PROCESS CHAIN ANALYSIS AND TOOLS FOR CABIN DESIGN AND REDESIGN ACTIVITIES

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Keywords: *process chain, cabin design, cabin conversion, optimization, tools*

Abstract

This paper describes the process chain for cabin design and cabin conversion activities. It than presents and applies a matrix-based methodology for optimizing the processes. Processes and tools strongly influence the degree of efficiency of the engineering work. It was found that certification related processes have highest importance. Tool functionality must match process requirements. The paper presents and evaluates suitable tools able to assist the design organization throughout the design / redesign process of aircraft cabins. The most important tool capabilities are compatibility for design and engineering tools and traceability for data management tools.

1 Introduction

1.1 Motivation

The goal of the design of an aircraft is to integrate aerodynamic, propulsion, structure and avionics to build an aircraft that can carry payload to a destination in its cabin and cargo hold. An aircraft cabin provides a safe environment for transporting passengers and their hand luggage. The goal of the design of an aircraft cabin is to account for required passenger comfort and for requirements from cabin systems like the environmental system, equipment and furnishings, electrical system and cabin electronics.

This paper approaches both cabin design and cabin conversion (or redesign) activities. A baseline method is presented for cabin architecture development. Then, the paper focuses on presenting and optimizing the process chain for cabin conversions.

Cabin design and redesign is required by customers who want to perform, for instance, VIP conversions or by airlines seeking to redesign or convert their fleet, according to new requirements. Forecasts show a growing market in this area. Existing design organizations able to cover this market segment are overbooked and the industry requires expertise to optimize the procedures. In this context, analysis and optimization of the processes behind the cabin design and redesign, correlated with appropriate tool selection, are vital for industry and provide the background for academic research.

1.2 Definitions

Process
Following the definition of EN 9100/2003, a process can be defined as the activity using re-sources and managed in order to enable the transformation of inputs into outputs [1].

Process Chain
A process chain illustrates the processes, as part of a system, and the relations between them.

Cabin
The cabin is the compartment surrounding passengers and crew. Cabin related systems, functions and services ensure a safe and comfortable operation both in flight and on the ground.

Cabin Design
Cabin design implies design and certification activities for the cabin related systems and cabin interior components of an aircraft; it usually refers to the creation of a new cabin, while used cabins are redesigned (or converted).

Cabin Redesign

Starting from Cabin Zero [2], which is the standard cabin of an aircraft, customers may require specific features for their product. A cabin conversion is defined as the sum of the activities necessary to transform the cabin from its original appearance to a new one, required for the new mission. Cabin Redesign can be: Pax-to-Pax, Pax-to-Freighter or Pax-to-VIP [3].

1.3 Objectives and Structure of the Paper

The aim of this paper is *first* to provide the reader with an insight perspective of the processes involved in cabin design and conversion. For this purpose, representation methods are studied while investigating the project management models appropriate to this field. (*Sections 2 and 3*).

A *second* major issue treated in this paper refers to optimization studies conducted with the purpose of improving the process chain. This is done in close connection with the representation method chosen for illustrating the process chain and the relations between its elements. Approached in this matter was the Dependency and Structure Modeling Methodology that uses Design Structure Matrices as a basic tool (*Section 4*).

A *third* focal point is the investigation towards the tools necessary to be implemented into an organization performing cabin design and conversion activities. Tools have a vital importance in designing, analyzing and archiving data. The research towards this topic includes the analysis of existing tools used in cabin related activities, and seeks to describe a range of further useful tools (*Section 5*).

The investigation is done with a medium sized engineering office in mind that wants to perform partial or complete cabin design (for VIP customers) or redesign (for airlines).

2 The Process Chain for Cabin Design

2.1 Process Chain Description

At a smaller scale, the cabin design reflects the process steps of aircraft design. Once the fuselage conception is completed, the cabin requirements for safety and operation must then be reflected in the cabin architecture development. This paper approaches cabin architecture development and focuses especially on the set-up of cabin conversions, which take place later in the aircraft life (Section 3).

This sub-section aims to determine the process steps when modeling the cabin architecture.

The cabin architecture needs to integrate a large amount of different systems and components:

- Cabin communication
- Entertainment system
- Air conditioning system
- Oxygen system
- Emergency floor path marking
- Lights
- Service (galleys)
- Utilities (lavatories, stowages)
- Seats (flight attendants and passengers)

The overall optimization and integration of parametric models becomes an important issue.

When observing the development of system architecture [4], the following process steps can be identified for the cabin architecture:

1.) Creation of a component library
2.) Definition of placement constraints
3.) Generation of an initial architecture
4.) Identification of relevant parameters
5.) Investigation of competing architectures
6.) Post-processing and analysis of the results

The input data required when defining the cabin architecture (i.e. an initial Step 0) is a fuselage shape optimized with respect to cabin requirements. An optimized fuselage shape accounts for both performance-based parameters, such as fuselage slenderness, and comfort-based parameters, such as number of seats abreast. Reference [5] presents a handbook method for fuselage preliminary design and cabin optimization.

Steps 1 to 6 use a Knowledge Based Engineering (KBE) approach. This approach uses knowledge databases and data association [6] in order to automate the design process. Section 2.2 details this concept.

Step 1.) refers to the implementation of a reusable component library into the architectural development. Items like seats, galleys, lavatories or stowage bins can be stored together with their parametric description and linked to the fuselage, inside dedicated zones.

Step 2.) defines first of all the regulatory placement constraints (e.g. no item needs to be positioned within a specified area near the emergency exits). However, operator constraints (e.g. the first overhead stowage bin on the right contains the In Flight Entertainment – IFE system) must be considered as well.

Step 3.) generates possible architectural layouts according to the previously defined constraints.

Step 4.) chooses the relevant parameters which bare the optimization. For the cabin design, a performance based optimization concentrates on reduction of drag, fuel consumption or mass. These parameters are influenced, for instance, by the fuselage slenderness parameter.

Step 5.) investigates the resulting architectures after running the optimization.

Step 6.) concludes upon obtaining the values of each parameter and evaluates the resulting configurations. In the end a valid configuration, fulfilling the constraints, will be generated.

Currently a KBE software called Pacelab Cabin, created by PACE GmbH, is available for generating preliminary cabin layouts. This tool is able to cover the 6 defined steps. However, the capabilities depend on the available database and the optimization possibilities are limited. An optimized cabin architecture can be achieved on the basis of Pacelab Cabin if all the systems in the cabin are considered at the same time. Currently the tool is not able to include for instance the Passenger Service Unit (PSU) and the overhead stowages layout in connection to the seats layout.

The fulfillment of the process steps enumerated above would ensure [4]:

– Optimized physical placement of cabin items.

– Optimized sizing with respect to regulatory, geometric, volumetric, electric and thermal constraints.

– Optimized centre of gravity variance and its impact on aerodynamics, mission and operational flight performance.

– Optimized cabin architecture changes against fuselage sizing process and the impact on mass, range, fuel burn and cost (this evaluation is especially important for cabin refurbishing and conversion).

2.2 The Knowledge Based Engineering Concept

The KBE concept was proposed as a viable approach for cabin architecture development. This sub-section aims to deliver the background for a better understanding of this concept.

Several studies have been performed on KBE and its utility. It is commonly agreed that Knowledge Based Engineering aims to capture and reuse product and process multidisciplinary knowledge in an integrated way. The results should reduce time and cost for engineering applications, automate repetitive design tasks (like multiple seat representation in the cabin layout), and support conceptual design activities. KBE allows manipulating the geometry and annexed knowledge and supports the investigation of multiple what-if on their design.

A tool using KBE, such as Pacelab Cabin, gathers technical rules, generated by customer or certification requirements, into a knowledge database. The rules can then be used, modified and updated or newly created by the user. During the negotiations phase in the case of cabin upgrades and conversions, it is important for an engineering office to be able to create fast cabin layouts and show to the customer the many modification possibilities. An illustration of some results obtained with this program is shown in Figure 1 (see also ref [7]).

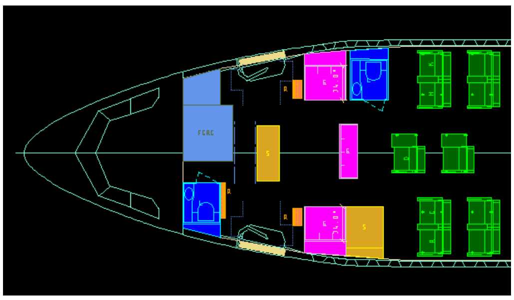


Fig. 1 Cabin layout obtained with Pacelab Cabin tool

3 The Process Chain for Cabin Conversion

3.1 Process Chain Description

There is not just one path towards achieving an optimized process chain for cabin conversion. The processes can be adapted according to the needs and the scope of each project. The only condition for the company is to have a Design Organization Approval (DOA) showing that the EASA prescriptions are fulfilled.

The flow of processes and documents for cabin conversion should be in such a way organized, that it minimizes parameters like: time, costs, effort and, especially, errors. A typical path is described below.

The first attempt to define the customer requirements is made in the *Offer Phase*. If the offer is accepted by both partners, then the technical document, describing it and the technical implications, serves as input for the *Conversion Processing*. The output of the processing, summarized in the *Hand Over Phase*, comes back to the customer, and a loop closes (see Figure 2).

In this paper, the proposed Process Chain is divided into three parts:

- Part A, referring to the offer phase description,
- Part B, referring to the description of the processes for completing the conversion,
- Part C, describing the end processes and the outputs received from the customer.

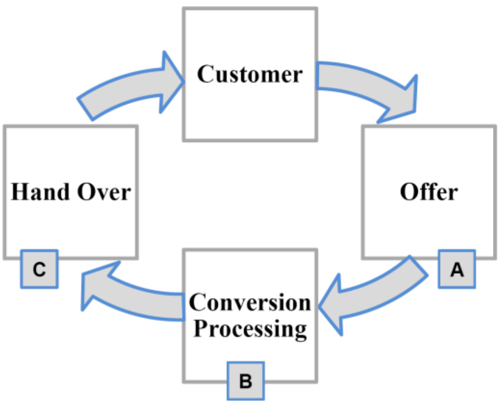


Fig. 2 Process chain concept for cabin conversions

3.1.1 A:Offer

The Offer Phase starts with the Customer Request which is formalized through a preliminary document briefly describing the requirements of the customer and the implications within the design organization. In the same time, this document represents the first decision gate for both partners. If the two parts agree, then the Technical Offer will describe in detail the actions which are to be followed in order to finalize the customer request.

Parallel to this activity, the engineering office should make a feasibility study, to see if it is a benefit for the company to accept the proposed task from the customer. For example, it would be quite difficult to comply with the requirements from customers having products not conforming to the type certification basis. If each decision gate ends with a “yes”, the outputs enter then the Process Chain B.

3.1.2 B: Conversion Processing

The conversion cycle gathers all the phases related to the design and certification of the conversion work. These phases are:

1) Concept
2) Definition
3) Design
4) Adjustment

Each phase has its own number of sub-phases, which can also be further divided into smaller processes. Their representation and optimization is performed in Section 4.

1) Concept Phase

The first stage in the development of a product is the conception. The actions required at the beginning of a project are mainly referring to:

- understanding and filtering the customer requirements,
- understanding and filtering the certification requirements,
- making an internal feasibility study,
- studying the design possibilities,
- organizing the work flow,
- developing the preliminary design,
- developing the testing and verification methods.

2) Definition Phase

The definition phase approaches the same issues more in depth, with the purpose of achieving the final version of the design. The main steps are:

- defining the certification basis,
- defining the Means of Compliance,
- defining the process steps,
- assigning and organizing a team,
- analyzing mechanical and electrical loads, tolerances,
- analyzing interference between components,
- testing the design,
- validating the design concept.

3) Design Phase

The design engineers perform the design work based on the prescriptions of a Chief of Design, assigned already in the conception phase, and those of the airworthiness engineers and Compliance Verification Engineers (CVE). Mainly, during this phase it is required to:

- perform the design according to the prescriptions elaborated during the earlier phases,
- verify the design (Design Verification Engineers),
- give feedback to the project leader.

4) Adjustment Phase

The adjustment phase sums up those activities aimed to improve the overall functioning of the company delivering the conversion. Some of the processes belonging to this phase are:

- getting feedback from every engineering department,
- detecting points of improvement,
- proposing optimized solutions.

5) Certification

According to CS 25.21 [8] the certification process of an aircraft means proving that the design complies with all the requirements stated in the specifications emitted by the Authority. For efficiency, the certification process should start from the early phase of the conception, in parallel to the design development activities. For reducing time and errors, certain aspects need to be already considered when the concept is developed. The certification process is under the responsibility of the Office of Airworthiness [9]. Mainly the steps are:

- establishing contact with the authorities,
- creating the means of compliance (tests and corresponding documentation),
- creating and approving the certification documentation, under DOA privileges,
- creating certification documentation for getting EASA approval (where the privileges do not apply),
- signing the declaration of compliance (responsibility of head of DO).

3.1.3 C: Hand Over

Once the design is performed and verified, the next step is to hand over the results to the customer. The form of the results is written documentation, describing the assembly process in detail. The size and complexity of the technical documentation depends on the size of the conversion project. Besides the technical documentation, assistance should be as well provided. The steps involved in this phase require:

- taking over the final version of the design documentation,
- creating the assembly instructions, based on the design documentation,
- verifying the documentation,
- providing assistance,
- delivering the results to the customer.

The output of the finalized conversion process becomes the input for the hand over phase, and receives the name “deliverable”. Together with the deliverable, the engineering office needs to provide assistance to the customer, once the work package is finished.

Under the hypothesis that the company performs only the design work, and not the manufacture and assembly, the deliverable is in fact a document, gathering all the data necessary for the design to be executed: technical documentation, procedures and instructions for assembly, part lists, instructions and cautions for continued airworthiness and maintenance.

3.2 The Completion Center Concept

A Completion Center can deliver a range of modifications from simple cabin upgrades to complete, highly specialized conversions, usually attributed to VIP aircraft. The range of cabin conversions throughout the commercial aircraft life can be as follows:

- *At age 0*: several initial standard cabin layouts are created by the aircraft manufacturer.
- *At age 5 to 20 years*: several cyclic cabin upgrades caused by worn out furnishing or due to change of aircraft ownership are undertaken inside a Completion Center; if the owner is a VIP, the design and engineering work normally demands a complex certification process, especially if the customer is asking for unusual furnishings.
- *After age of 20 years*: the only scenario possible is pax-to-freighter conversion, undertaken either by the aircraft manufacturer of within a Completion Center.

In common understanding, the notion Completion Center, refers to those organizations able to deliver aircraft cabin conversions independent of other companies.

Lately, several other possible ways to define the term Completion Center have come into use. Accordingly, a design organization (DO) can call itself a Completion Center even without seeing the aircraft, by delivering only the design work. Another possibility for a company to call itself Completion Center is to conduct the work for the customers through intermediaries, as a developer. Figure 3 illustrates all these possibilities:

- *Possibility 1*: the Completion Center covers only the design and engineering work (D&E) itself. The work embodiment, certification and organization of the whole tasks is done by other companies. Currently engineering offices working as subcontractors for aircraft manufacturers in the area of cabin conversions can grow into becoming an independent Completion Center according to this definition.
- *Possibility 2*: the Completion Center covers the work embodiment while other companies are responsible for organization of all the tasks and the documentation related to design, engineering and certification.
- *Possibility 3*: the Completion Center acts as a developer. A developer works like a building project organizer or a travel agency – it has neither the capability to perform the design and engineering work nor the work embodiment, but it is able to organize these tasks for the customer through third party involvement.
- *Possibility 1+2*: the Completion Center is able to ensure both design and engineering (D&E) as well as work embodiment. Since this type of Completion Center comprises all the work necessary for the conversion itself, an independent developer is not necessary. This definition of Completion Center is the one from the industry's common understanding. It is also the most common type of Completion Center; a well known example of this type of Completion Center is Lufthansa Technik.
- *Possibility 2+3*: the Completion Center acts as a developer and has the capability to do the work embodiment itself. D&E are outsourced.
- *Possibility 3+1*: the Completion Center acts as a developer. It also has the capability to ensure the D&E work itself. The work embodiment is subcontracted to another company.

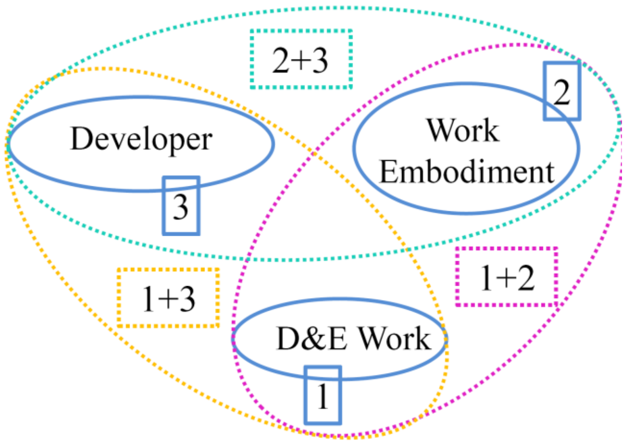


Fig. 3 Completion Center concepts

When looking at the companies dealing today with cabin conversions, some observations can be extracted:

- A frequent scenario is VIP Completion. VIP customers are usually high paying and high demanding. VIP completion on large aircraft can result in big contracts.
- Certification work is performed under the Aviation Authorities, which usually require a certificate showing the capability of performing the design (EASA and FAA call it DOA – Design Organization Approval). However, a company can function as a Completion Center without DOA, if certification work is subcontracted.

4 Optimization of the Process Chain for Cabin Conversion with Dependency and Structure Modeling Methodology

4.1 The DSM Methodology

The Dependency and Structure Modeling Methodology started in the 1980's from the idea of using graph theory in order to represent the sequence of design tasks of a complex engineering project as a network of interactions [10]. This network is represented by a quadratic matrix with identical row and column headings, called Design Structure Matrix (DSM), containing relations and interactions in their nodes (see Figure 4).

4.1.1 Types of DSMs and Their Application

There are several types of domains as well as relations which can be expressed through a DSM. This diversity leads to a DSM classification as shown in Figure 5.

Static DSMs do not depend on time, therefore the elements exist simultaneously. Such elements are components of a system, in which case the DSM is *component-based*, or members of a team, in which case the DSM is *people-based*. A static DSM analysis would provide results with respect to product decomposition or information flow among members of an organization [11], [12].

Time-based DSMs consists of time dependent nodes. The elements of the matrix can be represented by activities. In this case the DSM analysis provides their optimal sequencing. The nodes (or elements) can also be represented by *parameters* related to system activities. An analysis of such a DSM would help identifying activities that influence the design parameters [12].

		1	2	3	4	5	6	7
Offer	1	1						
Concept	2	1	2	1				
Definition	3	1	1	3	1			
Design	4	1	1	1	4		1	
Adjustment	5	1	1	1	1	5	1	1
Certification	6	1	1	1	1		6	
Handover	7	1	1	1	1		1	7

Fig. 4 Example of DSM showing the relations between the main phases of the process chain for cabin conversion [13]

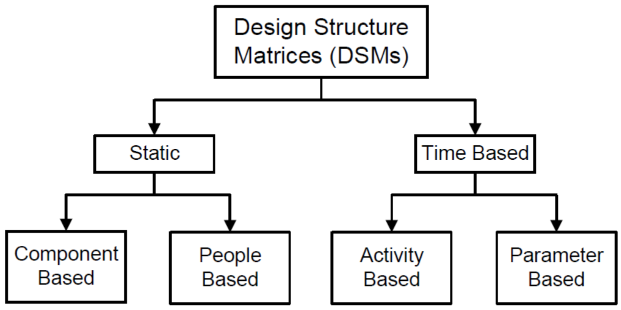


Fig. 5 Classification of DSM (based on [11])

The way to read a DSM can be shown based on Figure 4:

- The *input information* can be read along the rows – i.e. process 4 (design phase) receives information from processes 1, 2 and 3 (offer, concept and definition).
- The *output information* can be read along the columns – i.e. process 4 (design phase) gives information to process 3 (definition).
- The *information exchange* is marked through the logical operator *true / 1*.

The order can be inversed if the user decides to change this convention. In this case one can read the input information on the column and vice-versa. Usually this convention is indicated by an arrow mark above the matrix (as shown on Figure 4).

The logical operators only show the coupling between the nodes. It is possible to replace them by numbers in order to show the *degree of dependency* between the elements [14]:

- 1 – high dependency
- 2 – medium dependency
- 3 – low dependency

[11] and [15] use positive and negative numbers, called *coupling coefficients*, to express the ranking of the interactions (see Table 1). Negative numbers need to be carefully implemented into the tools which optimize DSMs, as they may not function properly.

The key factor in using the DSM methodology is the correct input of the logical operators, respectively coupling coefficients into the matrix. The researchers of this topic ([11], [15], [16], [17]) agree on the following preparing steps:

1. Clear definition of system boundary and functionality
2. Identification of system components

Proper fulfillment of Steps 1 and 2 make step 3 possible, which needs additional information from the members of the organizational staff and engineers:

3. Identification of interfaces between components.

Table 1. Interaction quantification scheme (based on [15])

Information	Weight	Information exchange is…
Required:	+ 2	…necessary for functionality
Desired:	+ 1	…beneficial but not absolutely necessary for functionality
Indifferent:	0	…does not affect functionality
Undesired:	- 1	…causes negative effects but does not prevent functionality
Detrimental:	- 2	…must be prevented to achieve functionality

The engineers need to be questioned with respect to the type and frequency of interactions between the components, in order to estimate the right position and intensity of the coupling coefficient. The additional sub-steps are required:

3.1 Preparation of questionnaires
3.2 Gathering and analyzing the results.
3.3 Implementing the results into the matrix

A Design Structure Matrix can only be used to analyze interactions between elements of the same type. In order to see for instance which team is suitable for which activity, one would need to combine a people-based DSM with an activity-based DSM and analyze the interactions as a whole. This analysis is possible in the frame of a *Domain Mapping Matrix (DMM).*

A DMM is a rectangular matrix which examines interactions between two domains. The literature about DMMs indicates that there are at least 5 major domains which interact in product development [16]:

1. Goals
2. Product
3. Process
4. Organization
5. Tools

The interactions *inside* the five domains listed above are represented in DSMs. The interactions *between* the domains are illustrated with DMMs (see Figure 6).

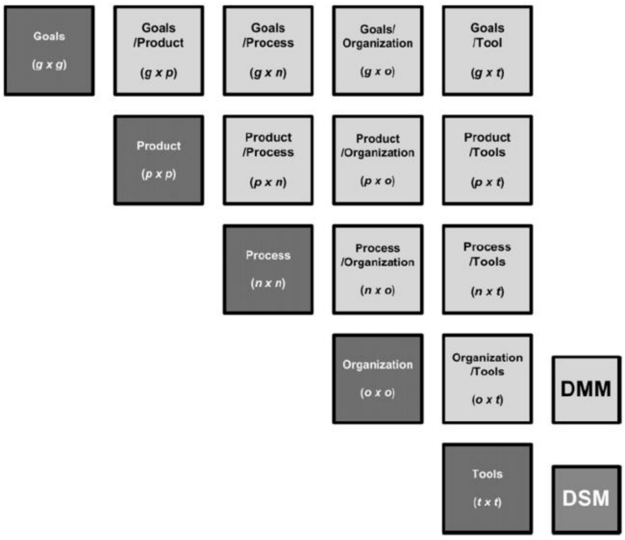


Fig. 6 DSMs and DMMs for the five project domains [16]

DMM analysis methods are relatively new, thus the literature is limited. The advantage of expanding the analysis beyond single domain information gives however enough reason to consider the DMM approach. To summarize, the main characteristics of both DSM and DMM are listed in Table 2.

Table 2. Main characteristics of DSMs and DMMs (based on information gathered from [11], [16], [17])

Criteria	DSM	DMM
Representation	*nxn* matrix	*nxm* matrix
Dimension	Single domain	Dual domain
Focus of Analysis	Tasks Activities Parameters Components People Information flow Deliverable flow	Components / Organization Project / Organizational Structure Functionality / Product Architecture Information flow

4.1.2 Optimization Algorithms

Several analysis algorithms are applicable depending on the type of elements represented into the matrices. The aim of the investigation towards the DSM methodology is to apply it for the optimization processes required to perform an aircraft cabin conversion. The interest of this technical note is therefore to highlight and apply those algorithms suitable for activity based components analysis.

[13] identified a number of 143 processes for completing a cabin conversion (while considering a low degree of detail). The analysis of a great number of processes with the DSM method requires the automation of the optimization. Highly detailed DSMs use programmed algorithms and computer aid.

If the purpose is to optimize the sequence of the activities, the suitable algorithm is called *partitioning* or *sequencing*. If the purpose is to assign proper personnel to specific tasks, the suitable algorithm is called *clustering*, as it allows grouping of the highly related elements into clusters ([16], [17], [18]).

Partitioning aims to reorder the sequence of the elements in order to obtain a *lower triangular matrix* (according to the convention from Figure 4, otherwise the algorithm would deliver an upper triangular matrix). This is achieved by manipulating the rows and columns of the matrix such that the coefficients move closer to the main diagonal and reduce the negative feedback between the elements. The result is a minimized waiting time between activities. The conclusion to be drawn [17] is that minimizing feedback eliminates the process iteration and spares time.

When looking at the matrix in Figure 4, it can be observed that coefficients above the diagonal indicate the necessity of a task to wait for the completion of another task which is to be fulfilled in the future.

The problem formalization can be expressed through the following exemplary question for element number 5: *Can process number 5 be fulfilled after processes 6 and 7? If yes, then insert 1. Do processes 1, 2, 3, 4 give information to process 5? If yes, then insert 1.*

The following observations after analyzing Figure 4 can be extracted:

1. The *concept* phase can suffer modifications after the *definition* phase.

2. The *definition* phase can suffer modifications after the *design* phase.

3. The *design* is influenced by the *certification* requirements, and can later suffer modifications accordingly.

4. All phases provide information for the *adjustment* phase.

5. All phases, besides adjustment and handover give information to *certification* phase.

6. *Handover* phase receives information from all other phases, besides adjustment, to which it gives feedback.

Applying the partitioning algorithm to the matrix in Figure 4 means reordering the phases in the most economical manner. Due to the fact that the dimensions of the matrix are small, a manual manipulation is possible. The following steps are required (based on [14]):

1. Identification of the elements which do not receive information from the others (by looking for empty columns) and moving them to the right.

2. Identification of the elements which do not give information to the others (by looking for empty rows) and moving them to the left.

3. If after steps 1 and 2 there are no remaining elements in the DSM, then the matrix is completely partitioned; otherwise, the remaining elements contain information circuits, which can be further optimized.

[14] provides a tool, developed at the Technical University München, which can automate the process of partitioning. Figure 7

shows the partitioned matrix obtained with this tool from the original matrix shown in Figure 4.

		Offer	Concept	Definition	Design	Certification	Handover	Adjustment
		1	2	3	4	6	7	5
Offer	1	1						
Concept	2	1	2	1				
Definition	3	1	1	3	1			
Design	4	1	1	1	4	1		
Certification	6	1	1	1	1	6		
Handover	7	1	1	1	1	1	7	
Adjustment	5	1	1	1	1	1	1	5

Fig. 7 The partitioned matrix obtained from the original matrix shown in Figure 4

From the results obtained, the following conclusions can be extracted:

- The adjustment phase was moved at the end of the sequence; it is the last to be fulfilled, once it receives the feedback from all other phases.
- There are still coefficients above the diagonal (market in light blue) but they are required for the proper functioning of the system.
- The light blue indicates that the information exchange is bidirectional, which means the three phases are coupled.

Besides partitioning, another algorithm may be of interest when it comes to setting up a completion center. The *clustering* algorithm will be further illustrated, but its application is beyond the purpose of this paper.

While partitioning is suitable for *time-dependent* elements, ***clustering*** is suitable for *time-independent* systems, such as product architecture or project organization [16]. Clustering focuses on identifying groups of items. It is, for example, useful when the elements of the matrix are people, which need to be grouped in teams. When it comes to designing a product, another application of the clustering algorithm is in the system decomposition and can help identifying the sub-components suitable for the system modularization. The procedure is similar to partitioning: columns and rows are reordered with the purpose to underline the elements which are highly interconnected. Interactions between clusters are, in the same time, minimized [17].

Table 3. Comparison between DSM and DMM (based on [16])

Dimensions	DSM		DMM
	Partitioning analysis	Clustering analysis	
Partitioning algorithm	Block diagonalization / Triangularization	Clustering in blocks along the diagonal	Move items into clusters
Result of the analysis	Sequence of items, activities	Cluster of items	Cluster of items
Visualization of dependencies	Feedback and circuits Loop of items Parallel items Sequence of items	Cluster of items Dependencies of clusters	Cluster of items Dependencies of clusters
Key words	Tasks Activities Information flow Deliverables	Parameters Components People Organization Information flow	Components / Organization Project / Organizational Structure Functionality / Product architecture

Partitioning and clustering are algorithms suitable for DSM analysis. When it is required to analyze the interaction between two domains within a DMM, the algorithms need to be adapted. [16] provides an analysis with respect to applicable algorithms for DMMs. His conclusions are summarized in Table 3.

4.2 Analysis of the DSM for the Process Chain for Cabin Conversion

In the previous section a DSM analysis was already performed on the coarse matrix (illustrated in Figure 4) with the purpose to exemplify the functioning of the partitioning algorithms. The following paragraphs will apply the algorithm for the fine matrix, which includes all the processes identified in [13]. Other two types of analyses are as well illustrated: the eigenstructure analysis and the cross impact analysis.

4.2.1 Partitioning Algorithm

The processes were introduced in the EXCEL tool [14] and the algorithm was run. By manipulating the rows and columns, a minimal feedback process configuration was obtained. Figure 8 illustrates, as far as possible, the partitioned DSM.

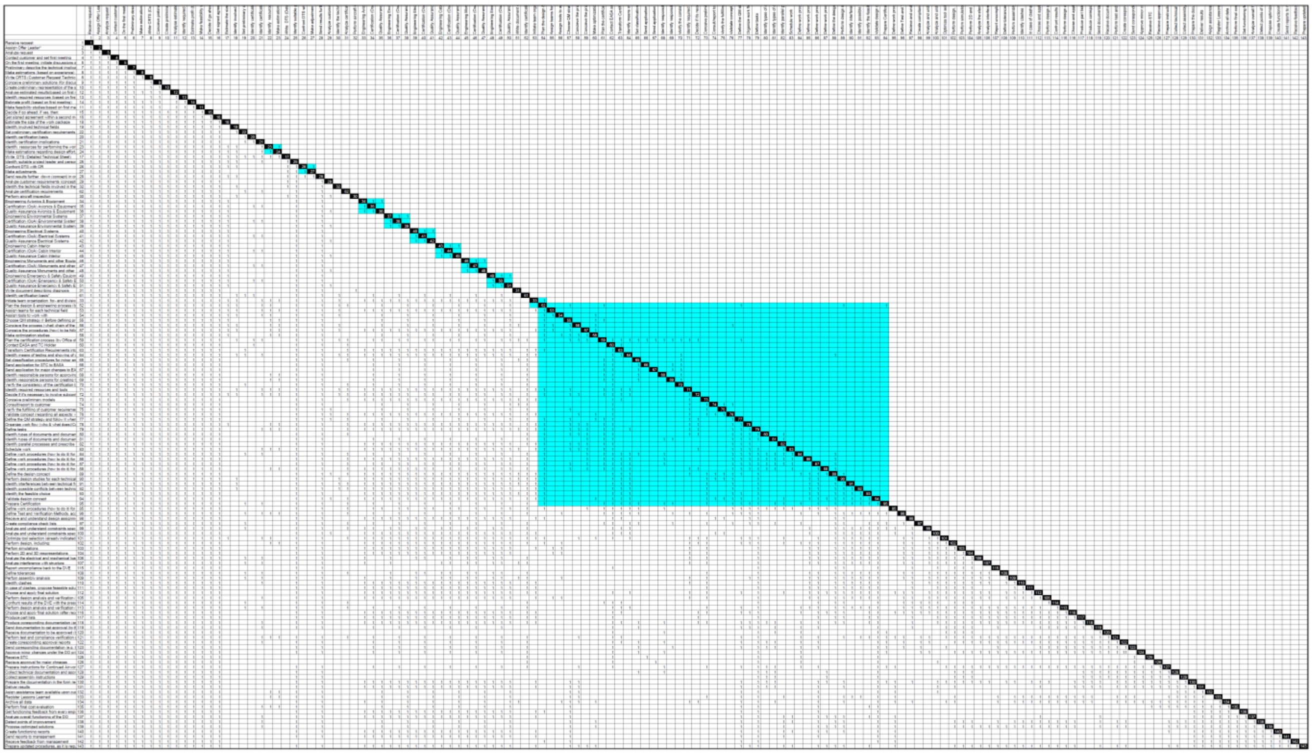


Fig. 8 The partitioned DSM resulted after running the partitioning algorithm on the original DSM matrix

This analysis required a long preparation time and the main difficulties consisted of:

- understanding the dependencies between each process,
- inserting them into the matrix,
- having a clear view over the whole complex structure.

After overcoming these difficulties and running the algorithm, the following conclusions were extracted:

- Definition, Design and Certification phases are coupled (light blue); they create an information cycle which needs iteration, and therefore further optimization.
- Other small couplings exist between the teams for engineering, certification and quality assurance.
- A detailed analysis of the matrix and of each of the illustrated dependency allows a better understanding of the results.

4.2.2 Eigenstructure Analysis

When aiming to optimize a large number of processes, it helps conducting an analysis which allows the extraction of the most important ones. The *eigenstructure analysis* for DSMs was developed by Smith and Eppinger in [19]. In our case it helps underlining those processes which have a major influence on the system.

The eigenvalues and eigenvectors determine the nature of the convergence of the design process in a similar way with the aircraft dynamics:

- the eigenvalues give information about the rate of convergence,
- the eigenvectors give information about the shape of the natural motion.

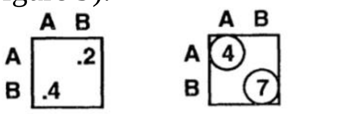
An interesting similarity between the dynamical behavior of a physical system and the behavior of the tasks/processes of an engineering system can be noticed. In both cases large magnitude positive eigenvalues give information about the convergence of the system.

Another interesting analysis is to optimize the duration of the development time [19]:

- Serial tasks can be evaluated by summing their individual times.

- Parallel tasks can be evaluated by finding the maximum of those task times.

In this case a Work Transformation Matrix (WTM) [19] needs to be used. Each iteration causes rework; the amount of rework is quantified through this matrix. The off diagonal elements of WTM represent the strength of dependence between tasks – for our analysis, the rework necessary for each task. The diagonal elements represent the time that it takes to complete each task during the first iteration (see Figure 9).



(a) Strength of Dependence Measures (b) Task Times

Fig. 9 Work Transformation Matrix (WTM) [19]

The eigenstructure analysis of the process chain was performed on the WTM under the consideration that the amount of rework is 100%. In this way the problem became simpler to handle (by inserting 1 instead of proportions of 1) and the results were covered by the largest safety margin possible. The steps for conducting the analysis were:

1.) Building the WTM.
2.) Calculating the eigenstructure i.e. eigenvalues and eigenvectors of the matrix.
3.) Interpreting the magnitude of the eigenvalues.

The results are summarized by Table 4.

Table 4. The processes with the largest eigenvalues

Process ID	Process Title	Eigenvalue
50	Organizing team for certification	6.43
51	Organizing team for quality assurance	2.21
52	Planning the Design & Engineering process	2.21
53	Assigning Teams for each technical field	2.31
106	Analyzing electrical and mechanical loads	1.62
113	Performing design analysis and verification	1.62
121	Perform test and compliance verification	1.00

Within a Completion Center, it seems that certification, along with quality assurance play a key role along with the planning the design and engineering process and the team selection. A second major importance is represented by the tasks grouped under the design analysis and verification. The results are plausible, especially when considering the way EASA developed the DOA requirements. For EASA the self control capability of each design organization presents a major importance.

4.2.3 Cross Impact Analysis

Another type of analysis which can be performed based on the DSM is the *Cross-Impact Analysis*. The data is analyzed by means of a Cross Impact Matrix, as illustrated in Figure 10. The red numbers represent the strength of the influence exercised by each factor / task over the rest of the factors / tasks. It is assumed for our analysis that the influence is always either 1 or 0. Depending on the convention, the tasks are either passive or active. The aim of the Cross-Impact Analysis is to identify several meaningful influence zones and the processes belonging to them. The values representing the strength of the relations are summarized per row and per column. The results are graphically represented as shown in Figure 11. There are five meaningful zones which can be identified:

1.) ***Zone I: Reactive Processes*** – Changes of elements in this area have a strong influence on the system; they give a lot of information to the rest of the components.
2.) ***Zone II: Dynamic Processes*** – Changes of elements in this area have an important influence on the system; the information exchange is strong on both sides.
3.) ***Zone III: Impulsive Processes*** – Elements in this area have a small influence on the system but are strongly influenced by other system changes.
4.) ***Zone IV: Low Impact Processes*** – Elements in this area have a small influence on the system and are poorly influenced by other system changes.

5.) ***Zone V: Neutral Processes*** – Elements in this area find themselves at the intersection with other domains; neutral means safe from unexpected effects.

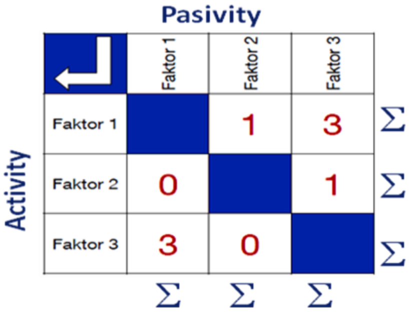


Fig. 10 Cross Impact Matrix example (based on [20])

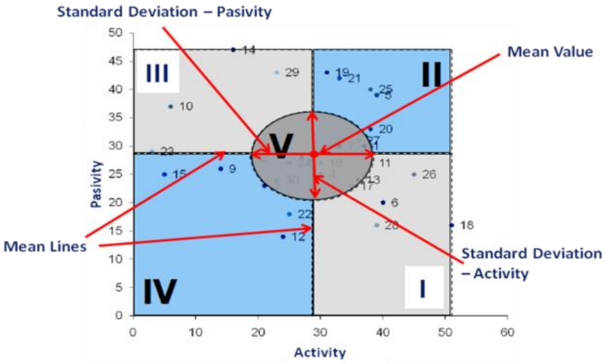


Fig. 11 Cross Impact Diagram (based on [20])

Based on the DSM, the following results for the parameters describing the diagram were obtained through EXCEL calculation (see Table 5):

Table 5. Results for the parameters describing the Cross-Impact diagram

Partitioned DSM	Activity	Pasivity
Sum	5271	5271
Mean Value	36.86	36.86
Standard Deviation	40.067	19.147
Minimum	0	0
Maximum	142	85

Due to the large number of processes the diagram is not easy to interpret. However ‘clouds’ of processes can be identified. The diagram is shown in Figure 12 and an overview of the results in Table 6.

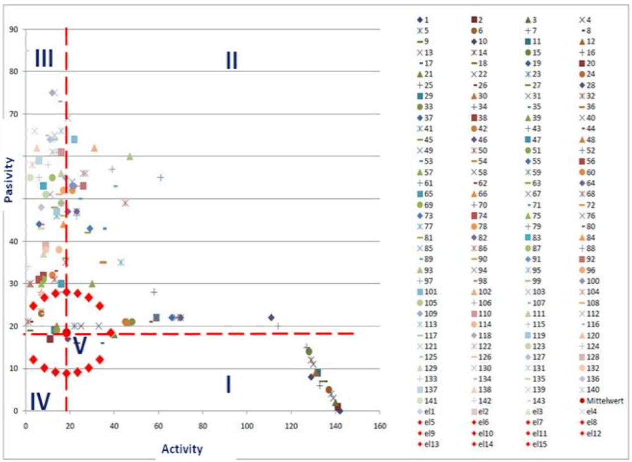


Fig. 12 The Cross-Impact Diagram based on the DSM

Table 6. Selected processes for each zone of influence

Zone I	(2) Assign Offer Leader (126) Receive approval for major changes (9) Conceive preliminary solutions for discussing it with the customer (based on the first meeting) (10) Create preliminary representation of the solutions found (12) Identify required resources (based on the first meeting) (14) Make feasibility studies (16) Get signed agreement
Zone II	(94) Validate design concept (87) Define work procedures for quality assurance (79) Define tasks (definition phase) (93) Identify feasible choice (when it comes to interferences) (design phase) (73) Conceive preliminary models(concept phase) (61) Identify certification basis (concept phase) (54) Plan the design and engineering process
Zone III	(137) Analyze overall functioning of the DO (133) Register Lessons Learned (75) Verify the fulfillment of the customer request (139) Propose optimized solutions (for the functioning of DO) (143) Prepare updated procedures for the functioning of the DO (138) Detect points of improvement (of the DO) (119) Send documentation to EASA (to get approval)
Zone IV	(27) Make adjustments of the DTS after confronting it with CR
Zone V	(17) Write DTS (18) Estimate the size of the work package (24) Make estimations regarding design effort (30) Perform aircraft inspection (31) Write document describing diagnosis (32) Identify the technical fields involved in the design process (concept phase) (62) Analyze certification requirements (concept phase)

Processes in zone I, like feasibility studies or getting the signed agreement, strongly influence the rest of the processes: unless the contract is signed and the technical proposal accepted, the rest of the processes are not run anymore.

Processes in zone II, like validating the design concept or identifying the certification basis, are very important for the functioning of the system and require a lot of information from the rest of the processes.

Processes in zone III, like proposing solutions for an optimized functioning are processes which require a lot of feedback information from the rest of the processes, while their influence may be important in the future, and not for the respective project / iteration.

Processes in zone IV, like adjusting a document, once new information is available, have a low impact on the system.

Processes in zone V, like estimating the size of the work package and design effort, are in the neutral zone. They are important for the system, but the results are rather expected.

5 Tools for Cabin Design and Redesign Activities

5.1 Categories of Tools and Corresponding Requirements

This section covers the selection process of a range of tools able to assist the Completion Center activities. There are several categories of tools indispensable for such an organization:

1.) ***Design and Engineering*** (i.e. Computer Aided Design Tools – CAD) – for creating 2D and 3D layouts,

2.) ***Analysis and Simulation*** (i.e. Computer Aided Engineering – CAE) – for stress calculation and mechanical simulation,

3.) ***Data Management*** (i.e. Product Data Management – PDM) – for data archiving and administration,

4.) ***Resources Management*** (i.e. Enterprise Resources Planning – ERP) – for resources management and process optimization.

Some of the selection criteria for each category from the point of view of a Completion Center are summarized in Table 7.

Regarding category *1.)*, it must be underlined that usually the work of a Completion Center is required late in the aircraft life. This is the reason why, due to the long aircraft lifetime, data can be very old and not compatible with the standards at the time of the cabin conversion. Additionally the CAD software of a Completion Center must be compatible with other necessary software (e.g. CAE for stress calculation) and with the data format from the manufacturer. Currently *CATIA* is already established in aeronautical industry as the most common and reliable CAD software. Thus the only aspect that would be interesting to analyze in comparison to other similar tools is its rendering capability. Rendering has a special significance in cabin refurbishing activities. A close cooperation with the customer is required in order to understand the requirements. Tools allowing rendering and 3D visualization play a key role during the negotiation phases, allowing time reduction in defining the preliminary design solutions.

With respect to category *2.)* it must be noted that there is a huge variety of packages available from each editor, that may include or not certain functionalities, such as: nonlinear analysis, post/pre processing, dynamics and motion, etc. Both CAD and CAE tools have been developed according to the needs of aerospace industry. This is the reason why the experience already accumulated in using them is a decisive criteria.

If the first two categories are quite well established in the industry, tools for categories *3.)* and *4.)* – Data Management and Resources Management are more difficult to evaluate and to implement. The main reason is the high customization required to match the needs of each company. The reference company used in this survey is a medium sized Completion Center, able to conduct small to complete cabin conversions.

A common criterion is the price of the licenses as well as involved expenses for each tool (e.g. investments for achieving necessary computer requirements). However, the technical capabilities should be of prime importance.

Table 7. Categories of tools and selection criteria

Category	Criteria
CAD and CAE	*Compatibility* with other types of software (CAD, CAE, PDM) or with old and future versions of the same software, *Operability* - such as duration of a medium sized task, *Functionalities,* *Visualization* capabilities – for CAD only, Already implemented in the CC or not.
PDM	*Operability* of the database , *Access management* for multi work and suppliers, SDM[1], PLM *capabilities,* *Integration* implications (e.g. set-up duration and complexity), Supplier *access.*
ERP	*Functionalities* *Operability* *Integration* implications

[1] SDM – Simulation Data Management

5.2 Evaluation of Relevant Commercial Tools

The following evaluation system was used:

- 0: tool function is not present or really disappointing.
- 1: tool function is basically performed.
- 2: tool function meets all requirements.
- 3: tool function ensures best performances.

Design and Engineering Tools with good rendering and visualization capabilities selected for the evaluation were: **(1)** *CATIA V5*, created by *Dassault Systèmes (DS)*, **(2)** *Rhinoceros V4*, created by *McNeel* and **(3)** *Showcase 2011*, created by *Autocad*. Results are indicated in Table 8.

Table 8. Evaluation of selected CAD tools with respect to visualization capabilities

Criteria	Tool (1)	(2)	(3)
Compatibility with CATIA -current and future versions	2	2	2
Operability	2	2	2
Duration of a medium difficult task	1	2	3
Necessary computer power	1	2	2
Ongoing modification possibility	0	0	2
Real time rendering	0	0	2
Total	**6**	**6**	**11**

It seems that the best rated tool is *Showcase 2011*. Still, it must be noted that *CATIA V6* has progressed in rendering tasks and that *Rhinoceros V5* will be soon commercialized with real-time rendering capabilities.

Data Management Tools selected for the evaluation were: **(1)** *Innovator*, created as an open source by *ARAS*, **(2)** *Windchill*, created by *PTC*, **(3)** *Teamcenter* created by *Siemens*, **(4)** *Enovia*, created by *DS*, **(5)** *EMK*, created by *ANSYS*, **(6)** *SimManager* created by *MSC Software* and **(7)** *Simulia* by *(DS)*. Results are indicated in Table 9.

For this category it appears that the two best tools are *Teamcenter* and Innovator. Innovator has weaknesses in SDM capabilities. These can be, however, easily overcome by adjoining dedicated software like *SimManager* or by adding this functionality to the program, as *Innovator* presents the open source advantage.

Table 9. Evaluation of selected CAE tools

Criteria	Tools (1)	(2)	(3)	(4)	(5)	(6)	(7)
Compatibility with CATIA	2	2	2	0	0	0	1
Database operability	2	2	1	2	2	2	2
Access management for multi work	2	2	1	1	2	2	2
Access management for suppliers	2	2	1	1	0	0	1
SDM capabilities	0	0	3	0	3	3	3
PLM capabilities	2	1	2	2	0	0	0
CMII certification	3	0	2	0	0	0	0
Others	3[i]	0	0	0	1[ii]	1[iii]	1[iv]
Total	**16**	**9**	**12**	**6**	**8**	**8**	**10**

[i] Open source
[ii] Supports data handling from other ANSYS products
[iii] Integrated access to SimManager from MSC applications, compatibility with other CAE application through web-browser interface
[iV] Configurable connectors with other CAD and CAE tools

Resources Management Tools selected for the evaluation were: **(1)** *Sage ERP X3 Premium Edition*, **(2)** *SAP Business Suite*, **(3)** *Oracle E-Business Suite* and **(4)** *Microsoft Dynamics*. The most important capabilities of the selected tools are summarized in Table 10. Usually the functionalities of this sort of tools are personalized for each company.

The tools analyzed in Table 10 provide almost the same functions. An ERP tool needs to match the needs of each user. An optimum selection should be performed based on a close cooperation with the tool editor. Certain functionalities can be appreciated only by testing them. The price, the availability and efficiency of the support service are other criteria which need to be matched. Based on Table 10, it seems that the two best candidates for a Completion Center are *Sage ERP X3 Premium Edition* and *Microsoft Dynamics*.

Table 10. Evaluation of selected ERP tools

Tool	Description
Sage ERP X3 Premium Edition	Access with simple browser Multiuser capability (up to 1500) Complete integration with MS Office Customer Relationship Management module PDA applications Automatic reading of documents Good customization capabilities
SAP Business Suite	Several modules for total quality management: Supplier and Customer Relationship Management, PLM, Supply Chain Management, Human Capital Management, Travel Management Good customization capabilities
Oracle E-Business Suite	Structures all supplier communication through a secure internet-based portal (called iSupplier Portal) Several modules: Customer Relationship Management , Supply Chain Management, Email Center (able to classify incoming e-mails and route them to qualified agents), Travel & Expense Management, Human Capital Management (with applications like iRecruitment, iLearning), Project Collaboration (providing real-time access to information related to each project) Good customization capabilities
Microsoft Dynamics	Able to connect to another ERP solution (Headquarters) Complete integration with MS Office Only compatible with Microsoft SQL Server or Windows Server Several modules: Customer Relationship Management , Supply Chain Management Good customization capabilities (in C++ or C#)

5.3 Case Study – Tool Certification under Configuration Management II

5.3.1 Background

Configuration Management (CM) serves to ensure that configurations conform to their requirements. Configuration management was introduced in the 1960s to resolve the inability of defense contractors to build a second product identical to the prototype. The Institute of Configuration Management was formed in 1984 and in 1988 the CM process was renamed *Configuration Management II* (CMII). It was adopted for the first time in the aeronautical industry in 1997.

Today CMII answers the question, how the processes of a business must be organized and which rules are necessary, so that the fewest possible mistakes, rework and unnecessary activities are avoided.

*Both **organizations** or **individuals** and **software tools** can receive a CMII Certification.*

Organizations can be certified in 5 process maturity steps from "Unaware" to "Excellent" according to the status of CMII implementation.

Individuals must run through 5 certification levels - from CMIIB (Basics) until CMIIP (Professional) certification. The internationally acknowledged certifications provide evidence about the individuals' skill level regarding CM and CMII (see Figure 13).

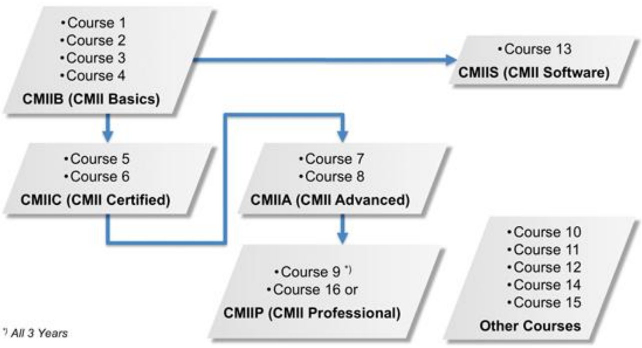


Fig. 13 CMII Certification Levels [22]

Software Tools must be in general capable of automating CMII principles. The detailed requirements are listed in a standard called *CMII Standard 400 Tool Rating Criteria* [21].

Depending on the amount of CMII functionality that the tool contains, it receives one or more "stars", up to a maximum of 5 (see Table 11).

Table 11. 5-Star Rating System for software tools [23]

5-Star Rating Scale for CMII Compliant Tools					
1	2	3	4	5	Criteria
*					The tool provides the mandatory elements of functionality required for CMII certification.
	*				The tool provides at least 25% of the remaining elements of desired functionality.
		*			The tool provides at least 50% of the remaining elements of desired functionality.
			*		The tool provides at least 75% of the remaining elements of desired functionality.
				*	The tool provides 100% of the remaining elements of desired functionality.

5.3.2 Summary of Tool Requirements

Certifiable tools under CMII are tools from the following categories:

- Product Lifecycle Management (PLM/PDM)
- Enterprise Resource Planning (ERP)
- Document Management
- Project Management
- Software Configuration Management
- Change Task Tracking
- Change Management

The certification steps to be followed are [23]:

1.) Product manager or another responsible person is CMII certified (successful participation in Courses 1 to 6).
2.) The tool fulfills the 44 minimum requirements contained in the catalogue of criteria.
3.) The responsible person can show how the minimum requirements plus possibly other requirements have been implemented in the standard version (out-of-the-box) of the tool. The demonstration (i.e. tool certification) can take place either at GfKM (Gesellschaft für KonfigurationsManagement mbH) in Stuttgart or at the Institute of Configuration Management (ICM) in Phoenix, USA.

Referring to Table 11, there are 44 mandatory elements of functionality of a tool complying with CM II. These requirements are connected with 17 *Core Business Processes (CBP)*:

1.) As-Planned and As-Released Baselines
2.) 4-Tier, 9-Step Development Process
3.) Naming, Numbering and Reuse
4.) Validation and Release Records
5.) Changes and Revision Records
6.) Information Systems
7.) Facilities
8.) Security, Safety and Environmental
9.) Business Program Management
10.) Research and Development Engineering
11.) Marketing, Sales and Contracts
12.) Supply Chain Management
13.) Order Fulfillment and As-Built Records
14.) Support, Operation and Maintenance
15.) Human Resources and Training
16.) Financial Accounting and Reporting
17.) Process Oversight and Internal Audit

Table 12 presents selected tool functionalities for each process, which are mandatory for the CMII certification.

Table 12. Selected tool functionalities mandatory for CMII Certification [23]

CBP ID	Tool functionality
1	*Baselines for End-Item products* **P**hysical item hierarchies are defined by bills of material which are treated as documents and identified by type, number and revision level. **C**licking on the ID number of a physical item results in an option to see the item itself or an option to see its metadata. **M**etadata for each physical item includes its documented requirements, source and cost information, item type, handling codes, control codes and so on. *Baseline Changes* **E**ach document has an effective date (which may or may not be the same as its release date). **C**licking on the ECN number results in an option to see the ECN or an option to see its detailed implementation plan. *Baselines for facilities systems and the enterprise* **E**nterprise requirements extend from business regulations and a strategic business plan at the top levels, to operating standards and procedures at the lower levels.
2	**W**ork packages for developing an end-item product are derived from its physical item hierarchy and the documented requirements for each item at each level. **T**he work breakdown structure for development is created and maintained within the as-planned/as-released baseline.
3	**A**ll primary items are assigned an internal identification

	number, including purchased items which may also carry the supplier's ID number. **I**nterchangeable items with different ID numbers are cross-referenced in an "equivalent item" record.
4	**E**ach relatively simple document is co-owned by a creator and a designated user. **E**ach complex document is owned by a creator and a cross-functional team of users.
5	**S**tandardized forms are used as templates to guide new releases and changes through the required steps of the closed-loop change process. **A** standard problem report form is used to report problems, describe the associated environment and the sequence of steps which led to its occurrence.
6	**R**equired functionality for enabling software tools is driven by the business process infrastructure and core business processes. **E**nabling software tools provide functionality needed to ensure that information repositories are secure and access is limited to authorized personnel.
7	**T**he operational status of each facility, each closed-loop system, each repairable item and each replaceable item is routinely updated and known at all times (NM[1]).
8	**I**n the interest of security, all assets are categorized and/or classified and protected in accordance with their level of importance (NM).
9	**A**ll work on a business program is accomplished via the core business processes, which includes monitoring cost and schedule performance (NM).
10	**R**esearch and development are jointly responsible for creating and maintaining standard part catalogs to be used across all business programs (NM).
11	**C**ommunications between Sales and other activities are achieved via the business process infrastructure, which includes translations from as-sold to as-built units (NM).
12	**P**lanning bills are derived from as-planned/as-released baselines and used to drive material scheduling systems such as ERP (NM).
13	**R**etained work authorizations include positive evidence that the finished items conformed to their documented requirements (NM).
14	**L**ogs are used to track the activity associated with each in-service item being operated and maintained (NM).
15	**J**ob responsibilities and required skills for each position are defined in position guides and are available on-line (NM).
16	**C**ost accounting is activity-based and costs are collected from the forms used to authorize and control work (NM).
17	-

[1] NM=Non-Mandatory

6 Summary and Conclusion

This paper aimed:

1.) to *describe and analyze the process chain* for cabin design and cabin conversion activities.

2.) to correlate the processes with appropriate *tools* able to assist the design work, and to evaluate them.

With respect to 1.) *Process chain description and analysis*: several DSM based analyses were performed:

– *The partitioning algorithm* – a DSM based optimization algorithm – delivered the optimal sequence of the basic processes inside the completion center. This algorithm had as an objective minimizing the feedback information. However, due to the high number of processes, the partitioning algorithm had to be run several times, and the results may still be locally invalid. Another point which influences the accuracy of the results is the fact that these processes are rather general processes; most of them can be further divided into sub-processes / subtasks. In this case an overall analysis with DSM would be impossible due to the large number of relations which need to be established. In this case the matrix would be too large, and the automation of the relations input is not possible. It makes more sense to conduct such an analysis on smaller DSMs characterizing a smaller subsystem, comprising of one or several phases.

– *The eigenstructure analysis*, based on the WTM extracted from DSM, started with the idea of finding similarities between the functioning of an engineering system and the dynamic behavior of an aircraft. The way such a system oscillates is similar with the 'oscillations' inside a design organization, when rework is required. The results underlined those processes with the largest eigenvalues, i.e. with the greatest influence on the engineering system. This analysis can be further extended if for each process the rework load is fractionally expressed. This type of analysis on WTM is especially suitable for reconversion tasks, as it allows the estimation of how much work is required for the rest of the cabin items if one item is being replaced / reconverted. It also allows the calculation of the total time or the partial times for performing the cabin conversions.

- *The cross impact diagram* delivered groups of processes belonging to five spheres: reactive, dynamic, impulsive, low impact and neutral. Indeed the process chain assumes tasks which are vital for the entire chain as well as tasks which do not have an important influence on the system. The results are plausible. They could be however used on smaller DSMs in order to identify especially those tasks which poorly influence the system. Such tasks may be further coupled or ignored.

With respect to 2.) *Tools*: several categories of tools were identified and appropriate commercial tools were evaluated. An important observation is that Product Data Management (PDM) tools and Enterprise Resources Planning (ERP) tools become essential for reducing rework, for avoiding delays, thus for optimizing the functioning of design organizations. Configuration Management II (CMII) provides criteria of evaluating such software tools. It also provides an integrated approach towards business management. For a Completion Center such an approach helps to accommodate change and keep requirements clear, concise and valid.

The best established CAD tool in aeronautical design and engineering is CATIA. For cabin conversion activities a CAD tool needs to have also good rendering and visualization capabilities. Based on a limited evaluation of the most well known tools conducted for this paper, it seems that *Showcase 2011* edited by *Autodesk*, can fulfill the required functionalities. For data management, it seems that the open source *Innovator*, created by *Aras* is the best candidate. *Innovator* also has a 4 stars CMII certification.

Acknowledgments

Among others, this research has been supported by the POLITEHNICA University in Bucharest, through the POSDRU project.

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