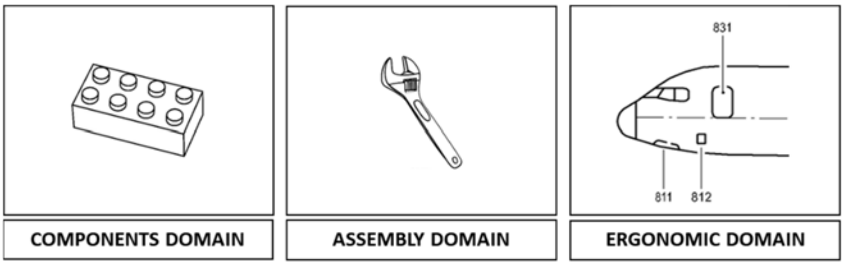


**Fig. 3.** – Three domains defined for the collection of assembly attributes

As an example, an extract of attributes defined for the ergonomic domain is presented below (**Table 1**). The reason behind the definition of domains is the possibility to bundle attributes that are inter-related. In this way, specific mathematical models can be adopted to couple attributes inside a domain and other mathematical models can be adopted to combine results between domains. For each attribute a scoring matrix is defined, thus general information is translated in numerical value.

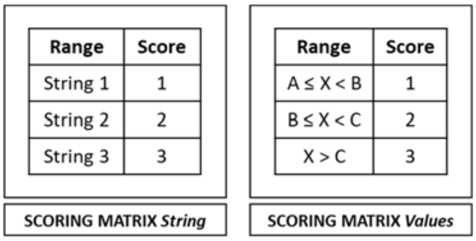
**Table 1.** – Attributes of the Ergonomic domain

| Domain | Attribute | Description |
|---|---|---|
| Ergonomic | Working Space Size | Represents the available space to perform assembly operation |
| | Zones | Describe the zone where operation needs to be performed |
| | Working Area | Represents the working area where operator needs to work |
| | Access | Describes the access to the working area |

## 2.3 Knowledge formalization

Nowadays, the formalization of the knowledge is becoming a great challenge for industries. Indeed, the translation of cases or lessons learned of previous product is necessary to keep internal knowledge [22]. This area of research is called Knowledge Engineering (KE). In the design field, many methods have been proposed to face this issue such as (i) expert system [6], (ii) Case-based reasoning [16], (iii) Design for manufacturing with KE [18,19,21].

In the proposed methodology, the formalization of knowledge is achieved by defining *Scoring Matrices*. Scoring matrices are defined through a concurrent design process, indeed a close collaboration between manufacturing department and architectural department is required. Scoring matrices allow to normalize information inside each attribute (i.e. from string or number to a value), making possible the application of mathematical models (**Fig. 4**). Scoring matrices remain unchanged among different analyses of product architectures, in this way a comparison between *as-is* configuration and *to-be* configuration can be performed.



| 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 |

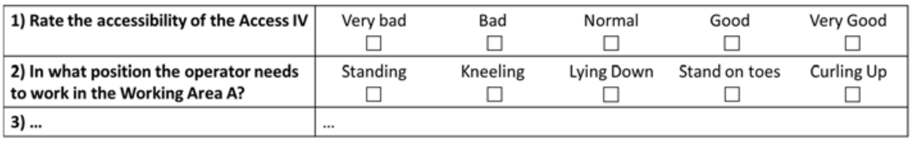
SCORING MATRIX *Values*

**Fig. 4.** - Scoring matrices

## 3 Case study

Knowledge formalization technique for the application of the conceptual design for assembly methodology has been applied on the nose section of Airbus A320. This assembly is one of the most complex component of the aircraft due to the presence of several design constraints and confined areas to perform assembly operations. The aim of this study is to test the robustness of the overall framework by a real example. For this reason, scoring matrices have been defined with a *concurrent design* approach. In particular, four meetings between manufacturing and product architecture department have been scheduled: (i) an initial *face-to-face* meeting, (ii) two follow-up *web* meetings and, (iii) a *final review* meeting.

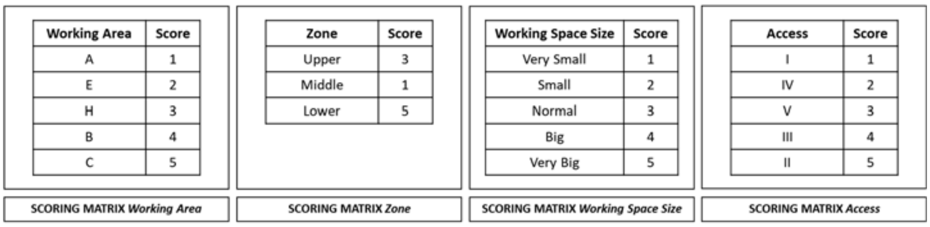
During the first meeting, the methodology framework has been presented and the necessity of defining scoring matrices has been explained. In the first follow-up *web* meeting, domains and attributes have been defined together with the company manufacturing and assembly department. The work has been carried out through a brainstorming approach. The brainstorming last, approximately, three hours. It is worth noting that brainstorming session allowed to define all and only attributes relevant for both manufacturing and architectural department. The identified attributes address the main features connected with assembly operations (valuable in the conceptual design phase) and then are clustered in the defined domains (Components, Assembly and Ergonomic domains). After this characterization, a *survey* with different questions for both manufacturing and architectural departments has been designed with the aim to define scoring matrices for each attribute of each domain. The survey consisted on a multiplechoice question where only one answer per question was allowed. Five levels of normalization have been chosen, thus the survey presented five multiple-choices, each one associated with a score ranging from one (1) to five (5). The obtained survey has been proposed during the second *web* meeting, in order to define scoring matrices. An extract of the provided survey for the definition of the Ergonomic domain scoring matrices is presented in **Fig. 5**.



| | | | | | |
|---|---|---|---|---|---|
| **1) Rate the accessibility of the Access IV** | Very bad<br>☐ | Bad<br>☐ | Normal<br>☐ | Good<br>☐ | Very Good<br>☐ |
| **2) In what position the operator needs to work in the Working Area A?** | Standing<br>☐ | Kneeling<br>☐ | Lying Down<br>☐ | Stand on toes<br>☐ | Curling Up<br>☐ |
| **3) …** | … | | | | |

**Fig. 5.** – Extract of the survey

From the outcomes of the survey, scoring matrices have been defined and applied on the methodology. In the final in-loco meeting, the obtained scoring matrices and the methodology results were shown. Scoring matrices for attributes inside the ergonomic domain are shown in **Fig. 6**. The other scoring matrices have been defined as well, but for the sake of brevity, they have not been reported in this work.



| Working Area | Score |
|---|---|
| A | 1 |
| E | 2 |
| H | 3 |
| B | 4 |
| C | 5 |

SCORING MATRIX *Working Area*

| Zone | Score |
|---|---|
| Upper | 3 |
| Middle | 1 |
| Lower | 5 |

SCORING MATRIX *Zone*

| Working Space Size | Score |
|---|---|
| Very Small | 1 |
| Small | 2 |
| Normal | 3 |
| Big | 4 |
| Very Big | 5 |

SCORING MATRIX *Working Space Size*

| Access | Score |
|---|---|
| I | 1 |
| IV | 2 |
| V | 3 |
| III | 4 |
| II | 5 |

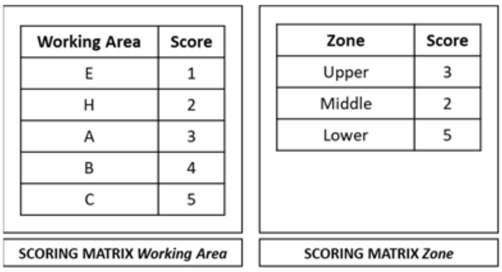
SCORING MATRIX *Access*

**Fig. 6.** - Scoring Matrices for Ergonomic Domain

Together with the scoring matrices, a document with explanation of each scoring matrix has been created (rationality). The document allows to storage and to transfer the internal knowledge created through scoring matrices.

## 4 Results

The definition of scoring matrices allowed the application of the methodology to assess the assembly time of product architecture at conceptual level. To check the goodness of the defined scoring matrices, the methodology has been tested over the already existing product architecture of A320 nose fuselage. The obtained results have been checked with the manufacturing and architectural departments. Among all, two (2) scoring matrices were updated (i.e. Working Area and Zone) based on the results derived from the application of the methodology. With the new scoring matrices (**Fig. 7**) results reflect the reality, highlighting modules that present difficulties from the assembly point of view. The definition of scoring matrices has been performed with four meetings, two face-to-face meetings and two (2) web meetings. The overall time invested in the activity was, approximately 8 hours, with few more hours, approximately two (2) hours, necessary to analyze and create documents (i.e. survey and document for knowledge storage).



| Working Area | Score |
|---|---|
| E | 1 |
| H | 2 |
| A | 3 |
| B | 4 |
| C | 5 |

SCORING MATRIX *Working Area*

| Zone | Score |
|---|---|
| Upper | 3 |
| Middle | 2 |
| Lower | 5 |

SCORING MATRIX *Zone*

**Fig. 7.** - Updated Scoring Matrices

During the first analysis, the five most critical modules and the five most critical interfaces, meaning modules and interfaces with the highest absolute score, have been identified. Results showed slight differences in relation with the real assembly and installation process. In particular regarding the modules assessment, among the most critical five modules, only one (i.e. Module-G) has not been highlighted by manufacturing department as critical. On the other side, regarding the interfaces assessment, the identified critical interfaces rebuilt the real assembly process (i.e. Interfaces E03, E29, E42 and A2). However, the list of critical interfaces is not fully reflected the ranking provided by the manufacturing department and scoring matrices required a fine-tuning. Based on the manufacturing feedbacks, scoring matrices have been re-worked and a new analysis has been done. It is worth noting that the scoring matrices have been reworked considering the main differences highlighted by the analysis results and the manufacturing department feedback (gap in attributes allocation). Indeed, only specific scoring matrices have been modified. This aspect shows the potentiality of the proposed framework, in terms of: (i) attributes characterization and, (ii) attributes clustering in domains. The second assessment, with new scoring matrices, has shown no discrepancy with the real assembly process. The result can be considered as good starting point in the conceptual analysis of nose fuselage fit for assembly; firstly, as a tool for the assessment of a given configuration/architecture and, secondly for the implementation of architecture design improvements. Further developments need to be done in order to increase the capability of results in the representation of assembly complexity and to fit with the real observation of the assembly line. Indeed, the methodology results for modules and interfaces give a score from zero (0) to one (1) for both relative and absolute results. At the current state, even if the assessment of critical modules and interfaces is in line with the real assembly observation, the gap among final scores does not represent the real fit for assembly performance. For example, considering module-G with a relative final score of 0.8 and Module-T with a relative final score of 0.4, it looks that Module-G is two times longer to install than Module-T. However, this is not compliant with the feedback retrieved by the manufacturing department where a smaller difference is noticed. Evaluations are highly conditioned by the low number of attributes in a given domain, the number of classes characterizing a score (scores from 1 to 5), the personal sensitivity of respondents, etc. This issue can be solved by refining the mathematical models at the basis of the methodology or adopting ponderation (weights) that allow to make the results closer with the real process. In this way it would be possible to evaluate *how much* one module/interface is more/less critical than another from the assembly point of view.

## 5 Conclusions

This work describes a design for assembly methodology for the development and the assessment of aircraft architectures early in the conceptual design phase. In particular, it provides a design methodology structure (framework), key performance indicators (attributes and domains) and, knowledge elicitation example (scoring matrices). All the three aspects have been evaluated within a specific context for the assessment and development of an aircraft system: the A320 nose fuselage. In particular, knowledge formalization results are acceptable in this first example where the main driver was the possibility to represent with preliminary design information and simple mathematical models the same criticalities observed during the assembly phase of aircraft systems. With this framework, designers and engineers can use the formalized knowledge to compare existing architecture with new ones. Moreover, knowing critical aspects (domains and attributes) which are driving "bad" score for a specific module or interface, enables to set directives to design new architectures

However, by developing this approach some drawbacks have been noticed: (i) knowledge formalization is a time-consuming procedure and requires multiple working sessions with a deep cooperation between manufacturing and architectural departments, (ii) the involvement of senior resources are mandatory to define scoring matrices, and (iii) some iterative steps are mandatory to refine the model (including both knowledge formalization and mathematical models).

Additional work is therefore necessary: (i) automatize the knowledge collection by linking the retrieved information with current product items and systems within the enterprise design repositories, (ii) create a software tool able to support manual data input and information collection, and (iii) derive design guidelines starting from the analysis of critical modules and interfaces to help engineers and architects in the development of new architectures.

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