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TOWARDS THE PREDICTION OF MULTIPHYSIC INTERACTIONS USING MDM AND QFD MATRICES

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1. Introduction

In the context of new product development, highly constraint multi-disciplinary systems are difficult to design and generally lead to a non optimal but acceptable solution [Seepersad 2008]. To design such product, designers from different design departments have to collaborate regarding several design aspects: product architecture, functional analysis and performance evaluation. Designers have also to take into account various point-of-views to optimize product performances. These design intrications lead to complexity in design.

Even a small system can be complex. As an introduction of our experimental study: the development of an onboard electronic card composed of seven components, with technological alternatives, lead between three design departments leave more than 200 design alternatives. It can be easily envisioned that without management tools a design team can decide to move into a non-optimal product as it happened in our example (18 months and few millions of dollars lost). More precise analysis shows that project stopped due to a poor interaction management: a design parameter in a physical connection has been not identify as a key in the design process. The chosen concept was over constraint and no dimensioning set can be found. The design team has expressed some difficulties to generate all design alternatives, to evaluate them and to choose the best one regarding aforementioned aspects. For all these reason, this article will focus on collaboration of design departments around the choice of concepts.

Based on presented analysis of caseindustrialcase, our research study aims atingat improving multiphysic design in the objective to help designers in theirs choices and optimization. We believe that clear mapping of design department interactions can improve considerably outcomes of the design process: increasing satisfaction of global performances, better follow up of design functions and better management of change propagation impacts.

This paper present the AID method which has for objective to analyze multiphysic interactions and to characterize them through indicators and heuristics. The literature concerning multiphysic design is not crossing product, function and multidimension performance analysis with design department point-of-views. In order to address this issue, the AID method is a MDM (Multiple-Domain Matrix) and QFD (Quality Function Deployment) matrix based tools. Finally, the method identifies key design parameters for design department collaboration, that will not be the object of this paper due to the limits imposedimposedThereby, AID methodpermits the multiphysic evaluation and the choice of concepts.

This paper is organized in 6 parts. After the presentation of the problem statement, an overview of the existing literature concerning tools and methods used to manage multiphysic design will be presented. In a third part, the AID method will be introduced focusing on using and defining new matrices for the design. Afterwards, our approach will be illustrated on an industrial example. In the end, limits as well as future research perspectives will be discussed.

2. Problem Statement

In view to customer growing demands, the products are becoming more complex in term of number of function integrated. A phone not is longer only a phone: the customers expect a product managing calendar, deliver mail services, IM, internet. For profitability and technological reasons, petroleum products follow the same path. Until 1980s, the drilling process started with a ground exploration and the outcome was used to drill along a predetermined pattern.Finally a verification that the drilling occurs in the expected earth layer was done. The measurements were done separely using independent instruments and products. Nowadays, directional drilling is able to correct in real-time drilling deviations outside the concerned layer and to perform simultaneous measurements to basically characterize rock (permittivity, permeability, ...). This multifunctional integration had two significant impacts on product design: firstly, the complexity has increased the number of design variables, constraints and objectives [Gomes 2006], and secondly, the integration implies that engineers must now collaboratetightly to ensure the achievement of desired performance. In consequence, the design of product by several design departments (called multiphysic design) – associated to different bodies of knowledge – is more challenging.

TThe design can be described as a value definition process for each design parameters representing one design concept. The collaboration between design departments, working together in the design of a product, consists of fixing a common value to shared design parameters. Due to their own constraints and performances, design departmentsprefer different values of common design parameters. Therefore the collaboration leads to design conflicts and the necessity to find compromises. Moreover, the management of interactions between performances, functions and parameters add complexity into already complex design processes.

This research study is conducted in collaboration with Schlumberger, worldwide leader in petroleum services. The increased needs for petrol extraction and the rarefaction of reserves implies that products are growing in difficulty: drillers need to resist to increased pressure (up to 200 bars), increased temperatures (up to 175°C) and shocks (up to 100g). Therefore the design process needs to integrate these constraints in a coherent manner with the same time delays. In this context of new product development, the design interactions induce the major part of development failures. As the design process is done concurrently, it is very hard to predict impact of design department choices on the others and on the future design steps.

The recent developments of onboard electronic cards are an example of this multiphysics problem. Electronic card has to be integrated in a box attached to a main mechanical component. The whole assembly is going in a tube (with a diameter limited by the drill). Therefore, dimensions of the system are highly correlated and highly impacting the design. In order to develop this product, the expertise of three design departments is needed (mechanical, electrical and packaging). Every department is optimizing their design to maximize performances, as for example the number of electronic card by product foot length. Eighteen () months after the concept choice, the project failed due to incapability to manage and control the impacts of the size of capacitor.In this square, few millions of dollars has been lost.

In order to illustrate complexity and difficulties to design such product, the Figure 1 represents a cross structural and functional analysis of the onboard electronic card. It's a complex multiphysic product accomplishing seven functions composed by six components. Each component has several alternatives matching more than two hundred design alternatives.

The orange frames represent the design scope of each design department (electrical, mechanical and packaging). The red frames represent the interfaces between design departments. These interfaces contain shared design parameters (DPs) between design departments.They They are also difficult to manage for designers because it's difficult to know how a design parameter will influence other design departments in the product design. As an example, related to our industrial experience, the height of the capacitor (Electronic DPs) is a key design parameter because it influences the size of the packaging (box around the electronic cardas) as well as the shape of the main mechanical component.

Finally, this local design parameter decreases a high level performance: the compactedness (the number of cards that you can put in the same section).

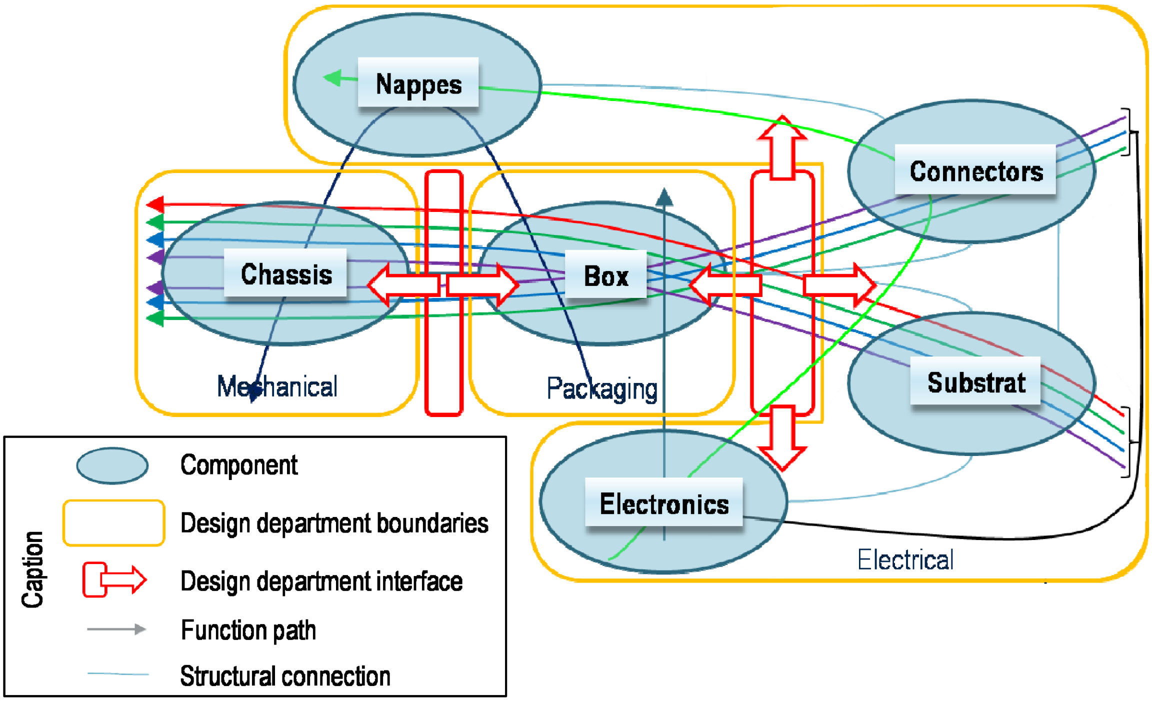


Figure 1. Structural and FunctionalAnalysis in a embedded electronic card

3. Literature review

The research literature is mainly addressing previous issues with the usage of different matrix based tools like Quality Functional Deployement (QFD), Design Structure Matrix (DSM) and Domain Mapping Matrix (DMM). The global success of matrix approaches is linked to their undeniable manipulation facility.

Our literature review analysis points out three main design stages that are addressed in different research streams concerning the product analysis: concept analysis, concept generation and evaluation.

Concept analysis is a preliminary work for the generation, the evaluation and finally the selection of "best" concepts. The aim of this stage is to identify usable informations to design concepts. The usage of the matrices permits: to identify the potential inconsistency of solutions, the identification of opportunity for the improvement of design concepts and to capture the design rules, thus defining different product architectures. Hellenbrand et al. [Hellenbrand 2008] propose a easy approach that combines different component alternatives in order to list consistent concepts. The clustering is done through the filling of a DSM by engineers. The only information available for designers is the possibility or not to combine two components. This is presented by a "_" or a "X" squares in the matrix.

Wyatt et al. [Wyatt 2008] propose to define inconsistency of concepts and to capture the rules through the identification of constraints. They define an "Architecture Schema" based on ontology where "components are linked to a component types and to a connection types". The constraints are expressed through DSM and DMM matrices. This work focuses on two mains constraints types: the number of connection types related to a component type and the relations between different component types. From this characterization of constraints, the system is able to extract rules as the possibility to combine two components into architecture. The inconsistency is here defined as the impossibility to assemble components.

Another research stream mainly deals with the issues of capturing rules. For instance Gorbea et al. [Gorbea 2008] propose a quite interesting method using MDM (mix of DSM and DMM) to map dependencies in architectures. Rule extraction and generation in this approach is based upon components and functions analysis. The proposed MDM is composed by three matrices: a functions-functions DSM, a components DSM and a Components-functions DMM. A set of these three matrices is generated for each architecture. Basic matrix operation, as sum and substraction, are used to compare several matrices and therefore extract rules for each architecture. Sum of MDMs enables the determination of which components apply to all architectures. Substraction MDMs, called delta MDMs, is useful in comparing differences amongst two architectures.

Maier et al. [Maier 2008] propose a method to identify opportunity for concept improvement. This method is introducing affordances in a QFD based tool. The so called matrix Affordance Based Design (ABD) puts in relation physical structure and requirements. Requirements are interpreted in term of affordances and organized in four categories: Positive Artifact-User Affordances (+AUA), Negative Artifact-User Affordances (-AUA), Positive Artifact-Artifact Affordances (+AUA) and Negative Artifact-Artifact Affordances (-AUA). The interior of the matrix is populated by (+) if the related components is a helpful relationship for each affordance,(-) is it's harmful or ( ) if they are no relationship.

As mentioned above, some of the research studies are interested in using matrices in **generation, evaluation and selection of design concepts**. Hellenbrand et al. [Hellenbrand 2008] proposes to list consistent concepts with an algorithm checking through the DSM filled by cross and empty squares. The algorithm generates a sequence of components that can be linked. Consistent concepts are those who are composed of a suffisant number of components. Hellenbrand et al. [Hellenbrand 2008] proposes an extension of his approach introducing the ranking of consistent concepts. For that, they introduce a notion of factors in matrices. These factors represent a positive or negative influence between two solutions. The rank of a concept is given by the sum of all factors composing it.

Wyatt et al. [Wyatt 2008] generate new concept from an empty DSM matrix. An algorithm is going through matrix and filling every square by a connection types when its possible (respecting rules previously defined). This generation gives the designers the possibility to see candidate architectures represented as DSM. The differentiation between architectures only made through component relationships is a limitation.

Maier et al. [Maier 2008] define few indicators to evaluate and to choose the best opportunity. For each components (and each requirements) the total number of helpful and harmful affordance is count. Reporting to the percentage, the ratio helpful to harmful is defined. The negative percentage difference for a component indicates a potential component that is an opportunity for future improvement.

Eigner [Eigner and Maletz 2008] presents their approach mixing MDM and QFD for requirement management. QFD is used to translate statement, describing the product, into more technical oriented requirements which are the further basis for the development of the product. In this approach, MDM and QFD are working independently in a static way.

Our literature review analysis point out that all approaches are addressing the component point-of-view. Physical connections are only defined as a possibility or not to assemble two components. This means that interactions are not taken into account as a choice in conceptual stage. Physical connections influence performances and they have to be take into account at the same level as components.

Moreover, the concept analysis is not related to functional analysis. Gorbea et al. [Gorbea 2008] propose a simple analysis of functional path in which we cannot achieve degree of participation of a component to the overall product performances. TThe evaluation of the design concepts is proposed embracing only one global performance. Therefore this does not permit the integration of different advantages or disadvantages in possible design solutions.

This literature review is not managing the fact that architecture can have different structures (architecture?)?)and that the

functional path can be achieved in different manner. The generation of concepts needs to integrate knowledge from all aspects to generate powerful concepts.

4. AID method: A three step process to predict difficulties in design interfaces

The goal of our approach is to map design department point-of-views, architecture alternatives, functional needs and expected performances. With this process, our approach aims at helping designers to model their collaborations with other design departments and to assess their impacts on the final product. We propose the AID (Analysis, Identification, Design) matrix based method that is organized in three steps:

1. **Analysis of multiphysic interfaces:** the objective of this stage is to identify multiphysic interfaces and to quantify their influences.

Assuming that component design is assigned to a design department, a DSM is introduced to identify physical connections and so design department physical collaboration. As discussed in the previous part of the paper, most of the DSM does not addresse the qualitative description of the physical connections. In order to support designers we developed a semantics of physical connections. This semantics contains the data on connection type represented in DSM by a letter. A multiphysic connection is a letter in a square linking two components designed by different design departments. Different architectures possibilities can be presented by several letters in appropriate squares.

A DMM is used to represent functions and components interactions. In the literature review, DMM does not address the question of the function path in the product architecture. In this objective, the AID method represents functions as a block diagram. DMM columns represent components and rows functions. A numeral information is used to integrate the function propagation. For instance, if three components are contributing to a function, the number 1, 2 and 3 will represent the deployment of the function. Therefore, it's possible to integrate data concerning the collaboration of design departments. For example, when the function goes from square mark "1" to square mark "2" with related components design by different design departments - Design departments have to collaborate to achieve the realization of this function. Moreover, the usage of the QFD will let us able to define a link between the components and expected performances. QFD rows represent performances and columns represent components, squares are filling by designers regarding a predefine performance scale [Holley 2008].

This crossed usage of matrices provides us data of : physical interactions – where design departments are physically connected, functional interactions – where design departments contribute to the realization of a function, and performance interactions – where design departments are working together to achieve shared performances. If two components physically connected, designed by different design departments, are contributing to the same performances their interfaces is significaly impacting.

2. **Identification of difficult interactions:** The objective of this step is to identify the potentially criticalcritical interfaces,indentifying the cross of metrics (indicators and heuristics) extracted from MDM (DSM - DMM) and QFD matrices previously filled.

An algorithm extracts from the DSM the total number of alternatives respectively to the number of overall iesofpossibilities of product concept (architecture). The algorithm verifies that components and physical connections can be associated to form a viable concept. Viable means that the concept is able to satisfy both functions and performances requirements defined by the project. In DMM, the path of a function through components indicates the collaboration between design departments. When a function is passing through two components designed by different departments, they have to collaborate to achieve the function and the attached physical connection will influence the performance of the function. This matrix gives also the data about the components which will contribute to the overall function. The QFD contains component evaluations regarding to the expected performances. The extension of this matrix with MDMallows firstly the generation of new concept and then the computation of global concept performances.Sly.Secondly it can be used to understand the contribution of a component to a function. Contribution define both participation of a component to a function and participation of their design interface with other components to function. Finally, advantage and disadvantage of each concept can be extracted.

3. **Definition of resolution process:** This third stepmerges the data from pervious steps with the information from a data model. This data model is built on multiphysic approach: for any physical connection type, a data sheet is generated with key design parameters controlled by design departments or shared by them. The information as dimensioning parameters, objective targets, and best practices for the optimization is also included. This aspect of the work will not bedevelop in this article.

Finally, the AID method is able to evaluate design alternatives (by crossing DMM and QFD information) and to generate better concepts (by correlation between DSM and QFD) less conflictual for design departments. The concepts are ranked to let team project focusing on the best products (mixing MDM and QFD data).

As method deliverable, design team has a list of the best concepts with their advantages and disadvantages. The method permit to identify the multiphysic interfaces, their interactions and the key design parameters that are the source ofofmultiphysic conflicts.Our research advocate a novel approach to multi-disciplinary design based on a pilot with interfaces and their interactions. We provide a taxonomy of multiphysical interactions, a semantic structure description, and an original combination of approaches matrix.Method allows to discuss about concepts versions with structural and functional architectures.

5. Experimental Studies

The proposed approach waswas implemented iin an industrial application who aims to develop onboard electronic cards under the scope of a project. The previous card developments were not able to achieve environmental constrains: high pressure, high temperature under shock and vibrations as required for our sub-project. Goals of our application were to propose new concepts as design orientations to satisfy project requirements.

The AID method has been applied during a three day workshop organized in a industrial environement with the contribution of one of suppliers. The team was composed of eight engineers respectively five and three from the supplier. The three day organization has been deployed as:

- The first day, the design team express the problem settings and made a creativity session to generate possible concepts. Finally the design team sponsor shown the five concepts they imagine.
- The second day, we list expected performances and failure modes, and then MDM and QFD empty matrices was created.
- The third day, engineers evaluate design solutions regarding every performances, due to the simplicity of our approach [Holley 2008], all evaluations have been made in only 4 hours. Finally, method evaluate two hundred design alternatives.

The Figure 2 represents a DSM matrix used to represent physical connections between possible architectures. For this example, the onboard electronic card is composed of two modules: a chassis and a box which can be made of respectively five and four alternatives, called design solutions. Design solutions are described by name in the second row and the second columns (This matrix is unidirectional and therefore symmetric). The blue row and columns represent the design control of the mechanical design department and the green one the packaging design department.

Analysis starts with an empty matrix that design department's engineers are filling. This process can be done through the description of imagined concepts as shown in Figure 2 (see concept number 1 and 2) or through the description of possible assemblies between two design solutions. The description is done through the designation of physical connection type (a simplified taxonomy that was used is shown in the Table A).

For instance, in the Figure 2, the physical connection between the denoted 'I' chassis and the denoted 'Basin' box (square crossing the two design solutions) which are describe by concept noted '1' is an 'E' physical connection. This 'E' is related to Elastomer in the table A (same figure). In the picture of the concept '1', we can see this assembly and the physical connection (the red are elastometric). An empty square means that no compatibility exists between the two design solutions. A square with two letters describe alternative in the physical connection.

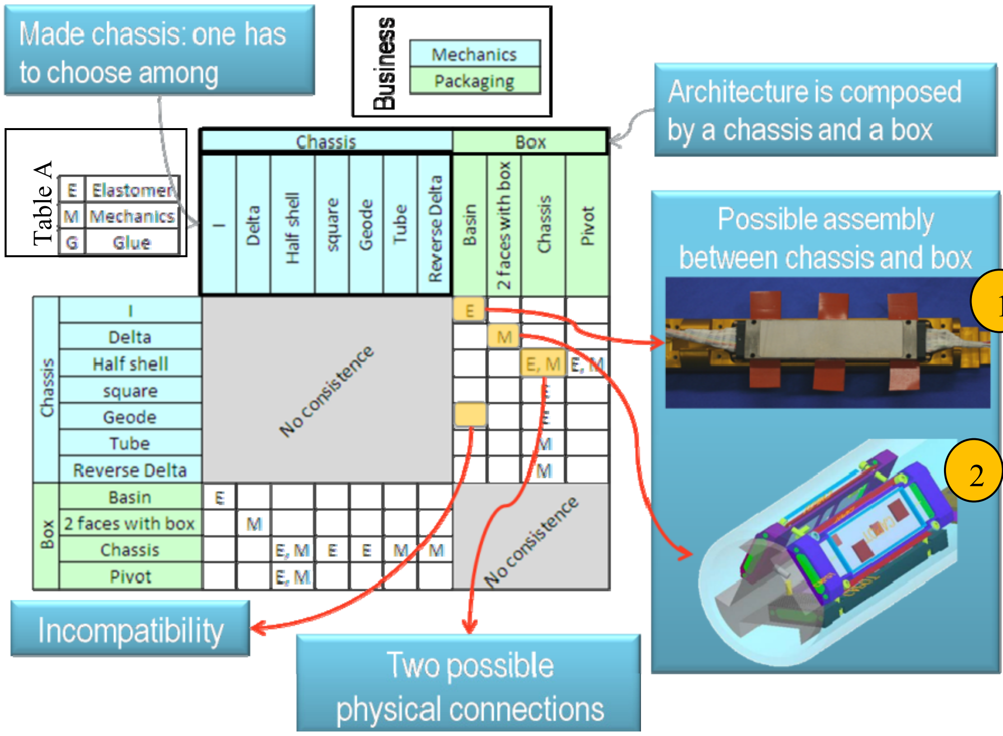


Figure 2. An illustrated example of the usage of a DSM

A valid concept is defined as a combinaison of design solutions making a concept (in our example, one chassis and one box). Valid concepts are extracted from DSM with an algorithm going through all squares. For instance, a concept cannot be composed by a chassis called 'geode' and a box called 'pivot' because crossing square is empty.

The Figure 3 represents a DMM used to represent dependencies between functions and design solutions. The presented example contains two functions, 'heat dissipation' and 'pressure resist'. The electronic card is more detailed here with 4 modules/components (chassis, box, connectors and collar). The components can be designes using respectively three, five, three and one design solutions. Each function can be satisfied through two paths and so the table contains two lines for each function. For instance, 'heat dissipation' has two paths: electronics (not represented here) are transmitting heat to box (denoted with a T3 in box squares); then the function is propagating through T4 (chassis) where the heat can be evacuated (first line, T5 doesn't exist) or then heat is transferred to T5 (collar) where flow will be evacuated. Difference between the two functional alternatives is that one can bring heat transfer until chassis and the other can bring heat to collar following design choice.

With this matrix, our method is able to achieve if a concept have a functional sense. For instance, the design solution called '2 faces without box' in box module cannot achieve heat dissipation (the squares corresponding to this function are empty), and therefore, without the existence of another manner to dissipate heat, this design solution doesn't have a functional sense. The concept denoted '1' in the Figure 3 is composed by a '2 faces with box' box module and a '2 non-hermetic integrated' connectors modules. In DMM, related concept columns shows that the concept is represented by one square participating to the function 'pressure heat' and one not participating. The concept have no functional sense, the physical explication is that a non-hermetic connector cannot resist to pressure.

The Figure 4 represents a QFD used for the evaluation of components in view to expected performances. In this matrix theperformances are reprensented in rows and module's design solutions in columns. A square crossing a performance with a design solution containts the evaluation given by experts (design department's one) of this component to the performance. In this way, in the method he voice of design departments is integrated in the evaluation of concepts. The top of the QFD is the imported from the DSM matrix.

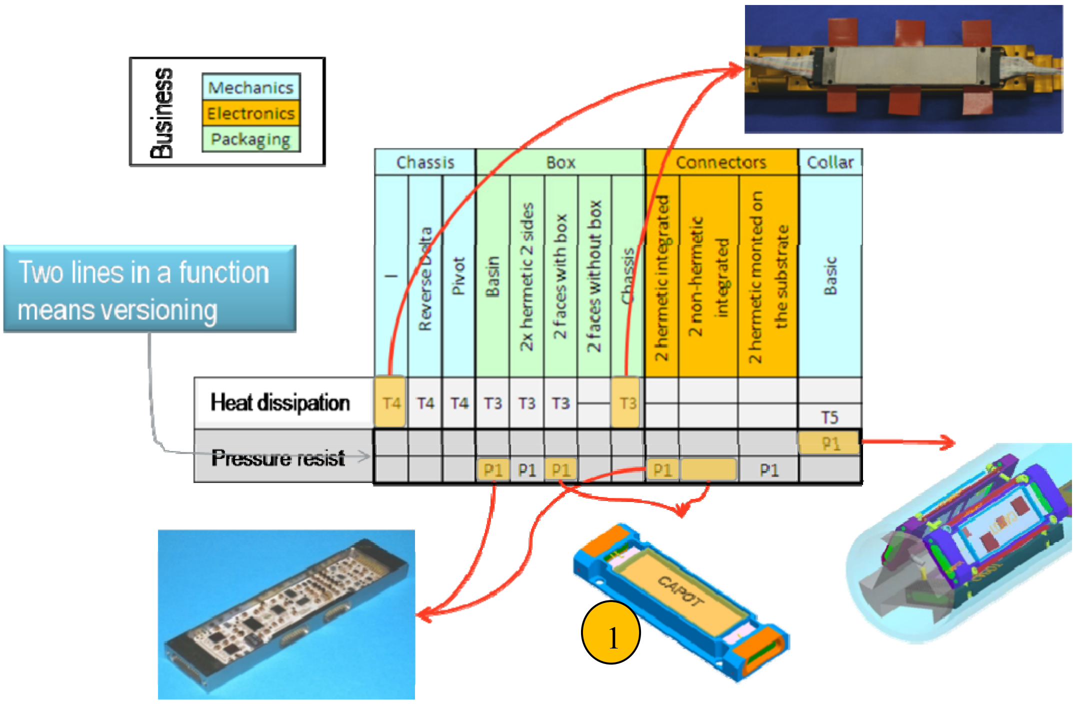


Figure 3. An illustrated example of the usage of a DMM

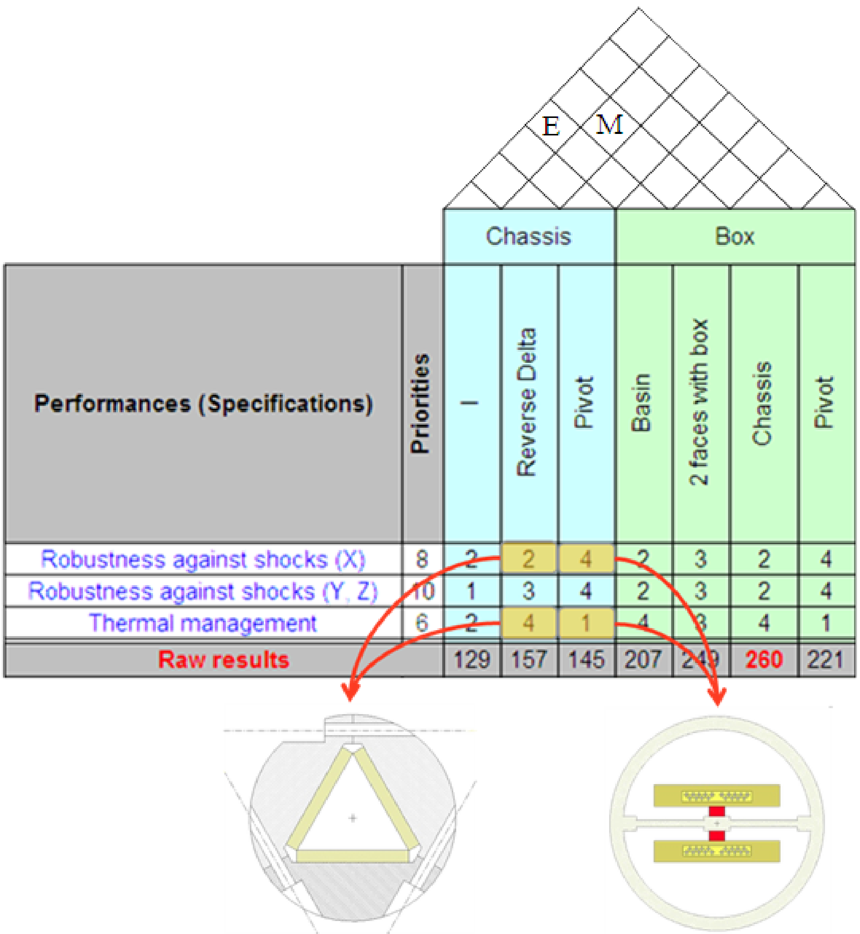
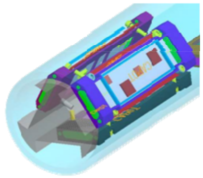


Figure 4. An illustrated example of the usage of a QFD

The row ‘raw results’ give a global component evaluation. With the details of notes to performances, advantages and disadvantages of design solutions can be represent.
As result of this processof the AID method the table with concept list (row in Figure 5) and their related evaluations (last columns in same figure) is generated. The middle of the matrix shows the design solutions constituting the concept.

Performances (Specifications)	Priorities	Chassis			Box				
		I	Reverse Delta	Pivot	Basin	2 faces with box	Chassis	Pivot	
Raw results		129	157	145	207	249	260	221	
Theoretical optimum							1		2303
7-Non-Hermetic Chassis			1				1		2234
5-Hermetic Chassis							1		2211
6-Disk							1		2078
1-HPHT		1			1				1887

Best result



Previous reference

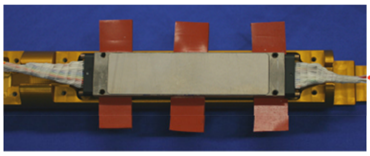


Figure 5. List of final results

This list of concept generated by our algorithm is evaluated (the representation of advantage and disadvantage is not present here) and ranked.

Our approach was used to analyze new idea imagined by designers, to generate better product from new design these ideas. Then the comparison was made between new product and reference. Finally, the method recommends the “best” choice regarding components analysis and their interactions with functions and performances through the identification of conflictual design parameters impacting design process and design departmenets.

6. Conclusion and limitations

This paper presents the AID method used for multi-physic product development. Based on our assumption that the decision impact comprehension by designers is helpful to optimize the design process and the choice of concepts, this work focus particularly on the complexity in the collaboration between design departments.
The proposed method is a matrix based product analysis approach that maps design department preferences (the voice of the design departments) in view to different possible architectures, functions and performance analysis. Our aim is to identify multiphysic design interfaces onflicts – collaborative design conflicts – with the objective to integrate such informations early in the concept choice. Finally, AID method is able to generate, to evaluate, and to propose new concepts to be considered in the product development.
Three matrices are used to model complex design problem: a DSM mapping physical connections into the architecture, a DMM to correlate functions with components and a QFD to link components and expected performances. The advantage of this approach is that: first the conjoint used of these three matrices, to our knowledge nobody mix MDM and QFD matrices in a non static manner. This combination allows to generate important information that engineers need to integrate in complex product analysis. We think that our approach can be considerably enriched by defining the semantics and taxonomy for multiphysic analysis. Connection types have been introduce into DSM which leads

to the capability to manage several possibility to assemble components – what can be seen as versioning – . This will let us able to connect a data model (not show in this article). Moreover, functional path is now represented through components.

Our work has two main limitations. First, our AID method is only managing physical connections. Other constrains have to be managed by constraint programming method. Second, our approach, and particularly, component evaluations can be quite long for a large system (over than five hundred evaluations). Nevertheless, the AID method has shown the potential when designing complex but relatively limited systems and permits the identification of potential conflicts and new potential solutions.

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