A method to envision highly constrained architectural zones in the design of multi-physics systems in severe conditions.

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A method to envision highly constrained architectural zones in the design of multi-physics systems for severe operating conditions

Une méthode pour prévoir les zones architecturales fortement contraintes dans la conception de systèmes multi-physiques en conditions opérationnelles sévères

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devant un jury composé de :

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This Ph.D. work is dedicated to:

my Mom,

my Wife, and

my Daughter.

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Abstract

Multi-physics systems design, including the design of mechatronics systems, involvings designers in different disciplines (e.g., mechanics, electronics, physics of sensors, etc.), particularly design for systems intended for operation in severe conditions (withstanding shocks, vibrations, high temperatures, and high pressures in limited dimensions), raises many of the challenging issues in the design of complex systems. Consequently, highly integrated products are characterized by multiple functional flows passing through common components. Very high performance requirements from the different designers may over-constrain **architectural modules**, as well as **connections**, and the **performance** of some functions. The integration of multi-physics functions within products of limited size that operate in severe conditions results in an intense interaction between design parameters and expected functionality. As soon as a design parameter is changed, the performance of several functions may be impacted. This is due to a high degree of performance optimization and the fact that several functions are part of the functional flow stemming from a single component. In addition, some **disciplines** may be more constrained than others, depending upon given performance challenges and the concept architecture being considered. Hereafter, we refer to architectural modules, connections, and disciplines as **constrainable objects**. Today, with no prediction tool for locating the aspects that are likely to be highly constrained, consequences may be dramatic. For instance, project management for systems in the oil industry is often responsible for unacceptable additions to project overhead costs and project timelines for a project that may simply fail in the end.

In our study, we propose to semantically enrich conventional representation models of product complexity. We use a design structure matrix (DSM) to represent admissible architecture connections and dependency configurations, a domain mapping matrix (DMM) to link functions and architecture, and quality function deployment (QFD), in a non-conventional way, in order to propagate the designers' aims for performance of the components more than the traditional "voice of the customer". We enrich DSM representations with a physical connection typology, allowing a range of choices at an early design stage. For a given connection, information regarding the nature of likely design difficulties is incorporated into a data model. We enrich DMM representations with functional flow sequencing along the architectural modules. We adapt the QFD method to capture the voice of the engineering disciplines involved in the project; this ontological enrichment of design data makes it easier to envision and manage design challenges for multi-physics systems. **Seven design assessment cards** are proposed to the design team as meaningful tools used to converge from a set of potential architectural configurations towards a single architecture. This convergence process is driven by the necessity of avoiding highly constrained constrainable objects, achieved by balancing and spreading the design constraints throughout the system. The seven assessment cards are organized into **two major design quality vectors**: the **ambition vector** and the **difficulty vector**. The ambition vector indicates degrees of freedom in exploration of the architecture design space. The difficulty vector offers heuristic information on the nature and levels of the difficulties in meeting performance targets.

The resulting method, which we call the *multi-physics design scorecard* (MPDS), was applied to the design of a power electronics controller (PEC), a regulator board involving three sectors: mechanics, electronics, and packaging. Data gathering and implementation of the MPDS method took the design team just one day. The method immediately generated improved architectures, guaranteeing at the same time a more robust further design process.

Keywords: Design engineering, design process, multi-disciplinary systems, complexity management, dependency management, collaborative design, interaction management

Nomenclature

The acronyms used in this paper are listed in Table 1.

MPDS	Multi-Physics Design Scorecard
DSM	Design Structure Matrix
DMM	Domain Mapping Matrix
PEC	Power Electronics Controller
MDM	Multiple Domain Matrix
QFD	Quality Function Deployment
SBCE	Set-Based Concurrent Engineering
PC-DSM	Physical Connection - Design Structure Matrix
FF-DMM	Functional Flow – Domain Mapping Matrix
VoDD	Voice of Disciplines Deployment

Table 1: Acronym nomenclature

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1. Design of multi-physics systems for severe operating conditions

In our research, we go through an analysis of Schlumberger issues with a *systemic approach* in order to identify domains from which we might be able to improve the *design of multi-physics systems for severe operating conditions*. In this part, we characterize severe operating conditions and perform the industrial audit within the company. Based on this audit, one has been able to feature critical anomalies and lacks in the current product development processes.

1.1. Extreme operating conditions

Schlumberger Limited provides oil extraction companies with measurements during drilling and extraction processes. An internal business unit designs, tests, and manufactures about one hundred tools annually, to be sold later to "field" business units. These tools are typically made of a few parts, each resembling a 7-to-10-meter needle, screwed together. Each elementary tool part is full of mechanical and electronics components, which deliver measurement data to the operational surface platform. These tools are exemplary of multi-physics systems that operate under extremely severe conditions.

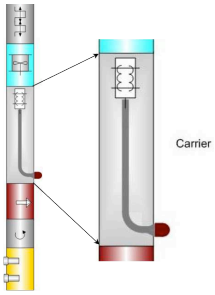


Figure 1: Modular tool screwed together

Wellheads (see Figure 2) are the entry point for ramifications of tubing that go deep in the subsoil, subject to high pressures (up to 300 bars) and high temperatures (up to 200 degrees Celsius). The tubing is full of a mix of water, mud, oil, gas, and acid. The power supplies for transmitters (which include nuclear power supplies), the corresponding receivers, and their electronic processors and encoding must all be integrated within the small diameters characteristic of the drills (typically 5 to 15 centimeters). They are integrated into mechanical packaging (see Figure 3).

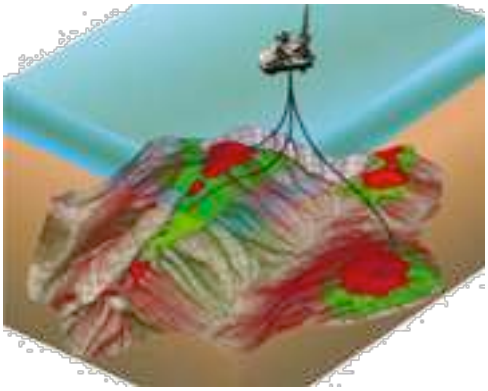


Figure 2: Wellhead ramifications involve high pressure, high temperature, and acid mud

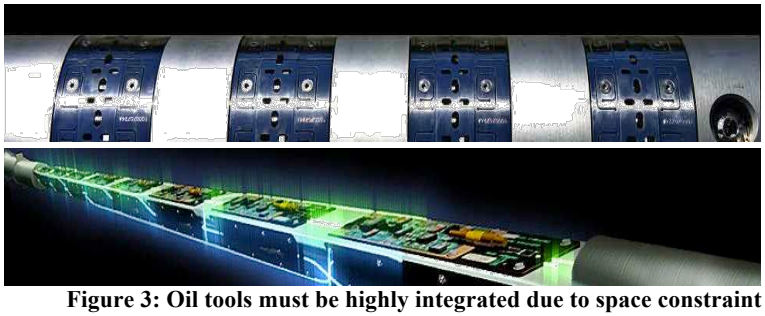


Figure 3: Oil tools must be highly integrated due to space constraint

The highest-constraint operating mode is when tools are located near the drilling head (see Figure 4), as they are subject to major shocks and vibrations. The tools are expected to last 200 hours under these extreme conditions and resist up to 200 g acceleration peaks. Due to the severity of the testing conditions, shocks, temperatures, pressures, and vibrations are applied separately during testing, which is clearly a limitation in validation of the tools.

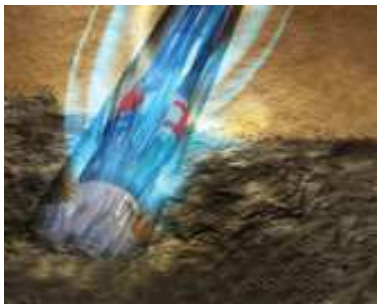


Figure 4: Oil drill bit

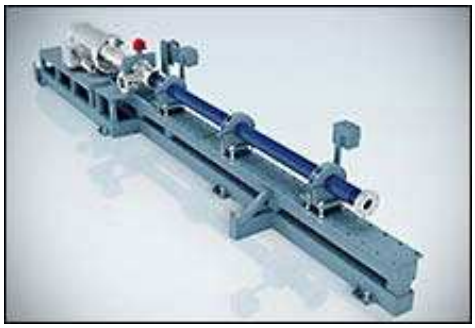


Figure 5: Shock and vibration testing set

1.2. Typical tool design projects: theory and practice

During concept and development stages, typical Schlumberger design teams are composed of 5 designers, who each represent a separate engineering discipline: mechanics, electronics, physics, software, and design architecture.

A standard product development process exists, the product lifecycle management process (PLMP). It is a structured stage-gate process starting with the description of an initial statement of the motivation of a development project and ending with commercial obsolescence.

The Clamart Schlumberger center has about 700 engineers working on more than 140 concurrent projects. It is not unusual to have some engineers working on two projects at the same time. One tenth of these projects, the “Large Products or Services” projects treated in this study, typically last about 7 to 15 years and cost, on average, about 5 to 10 million dollars per year per project. These durations and costs dramatically exceed what is generally planned for at the beginning of the projects: durations are lengthened 40% to 150%, and planned costs may be multiplied by a factor of two. The projects undergo many redesign iterations; sometimes they may suddenly need to be redesigned from scratch and, on other occasions, they may simply be stopped after several years of development.

In addition, most products are launched with reliability problems despite the years spent on their development and realization; 2 to 3 years of re-engineering are needed to achieve expected reliability after the first ground use has demonstrated and identified problems.

1.2.1. Our diagnosis of design project management

Explanations for this apparent lack of quality in the design of innovative product tools are multiple (HOLLEY 2008a; HOLLEY 2008b):

- The PLMP is very loosely defined (only 20 pages with 2-page templates for documenting each stage-gate) and not constrained enough to yield sufficiently structured design reports.
- Consequently, there is an extreme variability in the rigor with which a design project is deployed, organized, challenged, and documented. In all cases, there is a lack of traceability in decision-making during the project stages and gates, and thus no way to revisit decisions at a later time.
- There is no prescribed application of design tools for complex multi-physics systems, i.e. systematic use of CAD tools (there are no parametric models created for the designs) and failure modes and effects analyses (FMEAs). We are far from the Holy Grail of digital prototyping.
- There is no standardized or systematic use of project management methods and tools: basic preliminary risk analysis is carried out, but there is no management for changes in customer requirements and no systems engineering processes or documentation.
- There is no collaborative platform for managing design documentation, detailed task validations (apart from major validations of milestones), planning, etc. Documentation is basically stored on a large shared disk without any prescribed organization and with no fundamental version control protocol.

The reasons for this manner of working are beyond the scope of this study, but it may be explained in part by the culture of excellence in each discipline (engineers are actual experts in their domains) and also by the high return on investment of the oil market. Accepting this design culture, we choose to deal neither with project management nor knowledge management aspects of design projects, but rather to strengthen the core of multi-physics negotiations, namely consideration of system architecture.

1.3. Our need for a design tool

A thorough diagnosis (HOLLEY 2008a; HOLLEY 2008b) reveals that the Schlumberger design process can be greatly improved by using a simple user-friendly method and its corresponding implementation platform to highlight highly constrained architectural zones. We focus on the prediction of collaborative design difficulties between disciplines, including those from functional, structural, and performance standpoints.

In order to provide a clear framework for our applied research, consistent with the context we have presented above, we expect that our model must fulfill the following criteria:

- Efficient in:
    - Optimizing collaboration of multi-disciplinary design by taking the voices of the disciplines and their impacts on product performance into account,
    - Quickly highlighting collaborative difficulties, and
    - Not being time consuming, but rather presenting a good time to effort ratio (easy to use in design reviews and brainstorming sessions).
- Integrated in the design process and able to take several areas, such as manufacturing, into account.
- Permit system evolution in dynamically delivering decision aids to the disciplines.
- Suitable for:
    - Traceability in design decision-making,
    - Generation of design reports (modeling of design information exchanges between engineers), and
    - Supporting collaborative design (synchronization, validation of hypotheses, information seeking, etc.).
- Dynamic to be available for consultation whenever the experts need it, and thus to integrate their viewpoints as directly as possible.

2. Research question

In our research, we go through the Schlumberger design problem with a *systemic approach* in order to identify domains from which we might be able to improve the *global performance* of the official (in-house) Schlumberger Product Lifecycle Design Process, named PLMP. In part **Error! Reference source not found.**, we performed an industrial audit and made diagnoses on the current *PLMP* practices within the company. In this chapter, we clearly define the *scope of our research* and we formulate our *research topic* based on the performed diagnoses and the related research *issues in Collaborative Design of Complex System (see part 3)*.

2.1. Assumptions

A large part of the design of oil tools is driven by the recurrence of the need that induce a similitude in the high level system architecture in multi-generational tools. Such product is challenging for multi-physics design team that must improve global technical performances based on the improvement of sub-systems and interfaces. In this context, we set assumptions of our research work as:

- The high level system architecture of a product is known only sub-systems and interfaces may vary,
- Optimizing conflicting performances through architecture in different physics is challenging for individual engineers with no collaborative tool,
- Specialized discipline knowledge induces the difficulty in defining a common language,
- Architecture representation and functional flow scan form the basis of this common language.

2.2. Industrial issues

A thorough diagnosis (HOLLEY 2008a; HOLLEY 2008b) shown that the most impacting issues for Schlumberger in the design of collaborative complex system by a multi-physics team concern:

- **To predict design conflicts**. Design team member are experts in their domain but the integration of their works lead to several conflicts that decrease system performances and moreover, that can lead to an impossible integration.
- **To explore interface design impact on system performances**. The assessment of system performances is robust in each design department but system performances are greatly impacted by performances located in collaborative area between design departments (the so-called architectural zones where design constraints and performances achievement can be important).
- **To derive a robust architecture (compliant with multi-physics requirements)**. A robust architecture must be defined by the ability to achieve system requirements and also design department requirements. The achievement of both can be conflictual (sometimes the achievement of system performances involves to loosen achievement of design department performances).

2.3. Research questions

Based on our assumptions, industrial issues and the literature review (see part 3), we defined our objectives based on two research questions:

1. How to assess the feasibility of an **interface**, the probability of achievement of a **given performance** and the challenge for a **given design department?**
2. How to visualize this information through **graphical interfaces** so that the multi-disciplinary group can share a **common understanding** and make **common decision?**

3. Literature review

3.1. Framing the problem

The design of multi-physics systems for severe operating conditions involves designers from different design departments and is based upon cross-domain scientific knowledge.

In the context of the collaborative design of a system by design departments, we expect our work to serve as a tool for the collaborative effort. After a brief introduction of the point-based design approach, this section presents the set-based concurrent engineering design approach as a framework for the design of such systems. The ability to challenge the design of these systems is analyzed.

The section goes on to present complexity management; the number of design parameters that must be managed is exponential. The design of multi-physics systems by different design departments involves management of design interactions. Complex systems engineering has been deployed in order to manage such dependencies. In this section, complex systems engineering is introduced along with fundamentals of the complexity that must be managed. To manage these fundamentals, axiomatic design, an interaction modeling approach, and a comparison between graphical and matrix representations will be carried out.

Figure 6 represents the overall structure of the literature review proposed to respond to the needs of the design of multi-physics systems operating in severe conditions. Set-based concurrent engineering is defined as a tool for engineers involved in collaborative design processes. Complex systems engineering is reviewed as one of the answers to managing different types of interactions between design parameters, system functions, and cross-domain collaboration in the design of multi-physics systems. Matrix-based methodologies are used as a tool in the management of complexity.

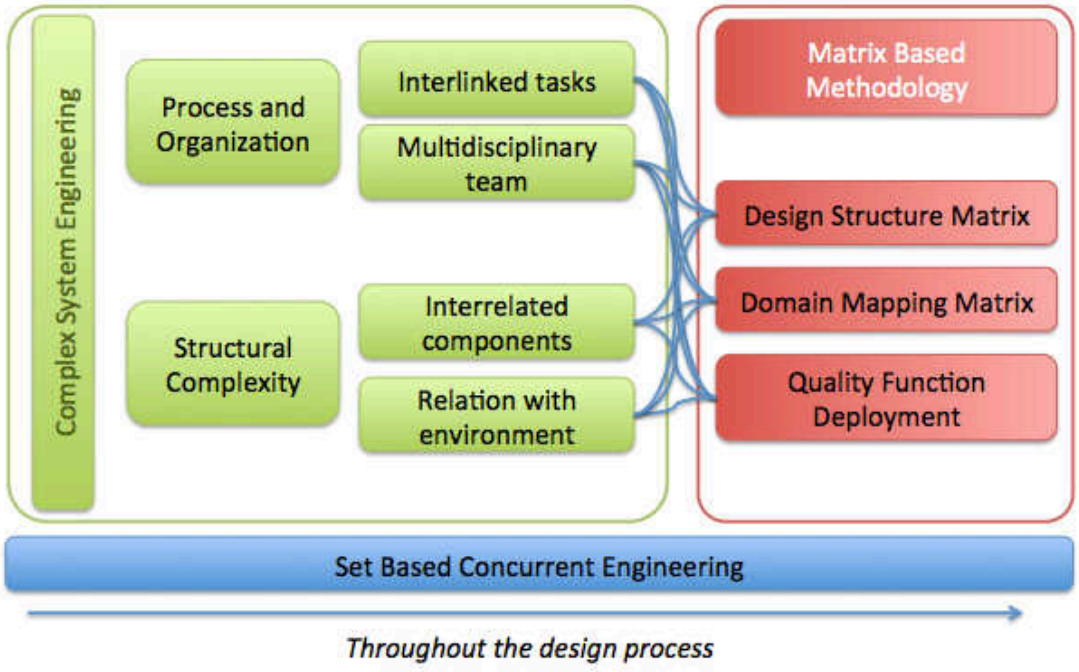


Figure 6: Literature review overview

3.2. New constraints for collaborative engineering design: the set-based approach as a tool for the design of systems

The quick evolution of the industry, increasing product complexity involving more design departments, has lead to the necessary improvement of the design process. In this section, we discuss the most recent developments of the design process and introduce the state-of-the-art in set-based concurrent engineering.

The traditional way to develop a product (we assume that it remains the most used in industries) is called "point-based design" or "point-based serial engineering". This design approach is based on successive design iterations by the design departments involved in the design of the system and is focused on local design optimization within a given department. Figure 7 illustrates an example from the automotive industry of the global path of the system linking the departments: "marketing" defines the product, then "styling" defines the shape of the car, after which the "system design" is carried out, and then "component design" is done. Finally, the system is transferred into "manufacturing". At each stage, the system can be redesigned to satisfy constraints that have not already been integrated into the design process.

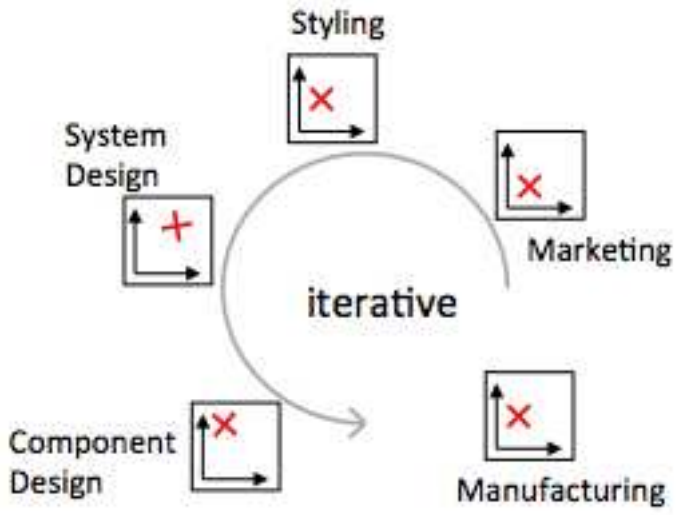


Figure 7: Point-based design (MAZUR, YANNOU et al. 2009)

Historically, Point-Based Design (PBD) was a natural allocation of responsibilities, but today it is obsolete in addressing new design challenges. PBD remains time-consuming, costly, and generally leads to a design that is "good enough" but not optimal.

In order to satisfy new design department integration needs, the research in product development has been focused on its global optimization (BOYD, GHOSH et al. 2003). Toyota recently improved their product development process to control project objectives (cost, time, delay, etc.) and product performance criteria (reliability for instance). These recent developments are presented in the book "The Toyota Product Development System" by Morgan et al. (MORGAN and LIKER 2006) and in several articles (WARD, LIKER et al. 1995; POPPENDIECK 2002). This new and rather interesting design development process, called set-based concurrent engineering, has been built up based on the following paradox: *delaying decisions can make better cars faster*.

3.2.1. Set-based concurrent engineering

Ward et al. (WARD, LIKER et al. 1995; WARD, LIKER et al. 1999) present set-based concurrent engineering (SBCE) as the fastest and most efficient vehicle development cycle. They demonstrate that, respecting a few principles that presented in this section, SBCE can be applied to any industrial sector.

3.2.1.1. SBCE philosophy

SBCE is a design approach based upon initial set (of possible solutions brainstormed by design team at the beginning of the project) convergence control (POPPENDIECK 2002). Instead of the classic point-based design (as shown in Figure 7), convergence begins by broadly considering sets of possible solutions and gradually narrowing the set of possibilities to converge to a final solution. According to Poppendieck (POPPENDIECK 2002), gradually narrowing design spaces means maintaining multiple options and delaying decisions in parallel to gradually reduce uncertainty. In this approach, constraints from all project stages are combined as shown in Figure 8, where the design of each sub-system converges in parallel (TOMMELEIN, STOJADINOVIC et al. 2007).

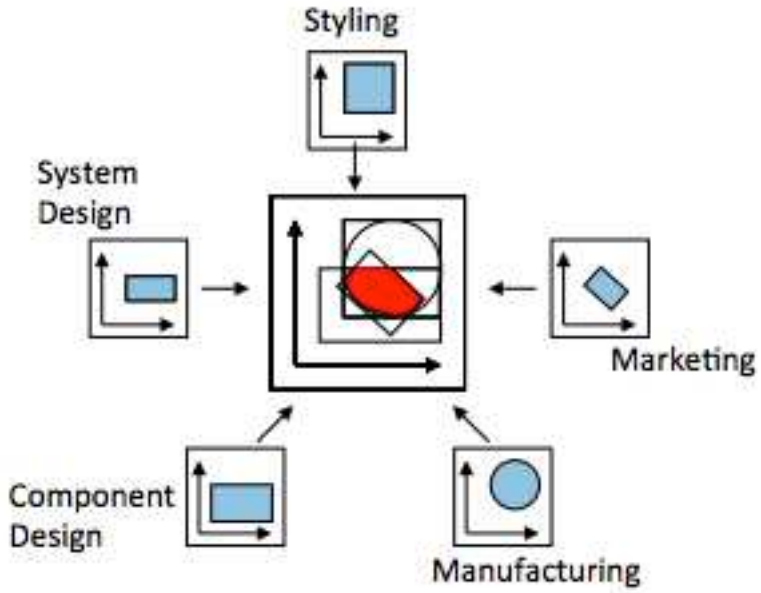


Figure 8: Set-based concurrent engineering (MAZUR, YANNOU et al. 2009)

3.2.1.2. SBCE principles

In the research literature, three broad principles are identified as important in most of the cases and can therefore be considered as an overall framework (WARD, LIKER et al. 1999):

1. Map the design space
    - Define feasible regions
    - Explore trade-offs by designing multiple alternatives
    - Communicate sets of possibilities
2. Integrate by intersection
    - Look for intersections of feasible sets
    - Impose minimum constraints
    - Seek conceptual robustness
3. Establish feasibility before commitment
    - Narrow sets gradually while increasing detail
    - Stay within sets once committed
    - Control by managing uncertainty at process gates

Mapping the design space involves the exploration and characterization of a set of alternatives (known as the "initial set") used in the convergence process. In order to define such an initial set, two levels of analysis are used (WARD, LIKER et al. 1999):

- ✓ On the individual project, the design team explores and communicates many alternatives by mapping out the possibilities associated with feasibilities and relative benefits or costs. The goal is to understand the set of design possibilities that apply to the problem.
- ✓ On the company project, learning experience from documenting alternatives, trade-offs, and technical design standards is used. Every engineering function has a checklist that details design guidelines in any number of areas.

Integration by intersection starts when design departments have understood considerations from their own perspective but also from the perspectives of others. The design team integrates subsystems by identifying solutions that are feasible to everyone. Toyota uses distinct approaches to system integration:

- ✓ Looking for intersections of feasible solution sets involves the identification of intersections of different functions, i.e., where feasible regions overlap. If Toyota can identify an intersection, it finds a solution to be acceptable to everyone.
- ✓ Imposing minimum constraints is ensured by "making each decision in its own time" as opposed to the general U.S. practice, which seems to be "making decisions as early as possible to avoid confusion" (WARD, LIKER et al. 1999).

Toyota's entire set-based development process might be viewed as a system to fulfill the third and last principle: "ensure that designs are feasible before committing to them." As the initial set of solutions becomes smaller, the resolution of each idea or design within the set grows sharper, as designers use increasingly detailed models. The value in communicating about solution sets is nullified if a team member jumps to a solution outside the originally communicated set. Toyota views its process as a continuous flow, with information exchanged as needed.

3.2.1.3. SBCE strengths and weaknesses

Two main benefits can be highlighted for set-based concurrent engineering:

- ✓ A greater variety of solutions are created which improves the chances of finding a good solution quickly. There is a smaller chance of not finding any feasible solutions (SEEPERSAD, MADHAVAN et al. 2008).
- ✓ In comparison with point-based design, SBCE is a time- and cost-effective approach that reduces the number of iterations required.

Two main disadvantages can be highlighted for set-based concurrent engineering:

- ✓ According to Tommelein et al. (TOMMELEIN, STOJADINOVIC et al. 2007), set-based concurrent engineering postpones commitment until all relevant information is considered. Paredis et al. (PAREDIS and MALAK 2006) demonstrate the verity of this sentence and conclude that "if we are not making a choice, we will keep several products until the end." These two works show that it is important to be able to control the convergence of the initial set of solutions throughout a set-based approach.
- ✓ According to Seepersad (SEEPERSAD, MADHAVAN et al. 2008), empirical experimentation demonstrates that, with SBCE, the solutions tend to be satisfying (SIMON 1998) or approximate solutions that are "good enough" but not necessarily optimal.

3.3. Complex system design paradigm

Set-based concurrent engineering is one of the most efficient existing development processes (WARD, LIKER et al. 1999), but it does not provide the design team with tools to map design spaces, including complex dependencies. This section introduces the characteristics of complex systems and tools to manage complex dependencies.

Historically, complexity science originated from cybernetics (WIENER 1948) and systems theory (VON BERTALANFFY 1950) (see Figure 9). Since the 1980's, complexity has focused on structural complexity management with matrix representation (STEWARD) and graphical/network representations (BARABASI 2003; BARABASI 2003; WATTS 1998). Both matrix and graphical representations are analyzed in the next section.

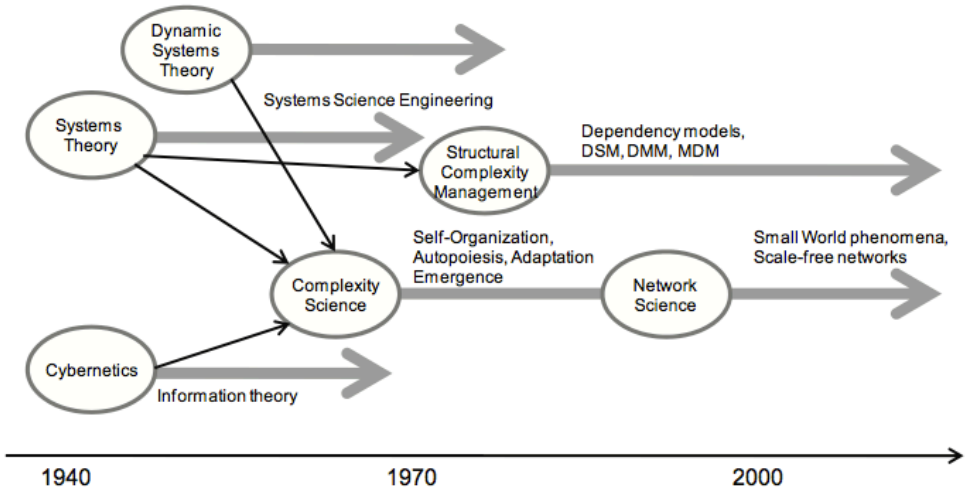


Figure 9: Evolution of sciences related to structural complexity (KREIMEYER 2009) (after (FACTORY 2009)

Today, complexity is present in many disciplines and has many facets (KREIMEYER 2009). The physics community sees it as the probability of reaching a certain state vector (HEISENBERG 2007), while in engineering, complexity generally addresses the high coupling of the entities of a technical system. Maurer's complexity definition (MAURER 2007) has been used as the basis of our research: "A system is created by compatible and interrelated parts that form a system structure, possess individual properties, and contribute to fulfill the system's purpose. Systems are delineated by a system border and connected to their surroundings by inputs and outputs. Changes to parts of a system can be characterized by dynamic propagation effects and result in a specific system behavior."

3.3.1. Fundamental characteristics of complex systems

Since the 1940's, several works have identified characteristics of complex systems. Minai, Braha, et al. (MINAI, BRAHA et al. 2006) identify the fundamental characteristics presented in Figure 10, while Johnson, Eckert, et al. (EARL, JOHNSON et al. 2004; KELLER, ECKERT et al. 2005) go deeper and identify four layers in which complexity can occur (see Figure 10).

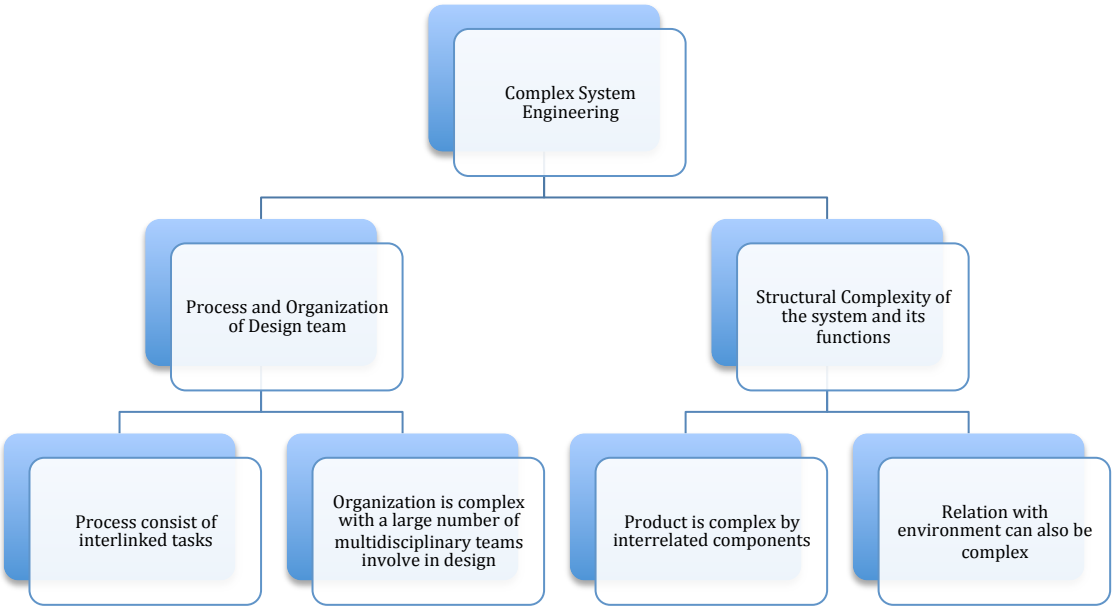


Figure 10: Complex system engineering map

The first fundamental characteristic involves processes and organization of the design team. This characteristic can be broken into two layers: process complexity consists of interlinked tasks, and organization is complex with a large number of multidisciplinary teams involved in the design. The second characteristic is the structural complexity of the systems and their functions. Their complexity is due to the complexity of interrelated components and the relation with environment.

Adding to the structure shown in Figure 10, Doyle et al. (CARLSON and DOYLE 2000; CARLSON and DOYLE 2002; LI, ALDERSON et al. 2004) have illustrated that most work in complex systems has focused on generic or typical systems within ensembles but well-designed and optimized systems that are rare and atypical (innovative) within their configuration spaces. The authors conclude that most work on the broad principles of complex systems (STAUFFER and AHARONY 1994; BAK 1996; BARABASI 2002; BARABASI and BONANEAU 2003) has not contributed much to the understanding of

real systems. We interpret this conclusion as lacking a map between the layers: the interdependencies and their impact should be understood and managed. This observation highlights a fundamental issue for engineering complex systems: the need for solution-rich configuration spaces (MINAI, BRAHA et al. 2006). "The challenge for complex systems engineers is to devise the components of their systems and the interactions between them in such a way that stochastic processes such as relaxation, annealing, swarming, evolution, etc. can find near-optimal configurations relatively quickly, which is only possible if such configurations are not too rare or completely atypical."

3.3.2. Complex System Engineering

The design of complex systems is introduced by the complex systems engineering approach, as defined by Bar et al. (BAR-YAM 2002; BAR-YAM 2003; BAR-YAM and KURAS 2004). This paragraph presents a summary of the unmanaged challenges in the design of complex systems extracted from (MINAI, BRAHA et al. 2006):

- ✓ The engineering process defines components and their interactions, but ensuring that the design produces the desired global functionality is the primary challenge for complex systems engineering.
- ✓ The complex systems engineer does not seek to design the system in all its details, but the design of local interactions is one of the biggest challenges facing complex systems research. We believe that local design must be integrated earlier in the design in order to understand their global consequences.
- ✓ Complex systems must be able to dynamically reconfigure themselves based on modified design information. Early in the concept stage, system configuration must be dynamically generated based on available data.
- ✓ In complex design, every system must be considered as a unique mix of tacit and explicit knowledge.
- ✓ In complex systems, the need for process redundancy increases. Recently, the notion of *degeneracy* of multiple processes with identical consequences has also been suggested as an important one (EDELMAN and GALLY 2001; SOLE, FERRER et al. 2002). Redundancy relies on internal duplication of process modules, so that when a few fail, others can take their place. It is useful to consider several structural module alternatives in the design of complex systems.
- ✓ The notion that complex systems are also based on the reuse of the design is an important one; we find that tacit knowledge must be capitalized and reused in the design of complex systems.
- ✓ In complex systems, the "combinatorial explosion" of the solution space, in combination with a mechanism for selective reinforcement, represents an opportunity rather than a problem (MAIMON and BRAHA 1996). It is useful to automatically map this combinatorial explosion in order to find better concepts.
- ✓ The robustness of complex systems goes beyond a simple optimization of system parameters. Robustness-by-structure can be achieved by appropriately designing the interactions among the system's elementary components (BRAHA and BAR-YAM 2006). It can enable the development of highly robust systems by effectively utilizing imperfect or faulty components. Interactions must be considered in thorough detail through the very design parameters that govern them (for example, drying time of the glue used as a connector.

- ✓ The literature emphasizes that complex engineering designs can evolve throughout the project. Processes must be flexible and enable system adaptation to real-world changes in components and their interactions over time. The existence of variety in the components at multiple levels of organization enables evolutionary selection to occur (MINAI, BRAHA et al. 2006).

Product architecture has been defined as "the scheme by which the function of a product is allocated to physical components" (ULRICH 1995). It is thus not sufficient to represent complexity as structural dependencies. Interactions (also called "dependencies") must be well understood in terms of potential impact on functional performances for the client. Systems must remain adaptable in time and must remain based on knowledge reuse.

3.3.3. Different approaches to adress the interactions in engineering design

3.3.3.1. Axiomatic Design

A major contributing factor to complexity is the numerous dependencies between components. Manipulating a component disrupts other components and vice-versa (LIM 2007). The understanding and the managing of such dependencies are possible using axiomatic design (AD).

Nam Suh (SUH 1990; SUH 2001; SUH 2005) demonstrates the correlations between customer needs (called customer attributes in a customer domain), their transcription into functions (functional requirements into a functional domain), their concretization in the physical system (design parameters into a physical domain) and their realization by processes (process variables into a process domain). AD provides a method to interlink domains (customer attributes, functional requirements, design parameters, and process variables, see Figure 11) using the "zigzag" design process and taking the independence axiom (ZHANG, CHA et al. 2007) into consideration. This systematizes complexity analysis and hence facilitates complexity reduction (LIM 2007).

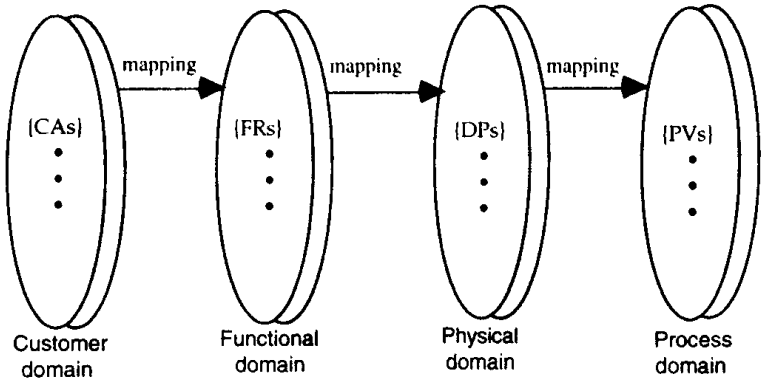


Figure 11: Axiomatic design (SUH 1995)

Lim (LIM 2007) proposes a matrix to map this zigzag process between domains. Figure 12 presents a zigzag illustration between the functional domain (FR on Figure 12) and the physical domain (DP on Figure 12); the A matrix given in Equation 1 represents the zigzag between domains.

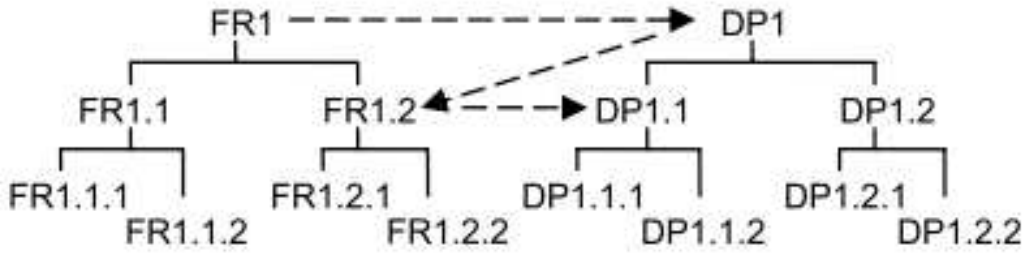


Figure 12: Axiomatic design map using DSM matrix (LIM 2007)

Equation 1: Axiomatic design with matrix representation

$$\{FRs\} = [A]\{DPs\}$$

This approach to mapping dependencies is of great interest because AD eliminates avoidable dependencies, whereas the DSM matrix manages the remaining inherent dependencies – they have different roles in reducing system complexity.

3.3.3.2. Interaction model

Sinha et al. (SINHA, PAREDIS et al. 2001) state that most of the research in configuration design has focused on modeling components, with very little attention paid to the dynamics of the interaction phenomena. Thus, they propose a model to map interactions inside the physical domain. In order to do this, they define interactions as physical phenomena that occur at the interfaces between connected components.

Many products have a modular architecture that is based on the selection and composition of off-the-shelf components and components reused from older designs (SINHA, PAREDIS et al. 2001). When the new design is created, components are selected and then connected together in a given configuration (see Figure 13).

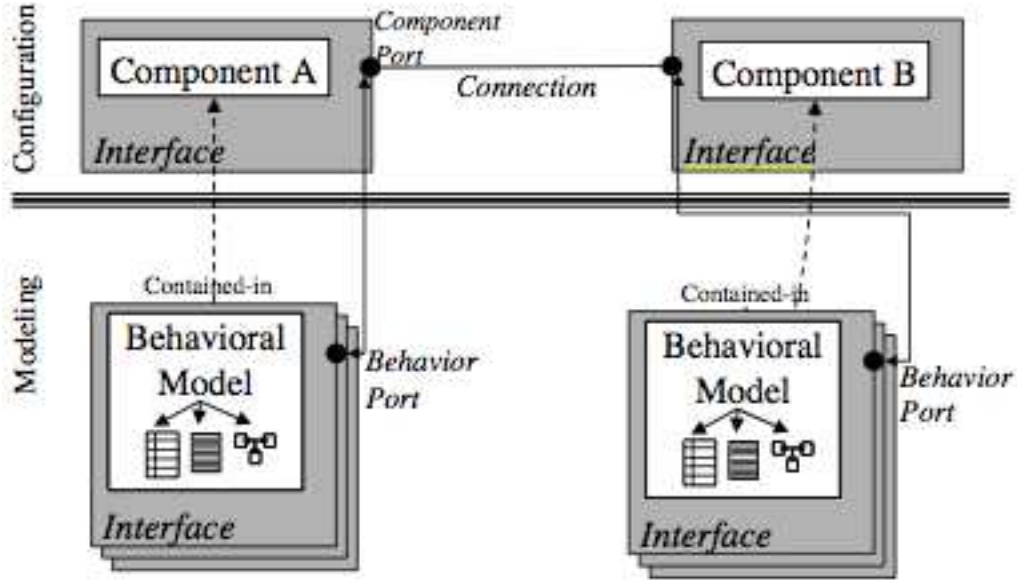


Figure 13: Sinha et al. (SINHA, PAREDIS et al. 2001) configuration of components design process

The Sinha et al. (SINHA, PAREDIS et al. 2001) framework is driven by the configuration of components. This configuration is supported by models analyzing the behavior imposed by theoretically formalized rules. In this configuration, components are interacting based on interaction model taxonomies (see Figure 13) and port type taxonomies (see Figure 15).

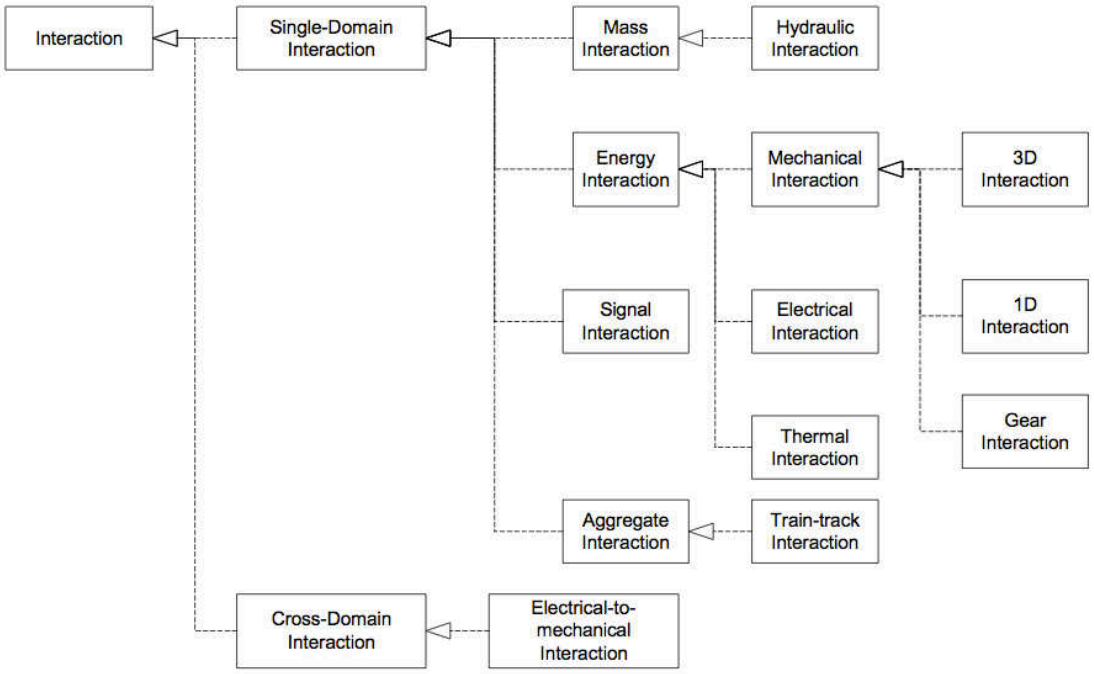


Figure 14: Sinha et al. (SINHA, PAREDIS et al. 2001) interaction model taxonomy

Interaction models define how two components are interacting. In a mechanical representation, this interaction model will characterize the number of teeth and the pressure angle between two gears. Figure 14 presents the taxonomy of interaction models: an interaction can be single-domain or cross-domain. The taxonomy is organized by the number of energy and information domains participating in the interaction. Within each of these domains, models are classified by the physical domains that they represent. The single-domain interaction is defined by a taxonomy of mass, energy, signal, and aggregate interactions.

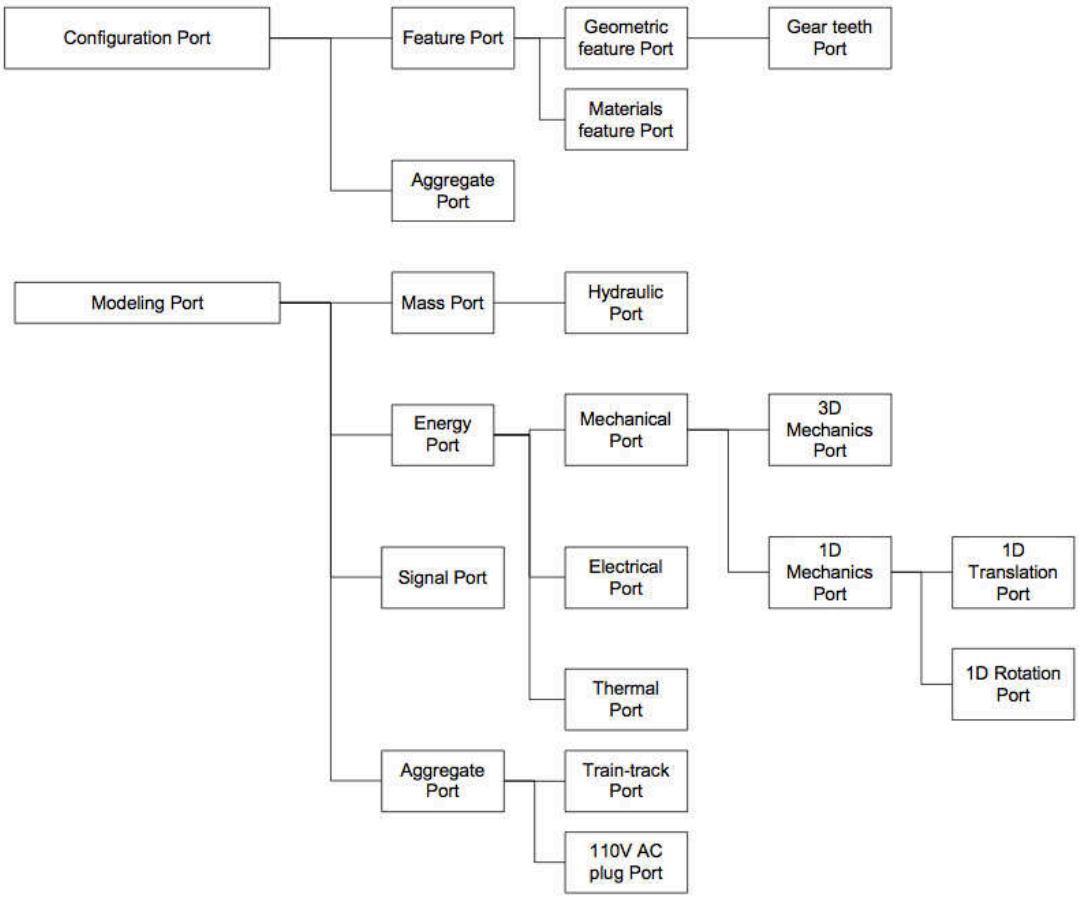


Figure 15: Sinha et al. (SINHA, PAREDIS et al. 2001) port type taxonomy

A port is a descriptor for a discrete point on the boundary of a component where the component interacts with its environment. Interactions range from abstract descriptions of connection semantics, as is the case for ports in the configuration level, to exchange of mass, energy, or information (see Figure 15). As a result of this interaction model, the train-track interaction is as presented in Figure 16.

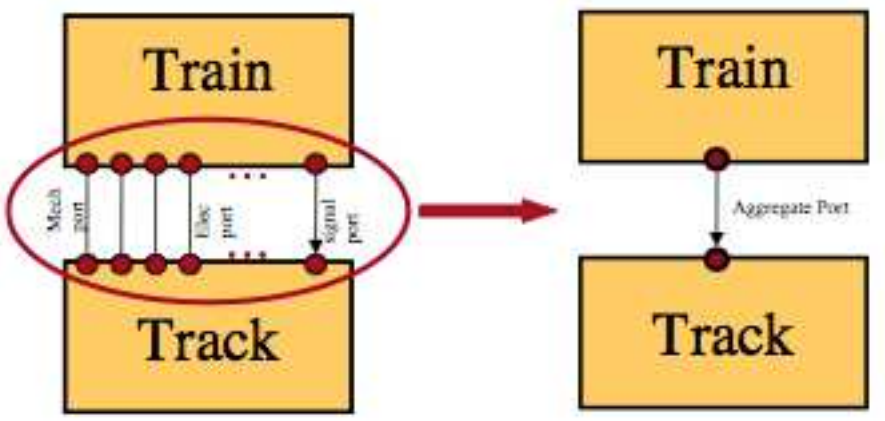


Figure 16: Sinha et al. (SINHA, PAREDIS et al. 2001) train-track Interaction example

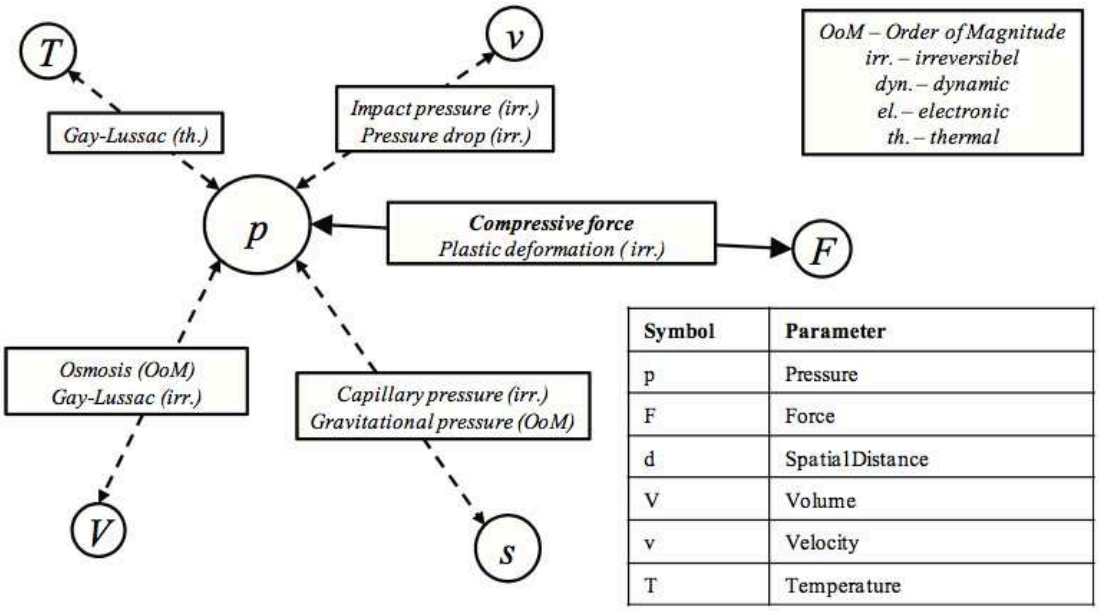
The interactions between a train and train tracks are of several types: mechanical, electrical, and signal. These different types are applied to several ports of the interface (see Figure 15); all are grouped into one aggregate port.

3.3.4. Structural representation models

Paragraph 3.3.2 presents the remaining challenges of complex systems; this section presents the two main representations that are found in the literature: graphs and matrices. To acknowledge the variety of product architecture representations used by multi-disciplinary teams (DANCKAERT, YANNOU et al. 2008), several representation modes are shown here.

3.3.4.1. Graphical concepts representation

Graebsch et al. (GRAEBSCH, DEUBZER et al. 2009) demonstrate that design problems can be abstracted to physical effects; they propose a graphical representation of networks of physical effects. Physical parameters can be linked to other physical parameters by physical effects that match their respective inputs and outputs (PONN and LINDEMANN 2008; GRAEBSCH, DEUBZER et al. 2009). With this level of abstraction, lists of physical effects can greatly widen the solution space (PAHL and BEITZ 1996; PONN and LINDEMANN 2008). Typically, these lists are sorted according to input and output parameters.



Symbol	Parameter
p	Pressure
F	Force
d	SpatialDistance
V	Volume
v	Velocity
T	Temperature

Figure 17: Graebsch's (GRAEBSCH, DEUBZER et al. 2009) graphical representation

3.3.4.2. Matrix concepts representation

Various authors have developed matrix-based approaches to model the dependencies between different engineering domains (KOH, CALDWELL et al. 2009). Table 2 shows various interesting uses of matrices that will be introduced in this section.

Table 2: Synthesis of selected matrix approaches

References	Work objectives	Used matrices	Data gathering	Typology of dependencies
(MOCKO, FADEL et al. 2007)	To analyze the inter-relationship between system requirements, functions, components, engineering characteristics and test	DMMs	Requirements, Functions, Components, Engineering characteristics, Test	Existence (X) or non-existence (_) of a relationship
(Hellenbrand et al. 2008)	To list consistent concepts	DSM	Component alternatives	"Quality" of connections
(Wyatt et al. 2008)	To define inconsistency of concepts and to capture the rules through the identification of constraints	DSM & DMM (MDM)	Components, Component type	Existence (X) or non-existence (_) of a relationship and (1) or (2) based on an ontology
(Gorbea et al. 2008)	To capture rules	MDM	Functions, Components	Existence (1) or non-existence (_) of a relationship
(KOH, CALDWELL et al. 2009)	To model five functional fields	MDM	Product components, design features, required attributes	Numbers rating interactions
(MAIER, MOCKO et al. 2009)	To compare requirements information in term of affordances, with physical structure	Affordance structure matrix (QFD)	Requirements, physical structure	Helpful (+) or harmful (-) relationship

Analagous to the axiomatic design description by Lim (LIM 2007), Mocko et al. (MOCKO, FADEL et al. 2007) describe the use of a matrix-based modeling scheme, which analyses the interrelationship between system requirements, functions, components, engineering characteristics and test. Their systematic method and matrix-based modeling scheme are developed to support the design of complex systems through 1) identification of repetitive or legacy requirements, 2) integration of functionality into a single component/assembly, 3) fulfillment of requirements and functionality by multiple systems, and 4) elimination of redundant and worst-case system testing. Figure 18 presents the computed matrices proposed by Mocko et al. (MOCKO, FADEL et al. 2007). These "populated matrices" filled in with knowledge from engineers make it possible to directly link requirements with the respective tests.

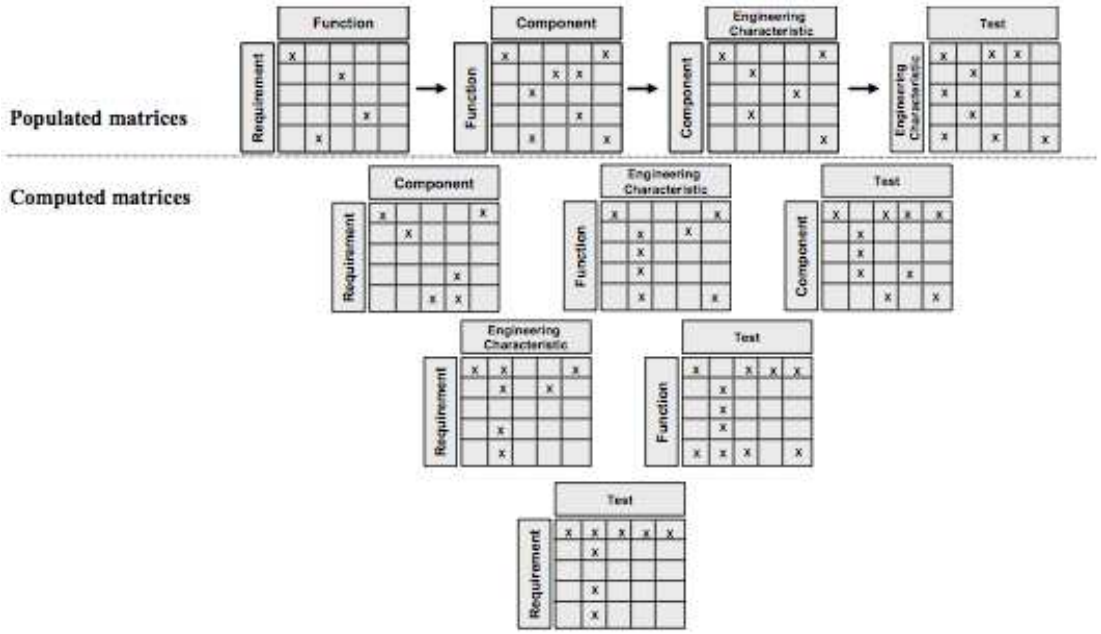


Figure 18: Matrix-based modeling scheme (MOCKO, FADEL et al. 2007)

For the physical domain, Hellenbrand et al. (Hellenbrand 2008) propose a simple approach that combines different component alternatives in order to list consistent concepts (see Figure 19). Engineers perform clustering by populating a DSM matrix. The only information available for designers is whether or not there is compatibility (in assembly) between two components. This is presented by an empty cell (“ ”) or an “X” in the matrix.

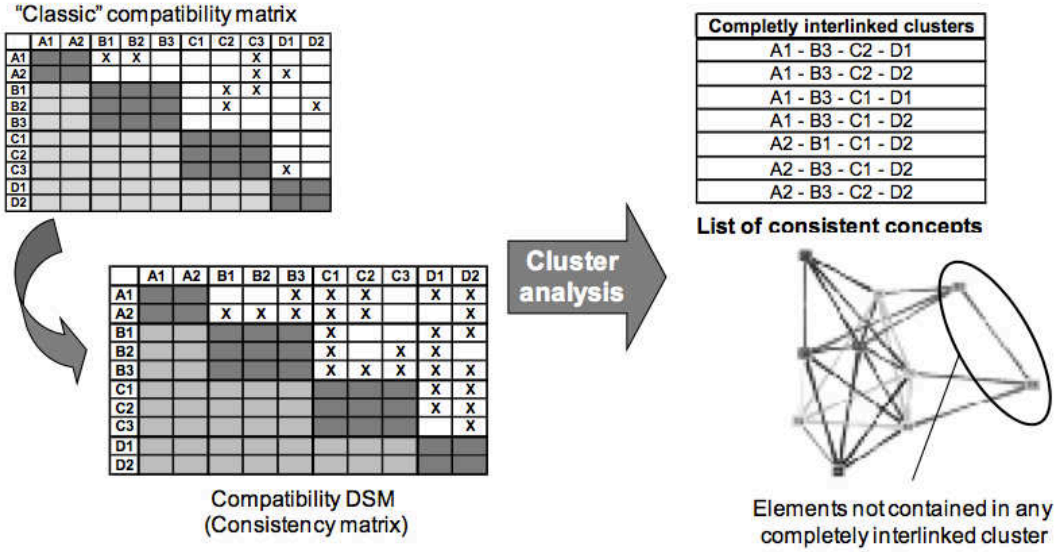
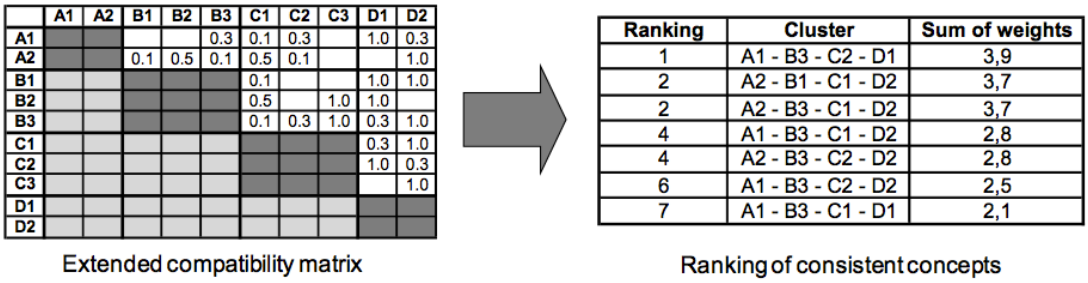


Figure 19: Compatibility matrix to identify completely interlinked clusters

Further development leads to the extended compatibility matrix with weighting factors (see Figure 20). These factors represent a positive or negative correlation between two solutions. Instead of just checking the incompatibility, the degree of positive or negative correlation between two concepts is inserted in the matrix.



Ranking	Cluster	Sum of weights
1	A1 - B3 - C2 - D1	3,9
2	A2 - B1 - C1 - D2	3,7
2	A2 - B3 - C1 - D2	3,7
4	A1 - B3 - C1 - D2	2,8
4	A2 - B3 - C2 - D2	2,8
6	A1 - B3 - C2 - D2	2,5
7	A1 - B3 - C1 - D1	2,1

Figure 20: Extended compatibility matrix and derived ranking of concepts

- ✓ Wyatt et al. (WYATT, WYNN et al. 2008) propose to define inconsistency of concepts and to capture the rules through the identification of constraints (see Figure 21). They define two classes of constraints:
    - *Connection requirements* ('syntax') specify which connections a given type of component may have, in terms of minimum and maximum degrees for each type of connection. For example, component might require between 1 and ∞ "attached to" connections, indicating that it *must* be attached to at least one other component but *may* be attached to an unlimited number.
    - *Path requirements* ('semantics') specify paths that must exist in the component DSM matrix. Path requirements are defined by the component types between which a path must exist and the connection types that may constitute the path, and are related to the overall function of the product. For example, in a hairdryer with overall function "produce a flow of hot air", there must be an airflow path from the heater to the outlet nozzle. The ontology of components, component types, and connection types, combined with the constraints, define an *architecture schema.*

To generate candidate architectures from such a schema, an exhaustive breadth-first search is carried out. The search starts from an empty component DSM matrix, and connections are added one at a time (up to a specified maximum search depth). Once all connection requirements (minimum and maximum) are satisfied, graph-search algorithms are used to test the path requirements. The resulting list of feasible architectures may then be reviewed by the designer to check that the schema is suitable, i.e., that it results in possibilities that "make sense". Each feasible architecture is then evaluated against defined objectives.

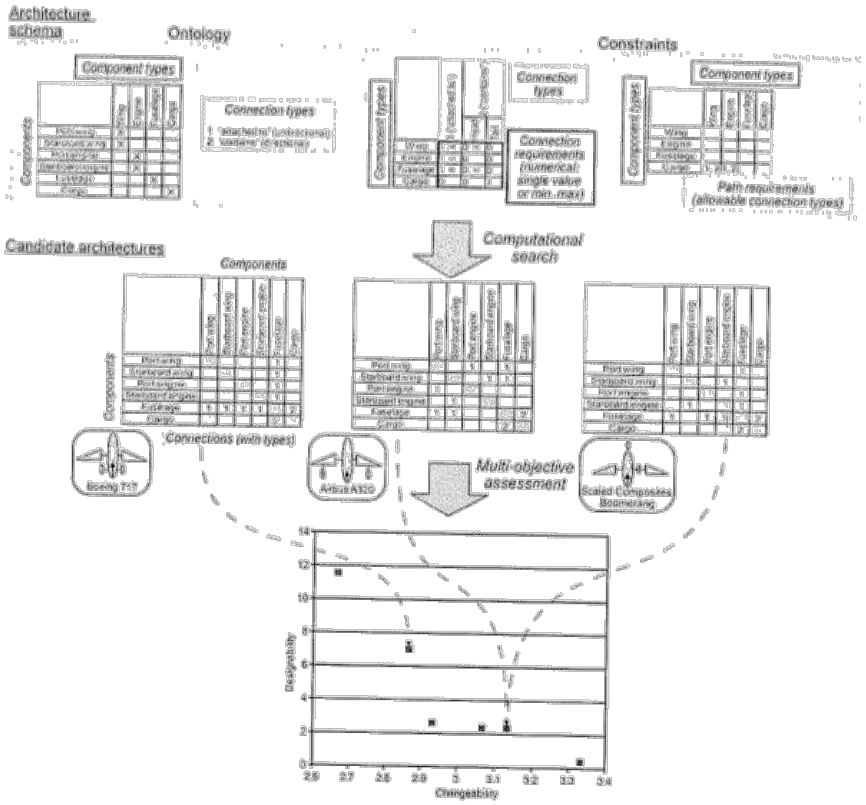


Figure 21: Inconsistency matrix (WYATT, WYNN et al. 2008)

Another research stream mainly deals with the issues of capturing rules (whatever design or design department rules there may be). For instance Gorbea et al. (GORBEA, SPIELMANNLEITNER et al. 2008) propose a very interesting method that uses the MDM matrix (a mix of the DSM and DMM matrices) to map dependencies in architectures (see Figure 22). Rule extraction and generation in this approach is based upon components and functions analyses. The proposed MDM matrix is composed of three matrices (see Figure 22): a functions-functions DSM matrix, a components DSM matrix and a components-functions DMM matrix. A set of these three matrices is generated for each alternative architecture.

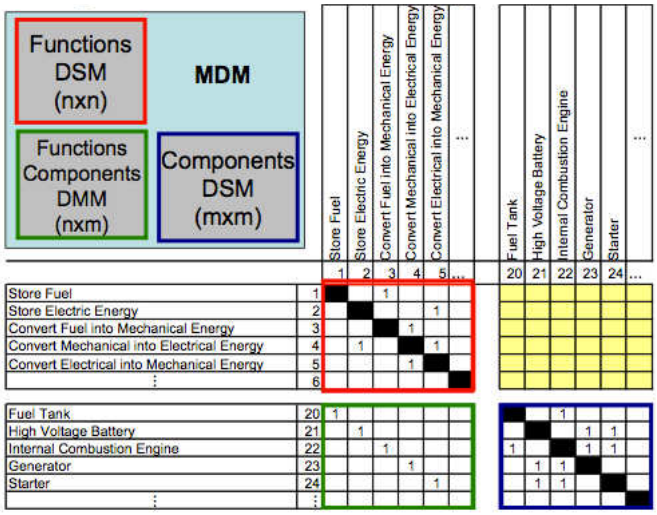


Figure 22: Gorbea's MDM (GORBEA, SPIELMANNLEITNER et al. 2008)

Basic matrix operations, such as addition and subtraction, are used to compare several matrices for each alternative adjunction of functions, components and their relations. The sum of MDM matrices enables the determination of components that are compatible with all architectures. The difference between two MDM matrices ("delta MDMs") is useful in comparing differences in the composition of two architectures.

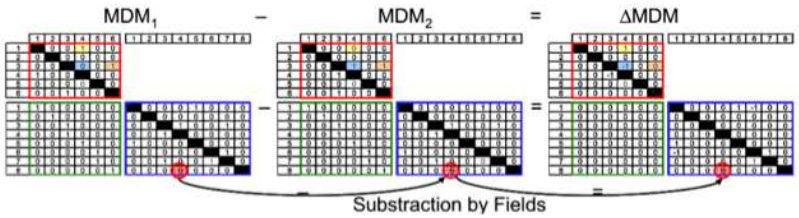


Figure 23: Delta MDMs

The sum of MDM matrices reveals patterns of which dependencies are always present between and amongst the component and function domains.

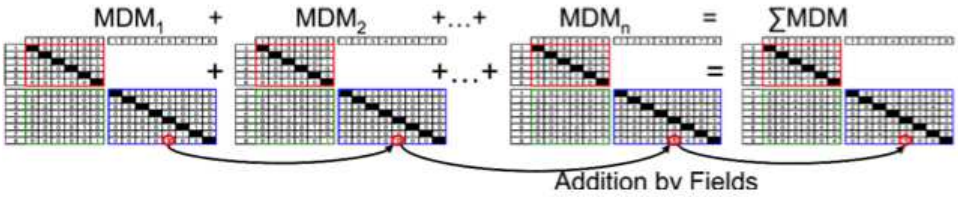


Figure 24: Sum of MDM matrices

Koh et al. (KOH, CALDWELL et al. 2009) propose an MDM matrix to model product components (see Figure 25), design features, and required attributes via five functional fields (SEEPERSAD, MADHAVAN et al. 2008). In Figure 25, Field A is given ratings of design features with respect to required attributes; these ratings can be acquired either through discussion or design databases. Subsequently, appropriate interaction ratings between design features are assigned to the opposite cells in field B. Field C maps design features to the appropriate product components. Then connections between components in field D are filled in.

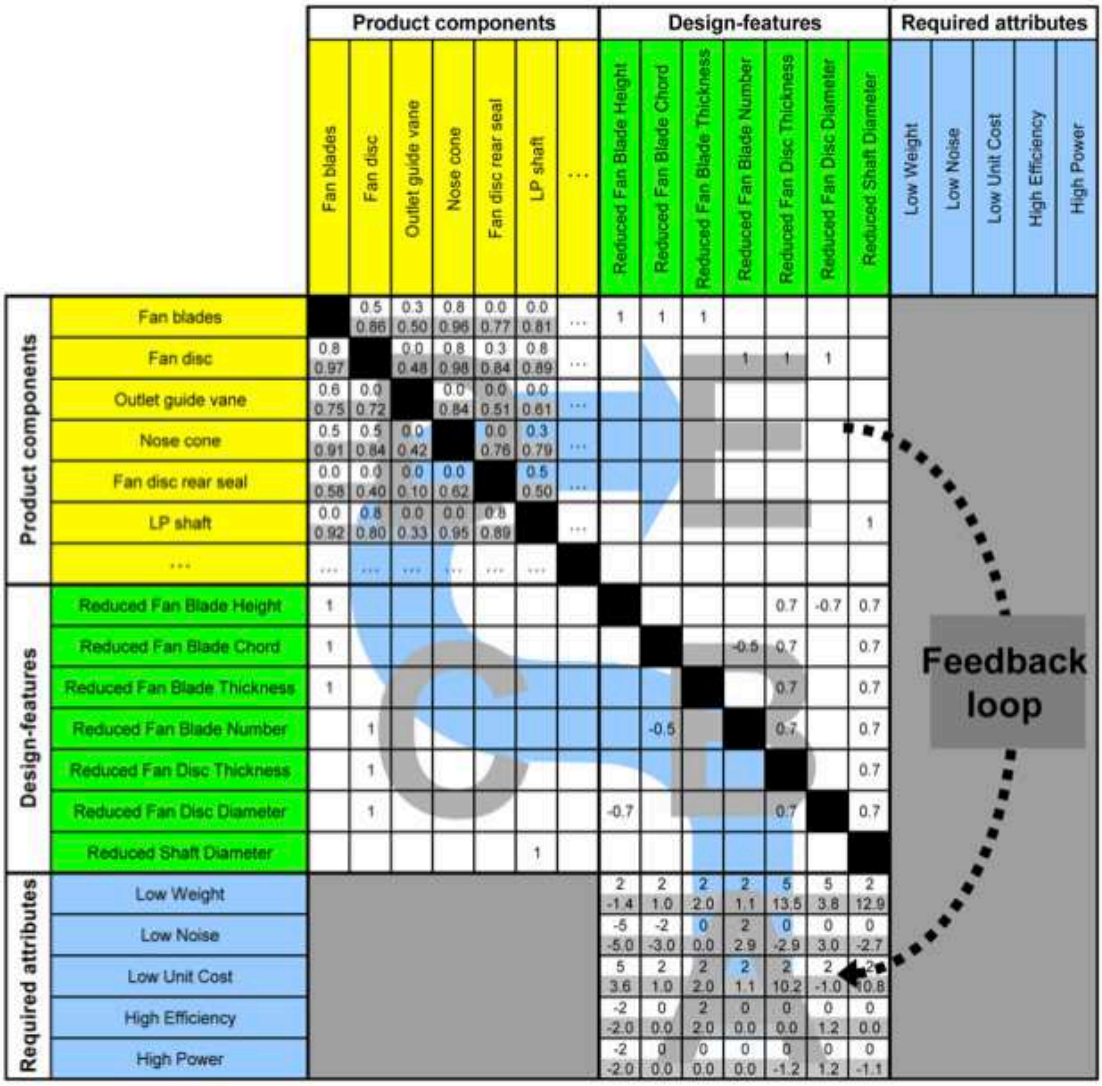


Figure 25: Koh et al. (KOH, CALDWELL et al. 2009) multiple domain matrix

The matrix is then computed using the Change Propagation Method. The computed results can then be used to support engineers in identifying critical areas and focus their discussion.

For product analysis and improvement, Maier et al. (MAIER, MOCKO et al. 2009) propose the affordance structure matrix as a tool to compare requirements information with physical structure in terms of affordances. An important difference between an ASM matrix and other similar matrices such as the house of quality and design structure matrices is the ability to distinguish whether relationships are helpful or harmful (+/-), not just existent or non-existent. The identification of helpful and harmful relationships enables additional metrics. In particular, the total number of components (or sub-systems) that are helpful with respect to each affordance can be calculated, as well as the total number of components (or sub-systems) that are harmful with respect to each affordance (MAIER, MOCKO et al. 2009).

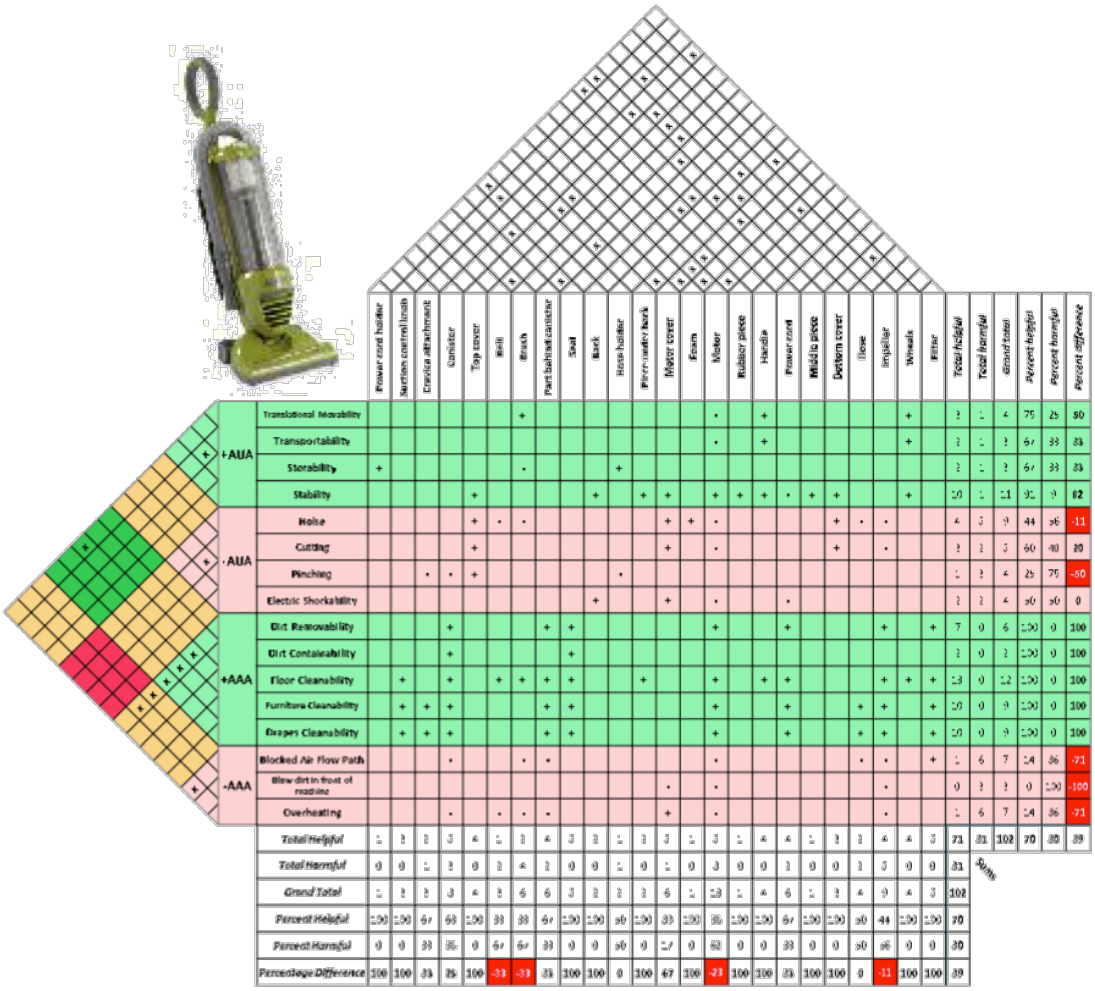


Figure 26: Affordance Structure Matrix (MAIER, MOCKO et al. 2009)

An affordance represents the gain for the user or an artifact without incurring other difficulties. Requirements are organized into four categories: positive artifact-user affordances (+AUA), negative artifact-user affordances (-AUA), positive artifact-artifact affordances (+AAA), and negative artifact-artifact affordances (-AAA). The interior of the ASM matrix is populated by considering whether each component has a helpful (+), a harmful (-), or no ( ) relationship with each affordance. The "roof" of the ASM matrix is a design structure matrix (DSM) that captures the relationships between components. The left side of the ASM matrix similarly captures the relationships between affordances.

3.3.4.2.1. Shortcomings of matrix-based methodologies

Kreimeyer et al. (KREIMEYER 2009) identify remaining shortcomings of matrix-based methodologies. The below shortcoming is outside the focus of their work.

- Matrix-based models are mostly designed as qualitative models and not as quantitative models.
- There has not been any systematic research to generate a catalogue of structural characteristics.
- There is no methodology to generate alternative structures, to compare them, and to generate an improved structure based on a common matrix-based description.
- Matrix notation is unable to accommodate complex conditional settings; even for static, non-conditional relations within a system, no notation supports the use of existing algorithms.
- The evolution over time remains unsolved, although many problems represented in matrices undergo changes, e.g., team structures; however, no real mechanism of evolution of a matrix has yet been found.
- The management of hierarchical decomposition within a cell is still difficult to consistently describe (DANILOVIC and BORJESSON 2001). Often, it is necessary to go into detail for a few cells only; while it is possible to zoom in to such a matrix within a single cell, no description is available for reinserting the multitude of relationships from the detailed view of the matrix cell into the higher-level matrix.
- The intuitive and graphical representation of MDM matrices is still unsolved. Diehl (DIEHL) proposes a 3D hyperplane visualization, but this is only applicable for small systems.
-

3.3.4.3. Comparison of graphical and matrix representations

Adjacency matrices or design structure matrices (DSM matrices) and node-link diagrams are both visual representations of graphs and are a common form of data in many disciplines (KELLER, ECKERT et al. 2006).

Keller et al. (KELLER, ECKERT et al. 2006) demonstrate that the main factors that influence the readability of DSM matrices are the size and density of the underlying graph structure, which significantly influence both response times and error rates of participants. They also demonstrate that experience and prior knowledge of a network have a great effect on how well users can read information from visual representation of a graph.

Finally, as shown in other studies, the work of Keller et al. (KELLER, ECKERT et al. 2006) confirms that node-link diagrams are better suited for reading information from small and sparse graphs and when assessing indirect paths between two nodes. Moreover, the most appropriate choice of representation depends on the detailed properties of the connectivity model and the specific task that needs to be carried out (KELLER, ECKERT et al. 2006).

3.3.5. Design indicators

Literature has defined several analysis criteria for collaborative design (LINDEMANN, MAURER et al. 2008). These criteria are used for the characterization of graphs in which connections between collaborators are called edges and the collaborators called nodes. Clusters with high dependencies are called subsets.

	Structural feature	Meaning
Graph Theory	Adjacency	Immediate neighboring of two nodes
	Connectivity	Integrity of the overall network
	n-partite-ness	Existence of distinct, disconnected groups within the networks
	Paths	Channels of navigation through the network
	Cycles	Paths that end at their start node
	Reachability	Existence of at least one path to another node
	Planarity	Representation of network with no edges crossing each other
DSM	Sequencing	Ideal sequence of nodes in flow-oriented network
	Tearing	Iterations that inhibit an ideal sequencing
	Banding	Groups of independent nodes
	Clustering	Mutually related nodes
Network Theory	Size	Extent of network
	Small World Effect	Existence of shortcuts across network
	Transitivity	Probability of connectedness of neighboring nodes
	Degree distribution	Existence of hubs and spokes in network
	Mixing patterns	Relation of clustering to further attributes of the network
	Navigation	Relevance of shortcuts in Small World Network
	Centrality	Integration of a node into functioning of the overall network
	Motifs	Fractal patterns across different levels of abstraction
Structural Characteristics (MDM)	Isolated node	Node that is disconnected from the network
	Leaf	Node that is connected via only one edge
	Transit edge	Edge that lengthens a path without adding structure
	Transit node	Node that is transited by a path without adding structure
	Bridge node	Node that connects two structural characteristics
	Splits/joins	Node with few-to-many correlation of adjacent edges
	Bus	Combined split and join
	Hierarchy	Set of reachable nodes from a given node
	Similarity	Set of nodes similarly connected to rest of the network
	Biconnected component	Set of nodes that can be reached via at least two paths
	Spanning tree	Representation of minimum necessary reachability of a network

Figure 27: Summary of features of structural analysis in different disciplines (KREIMEYER 2009)

3.4. Discussion

Set-based concurrent engineering is a useful improvement of the design process, especially in terms of its ability to control project objectives (time, cost, norms, and standards) and product achievements (technical objectives). But this approach remains problematic for multi-physics design team in three main aspects: 1) efficient mapping of the design space, which is not straightforward in multi-physics design due to complex dependencies, 2), product integration considered in terms of the intersection of its components, which is not straightforward in terms of multi-physics systems management without some type of methodological support, and 3) establishment of feasibility before commitment, which is difficult until the dimensioning of the entire system. The convergence of the design does not appear to be easy without tools to account for these three aspects.

Complex systems engineering addresses two interlinked fundamental characteristics. The first splits the process into interlinked tasks and organization of multidisciplinary teams involved in the design, while the second splits the product into interrelated components and the system relationship to its environment. We keep in mind some remaining challenges:

- ✓ The initial set of solutions should be mapped automatically to take advantage of the opportunity to find an excellent concept afforded by the combinatorial explosion,
- ✓ The dynamic generation of system configuration must be based on generic information (a mix of tacit and explicit knowledge),
- ✓ The design of local interactions at a system level. The robustness of complex systems surpasses a simple optimization of system parameters.

Interesting models exist for managing complexity: the axiomatic design used to map complexity between customer, functional, physical, and process domains and the Sinha et al. (SINHA) approach that maps physical domains with the introduction of interaction models and port type taxonomies. Complexity representation is proposed in the form of graphs or matrices, each of which has its advantages and disadvantages. The choice of the representation mode depends on the specific task that needs to be carried out. However, matrix-based methodologies have shortcomings we have already pointed out:

- ✓ Matrix models are mostly qualitative and not quantitative models
- ✓ There is no catalogue of structural characteristics
- ✓ There is no methodology to generate and to compare alternative structures in a common matrix-based description.

The behavior of individual engineers should be taken into account as the voice-of-the-designer analogous to the voice-of-the-customer. Modularity is a partial solution, i.e., breaking down the physics of the product in order to support this accounting for the behavior of individual engineers. The integration of multiple points of view is a difficulty in the collaborative design of complex systems. The confrontation of divergent points of view leads to design conflicts that must be managed. Typologies and methodologies for the solving of conflicts is well-defined in the literature. Confrontations are mostly seen through expression of viewpoints; to our knowledge, no method exists for the prediction of possible design conflicts.

Finally, we remain convinced that some improvements are needed for the design of complex systems. First, descriptions of architectures must integrate descriptions of interfaces. Second, the mapping of functions and structures must represent internal functional analyses, as should the mapping between functions and technical

performances. Third, the individual behavior of engineers should be represented as a point of view in the choice of concepts, which is not currently the case.

4. Experimental validation: power electronics controller case study

For further reference throughout this paper, this section presents a case study of the design of a power electronics controller (McMANUS and MILLARD) by a multi-disciplinary team. PEC projects are recurrent in the design of the product. The framework of this experimental validation resides in the initial solution set definition stage; the scope of the study is illustrated in Figure 29.

4.1. External Functional Analysis

The PEC studied is a regulator board used to generate the +3.3V and +1.9V power supplies for motor control and main controller boards. Figure 28 presents an external functional analysis of the system.

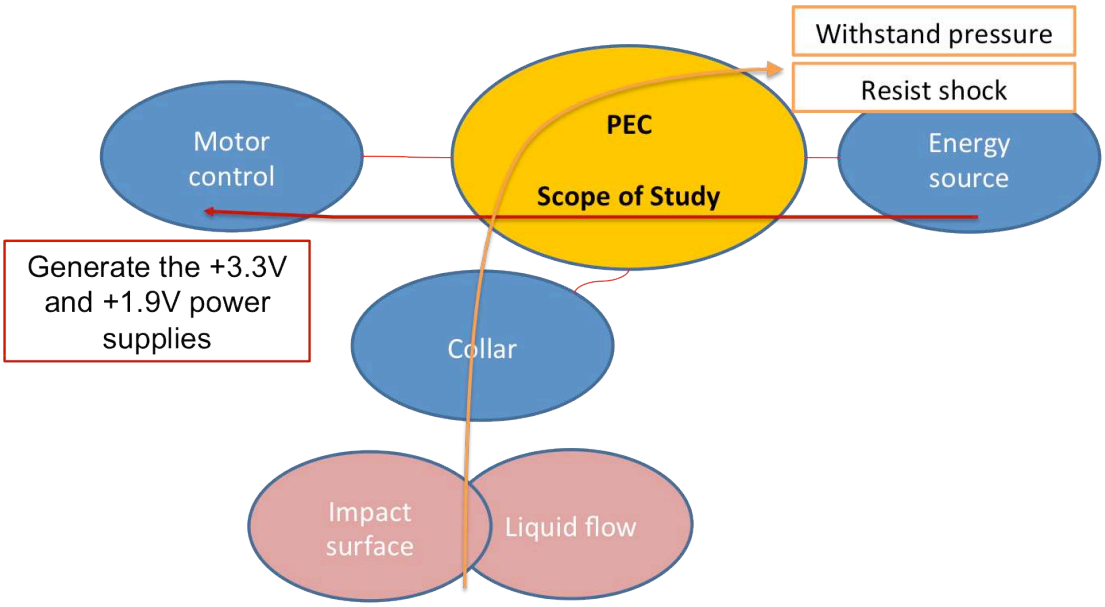


Figure 28: PEC external functional analysis

The "collar" is the product casing that contains the PEC. The design team identified two external environments: the impact surface (rock) against which the product experiences impact shocks and the liquid flow (the mixture of oil and mud) in which it operates. Pressure endurance and shock resistance are thus environmental constraints.

4.2. Structure breakdown

Based on the functional breakdown of the PEC, the team proposed the architecture shown in Figure 29.

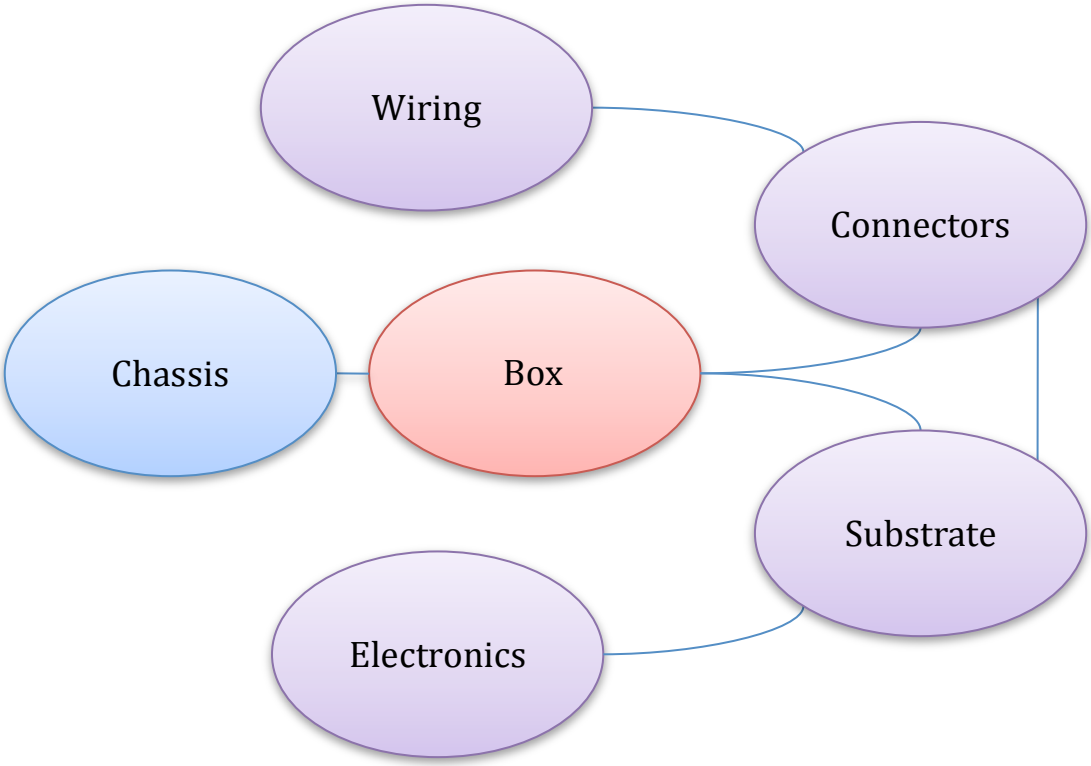


Figure 29: PEC architecture

The PEC is composed of a "substrate" supporting "electronics" components, both of which are contained in a "box". The PEC communicates with other systems (motor control and energy source) through "connectors" and "wiring". The box is mounted in a "chassis". The overall assembly is fixed in the "collar" - this part is outside the scope of our analysis. The design team mechanics group is in charge of designing the chassis, the packaging group designs the box, and the electronics group designs the other modules. Physical connections are represented by blue line links in the PEC structure breakdown (see Figure 29).

4.3. Internal functional analysis

Figure 30 represents the internal functional analysis of our PEC.

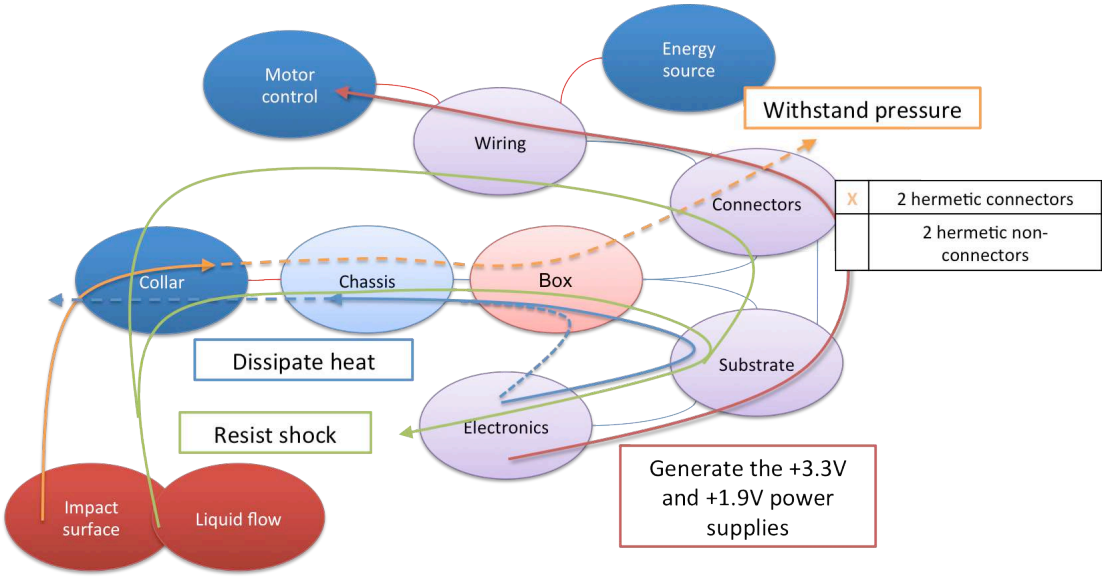


Figure 30: Internal functional analysis of PEC

The functional analysis is based on the research of Aoussat et al. (AOUSSAT, CHRISTOFOL et al. 2000). The function "generate power supplies" starts with "electronics", where regulated voltage is generated; +3.3V and +1.9V are sent to "motor control" via the "substrate", "connectors", and "wiring", in this order (see arrow in Figure 30). As the "electronics" generate power, there is a need for "heat dissipation": since electronics are the source of the heat, the "heat dissipation" function starts from "electronics". There are 2 solutions for this dissipation: either the function passes through the "substrate", the "box", and the "chassis" where it is then dissipated (see continuous arrow in Figure 30); or, depending on the chosen solution for the "chassis", it can go through the "chassis" and then be dissipated through the "collar". A parallel mode of heat dissipation may be considered in the case of both of the solutions just described: that induced by air flow against the "box", "chassis", or "collar" (see discontinuous arrow in Figure 30). The PEC must resist the surrounding liquid flow and, more specifically, must "withstand pressure". If the liquid flow remains outside the system by way of the "collar" (see continuous arrow in Figure 30), it is only the collar that must be pressure resistant; if the liquid flow enters the system, the "chassis", "box", and "connectors" must also be pressure resistant (see discontinuous arrow). The small table in Figure 30 indicates the incapability of the technical solution "2 hermetic connectors" to achieve the required pressure endurance. The PEC must also "resist shock" caused by the constant impacts against rock dealt to the "collar". Shocks are transmitted to the "electronics" via the "chassis", "box", and "substrate" (see arrow). Shocks are also propagated to "electronics" via the "wiring", "connectors", and "substrate" (see arrow in Figure 30).

4.4. Concept generation brainstorming

In the concept generation phase, one of the main steps is to organize innovation and feasibility workshops. Some of the concepts that were generated during brainstorming activities are represented in Figure 31.

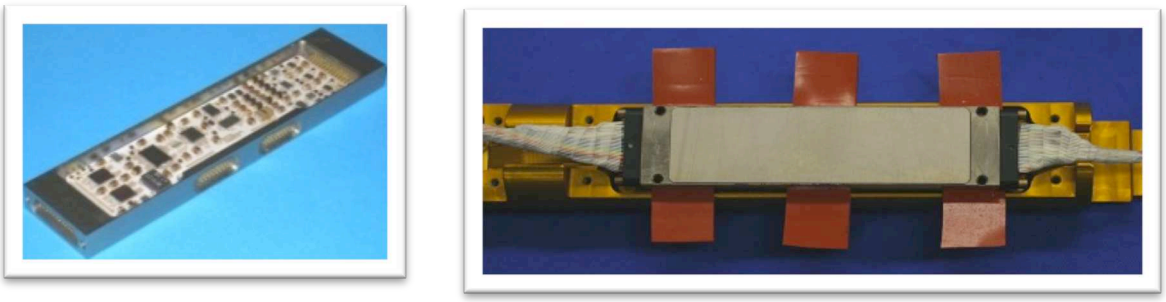


Figure 31: The PEC "HPHT" concept

Figure 31 (left image) represents the box (casing open) with the substrate and electronics components inside. Figure 16 (right image) shows the integration of the box with the chassis, wiring, and connectors. The chassis shown (yellow part in the image), represents the "I" technical solution (see Table 2) and the box represents the "HPHT" technical solution.

The third column of Table 3 lists possible technical solutions brainstormed during the design of the modules.

Table 3: Technical solutions proposed during brainstorming

Discipline	Module	Technical solution
Mechanics	Chassis	I
		Delta
		Pivot
		Reverse Delta
Packaging	Box	HPHT
		2 faces with box
		Pivot
Electronics	Electronics (parts)	(Singular solution: unnamed)
	Substrate	(Singular solution: unnamed)
	Connectors	2 hermetic integrated
		2 non hermetic integrated
	Wiring	(Singular solution: unnamed)

All of the illustrative matrices concerning the PEC design case study are necessarily incomplete and simplified since the purpose is not to exhaustively detail the PEC but to illustrate the design considerations and advantages of our proposed method.

5. Product structure modeling: integration of interface knowledge

Data collection represents the foundation of our approach and is necessary in order to obtain reliable analysis results. In this section, we introduce the defined data collection protocol used for filling in matrices and incorporating design risk lessons learned into the collaborative-FMEA (see Figure 32), in the MPDS method. In order to represent the global logic of the MPDS method, we use the following acronyms for the matrices that hold the data collected in the MPDS approach:

- FF-DMM (Functional Flow – Design Mapping Matrix),
- PC-DSM (Physical Connections – Design Structure Matrix), and
- VoDD (Voice of Design Department Matrix).

In this section we address the global process that is proposed for the MPDS method. The process is modeled using an SADT modeling language. Afterwards, we give the definition of each type of matrix, an explanation of their use in our approach, and a presentation of the data needed to complete them.

The data gathering must be broken into two stages: the gathering of project data and the incorporation of MPDS results in a Collaborative-FMEA. These two stages are connected through the connectivity maps that are further detailed in section 1. The objective of gathering project data is to model "functional analysis" and "concepts brainstorming" into three matrices: the FF-DMM, PC-DSM, and VoDD matrices, which will be used to generate six design assessment cards based on connectivity maps. Details and required data are given in Sections 5.1.1, 0, and 0. Incorporating the MPDS results in a C-FMEA is intended to quickly highlight collaborative design risks in the project. The six design assessment cards extracted from connectivity maps are used as an input.

5.1. Analysis of multi-physics concepts: data gathering

Multi-physics design scorecards use three matrices for the design concept analysis process and the concept evaluation: FF-DMM (functional flow – design mapping matrix), PC-DSM (physical connections – design structure matrix) and VoDD (voice of design department matrix). Data gathering for each of these three matrices is explained in this part of the document. The processes of analysis and assessment are presented in section 5 of this document.

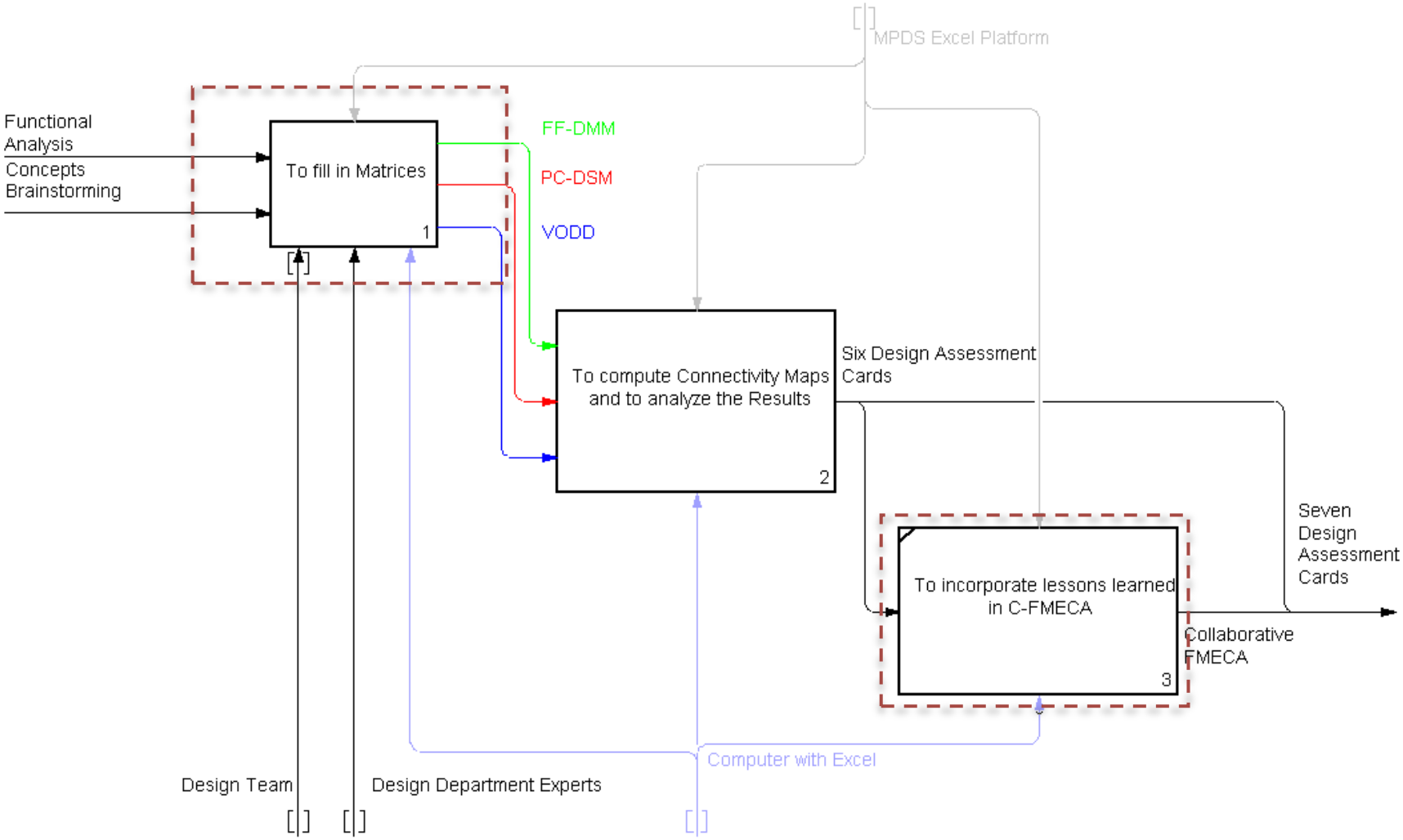


Figure 32: A1 SADT of MPDS method

5.1.1. Integration of client needs into product functions and architecture

The FF-DMM matrix is a cross functional flow and architecture mapping matrix populated with data retrieved from the functional analysis performed earlier in the MPDS process. It uses a DMM matrix format that is enriched with the integration of a functional flow. The data model ontology employed in the use of the FF-DMM matrix is presented in Figure 17 using the unified modeling language (UML) model. The following introduces the UML objects used in the diagram (Figure 17):

- *Design Team* represents the team in charge of the design of the product. It is identified by its project name and its project chief name.
- *Product* represents what the design team must design to achieve client needs. It is identified by a concept name.
- *Design Department* represents the department in charge of the design of a module of the system. The design department is identified by its name and its area of expertise.
- *Function* defines both what the product must do to meet client requirements (main functions) and what it must do to stay in working condition (service functions). Functions are characterized by a name and a utility. The utility corresponds to the goal of the function (whatever the client needs or the function needs to keep the system in working condition).
- *Functional Flow* represents functional flows through the architecture of the product. Function chains are sensitive to the order of deployment of functions from one module to another module.
- *Module* designates a part of the system that must exist in order to perform a function. Each module has a name.
- *Technical Solution* represents a potential solution to the design of a module. Each technical solution is assigned a name.

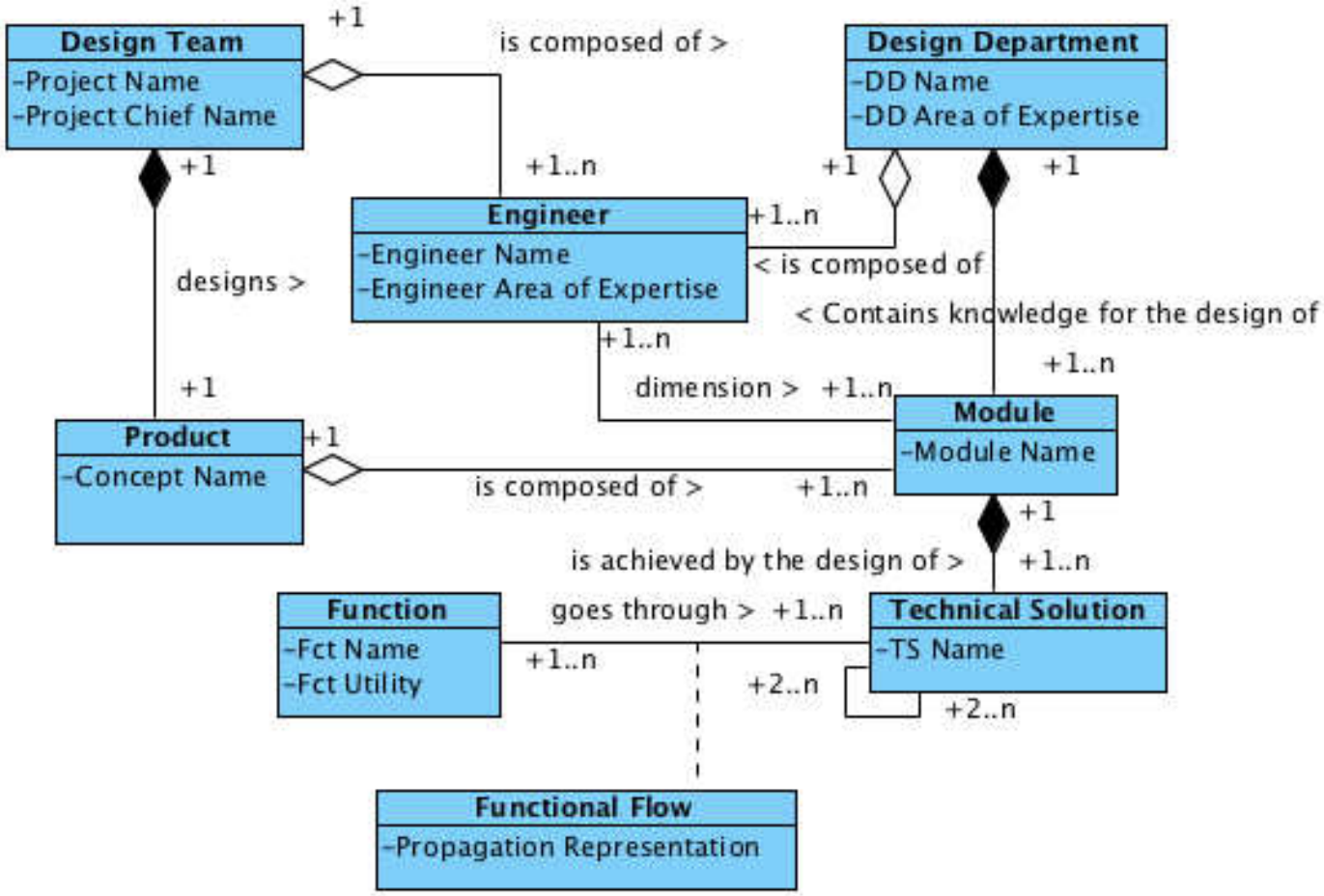


Figure 33: FF-DMM Model Ontology

The design team is composed of as many engineers as necessary to cover all of the domains required by the project. Therefore, the *Design Team* class has an aggregation relationship with the *Engineer* class. As a design team is in charge of the design of a product, the *Design Team* class has a composition relationship with the *Product* class.

As such, the *Design Team* class has an aggregation relationship with the *Engineer* class. An engineer is defined by a name and an area of expertise. As an engineer dimensions modules and collaborates on the design of physical connections, the *Engineer* class has an association relationship with the *Module* class and the *Physical Connection* class.

The design department is composed of engineers and experts representing areas of expertise required for the design of one or several modules. It is in charge of the module, which is dimensioned by engineers and whose performance is evaluated by experts. As such, the *Design Department* class has aggregation relationships with the *Module* class, the *Engineer* class, and the *Expert* class.

The product is broken down into modules. Therefore, the *Product* class has an aggregation relationship with the *Module* class.

A module's objectives are achieved by the design of technical solutions. Therefore, the *Module* class is an aggregate class composed of the *Technical Solution* class. The *Module* class has an association relationship with the *Engineer* class, as engineers design modules.

A function is defined to satisfy client need. The *Function* class has an association relationship with the *Technical Solution* class through the association class *Functional Flow*. The *Functional Flow* class is defined by its propagation representation, which is a representation of the propagation of functional flows via technical solutions. It expresses the contribution of the *Technical Solutions* class to the realization of the *Function* class.

Figure 34 shows the interaction of the FF-DMM matrix with the other two matrices and how it is built based on data extracted from the functional analysis and the concepts brainstorming.

Any team member can construct the FF-DMM matrix after the functional analysis and concepts brainstorming. The main results of the functional analysis are functions defined by names and functional flows. The principal results of the concepts brainstorming are concepts defined by modules and technical solutions.

The data collection process for the FF-DMM matrix, represented in Figure 35, is as follows:

1. Add function names to the matrix ("1" in Figure 35).
2. List technical solutions (e.g., "I", "delta", "pivot") below their modules (e.g., "chassis"), see "2" in Figure 35.
3. Assign a color to each design department, and use it to shade in the name of the module it designs (in Figure 35, each design department is assigned a color).
4. Fill in the body of the matrix ("3") with the results of the functional analysis (rules for filling in the body of the matrix are explained after Figure 36).

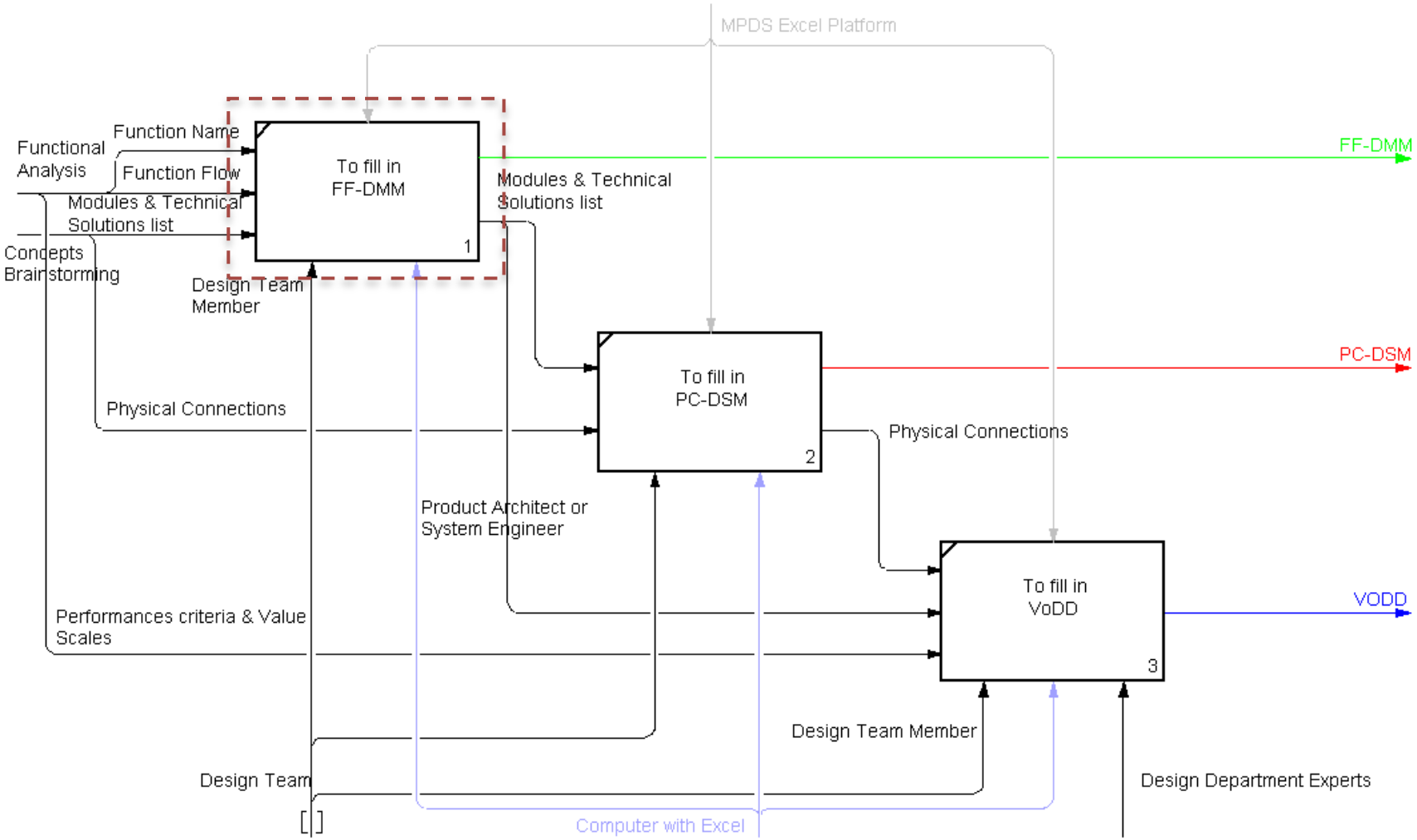


Figure 34: A11 SADT of MPDS method

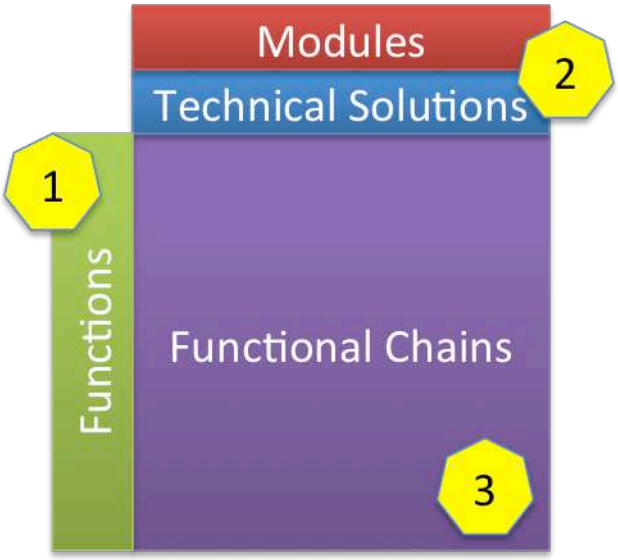


Figure 35: FF-DMM formalism

Functions are expressed in rows ("1" in Figure 35); modules and their technical solutions are expressed in columns ("2"). The data contained in the matrix ("3") presents the potential correlation between the technical solutions, which represent the architecture, and the functions. Functional flows are described by horizontally filling in boxes with a number. The number designates the order of deployment of the function through each of the technical solutions.

	Chassis				Box			Connectors		Collar	Substrate	Electronics	Wiring
	I	Delta	Pivot	Reverse Delta	HPHT	2 faces with box	Pivot	2 hermetic integrated	2 non-hermetic integrated	Basic			
Generate power								3	3		2	1	4
Withstand pressure										1			
					1	1	1	1					
Dissipate Heat	4	4	4	4	3	3	3				2	1	
										5			
	3	3	3	3	2	2	2			4			
Resist shock (X)								3	3	1		5	2
	2	2	2	2	3	3	3				4		

Figure 36: PEC FF-DMM matrix

We present an example of four functions specific to the PEC (Figure 36):

"Generate power" is a function going from electronics (indicted by a numeral "1" in the first row of Figure 36), where power is regulated, to substrate ("2"), then to connectors ("3"), and then to wiring ("4"), where motor control is connected; there are no other possibilities to achieve this function even in the case of the other concepts.

The constraint function “withstand pressure” can have two alternative paths depending on the concepts selected: pressure can be applied on the box and on the connectors or on the collar. Functional flow alternatives are represented in parallel rows: pressure applied to the collar is noted with a single numeral “1” in the corresponding module, and pressure applied to the box and connectors is indicated, in another row, with the numeral “1” in both the box and connectors modules (the “2 non-hermetic integrated” connectors field is unmarked because they cannot withstand/endure pressure, as noted in section 4.3).

Experiments carried out by engineers on this project showed that shocks have two different propagation pathways within the PEC. Therefore, the function “resist shock” has two different functional flows. In both cases, shocks propagate from the collar (indicated in a merged field by a numeral “1” in the final two rows of Figure 36) to electronics (“5”). Based on internal functional analysis (see Figure 30), shocks can either propagate through the chassis (“2”), box (“3”), and substrate (“4”) or, as indicated in another matrix row, through wiring (“2”) and connectors (“3”).

“Dissipate heat” is the most complex function to represent with an FF-DMM matrix, because it has aspects of both parallel and alternative functions (see Figure 30), depending on the concept selected. In any case, this function starts from electronics (indicated in a merged field by a numeral “1” in Figure 36). Then it can be propagated in parallel through the box (“2”) and the chassis (“3”), where it can either be evacuated or it can go into the collar (“4”) before it is dissipated. Or the function can be propagated through the substrate (“2”), box (“3”), and chassis (“4”), where it can either be evacuated or it can go into the collar (“5”) before it is dissipated.

Aside from capturing data from experts regarding the different concepts, the FF-DMM matrix also aims to validate the capacity of different brainstormed concepts to satisfy the functions requested by the client. For example, a concept composed of a “pivot” type box and “2 non-hermetic integrated” connectors cannot achieve the function “withstand pressure” when mud enters through the collar (the second row of the function “withstand pressure” in Figure 37).

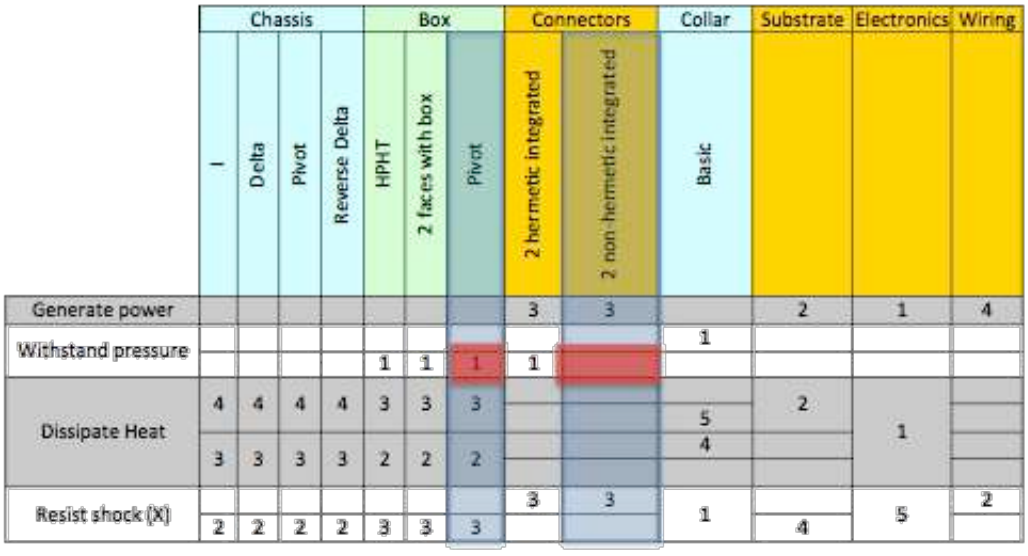


Figure 37: Functional ability of initial set of concepts presented in the FF-DMM matrix

Rows and columns can easily be added to the FF-DMM matrix in order to track project progress and change. In order for the FF-DMM matrix to remain clear and as simple as possible to understand, columns are hidden according to the convergence of the initial

set of concepts. A part of the matrix can be extracted by a given design department, for more precise analysis of its own objectives, and then brought back to the original FF-DMM matrix with more details.

5.1.2. The high-level architecture description as result of design team brainstorming

The PC-DSM matrix summarizes possible physical connections in different concepts based on their typology. The data gathering is based upon "rule-based formalism". The matrix is linked to the data model for physical connections. This data model contains expert knowledge concerning different design parameters influencing the architecture and the correlation of these parameters. The ontology representing this data model is shown in Figure 21:

- *Design Team* represents the team in charge of the design of the product. It is identified by its project name and its project chief name.
- *Product* represents what the design team must design to achieve client needs. It is identified by its name.
- *Design Department* represents the department in charge of the design of a module of the system. The design department is identified by its name and its area of expertise.
- *Module* designates a part of the system that must exist in order to perform a function. Each module has a name.
- *Physical Connection* describes assembly between technical solutions that have the possibility of being physically assembled. It has a name and a type and is associated with an area of expertise, a data model, and the person who designs it.
- *Technical Solution* represents a solution to the design of a module. It has a name.

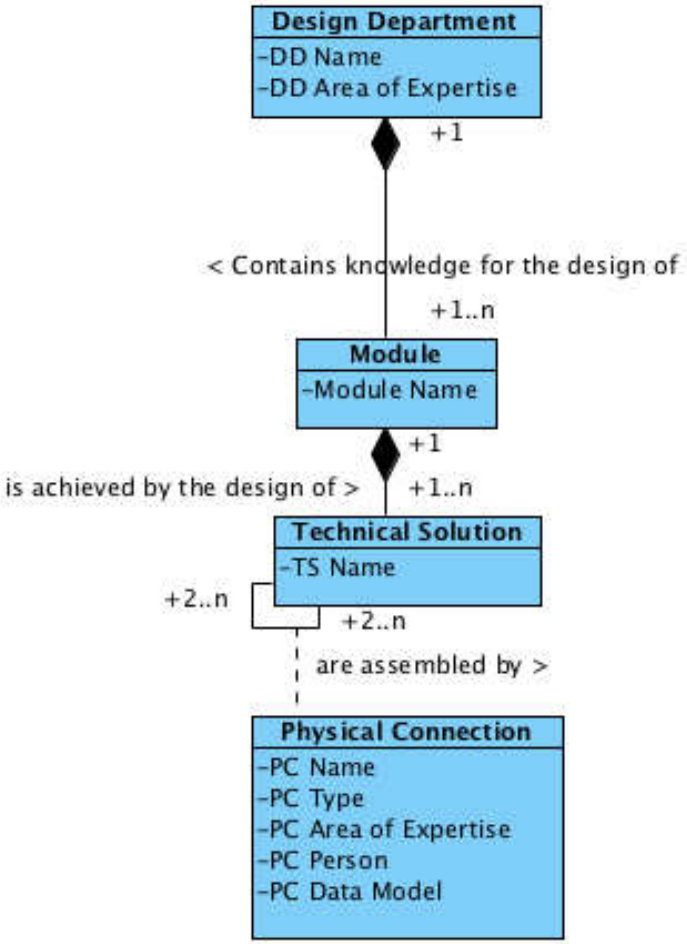


Figure 38: PC-DSM Model Ontology

The design department is composed of engineers and experts representing the areas of expertise required for the design of one or several modules. It is in charge of the module, which is dimensioned by engineers and whose performance is evaluated by experts. As such, the *Design Department* class has aggregation relationships with the *Module* class, the *Engineer* class, and the *Expert* class.

A module's objectives are achieved by the design of technical solutions. Therefore, the *Module* class is an aggregate class composed of the *Technical Solution* class. The *Module* class has an association relationship with the *Engineer* class, as engineers design modules.

An assembly of technical solutions constitutes a concept. The *Technical Solution* class has an association relationship with itself through the *Physical Connection* class. The physical connections represent every possible mating pair of technical solutions. A technical solution fulfills a module's requirements by satisfying the technical performance criteria of the associated function(s). Therefore, the *Technical Solution* class has an association relationship with the *Function* class and an aggregation relationship with the *Technical* Performance class.

Figure 39 shows the interaction of the PC-DSM matrix with the two other matrices and how it is built based on data extracted from the concepts brainstorming.

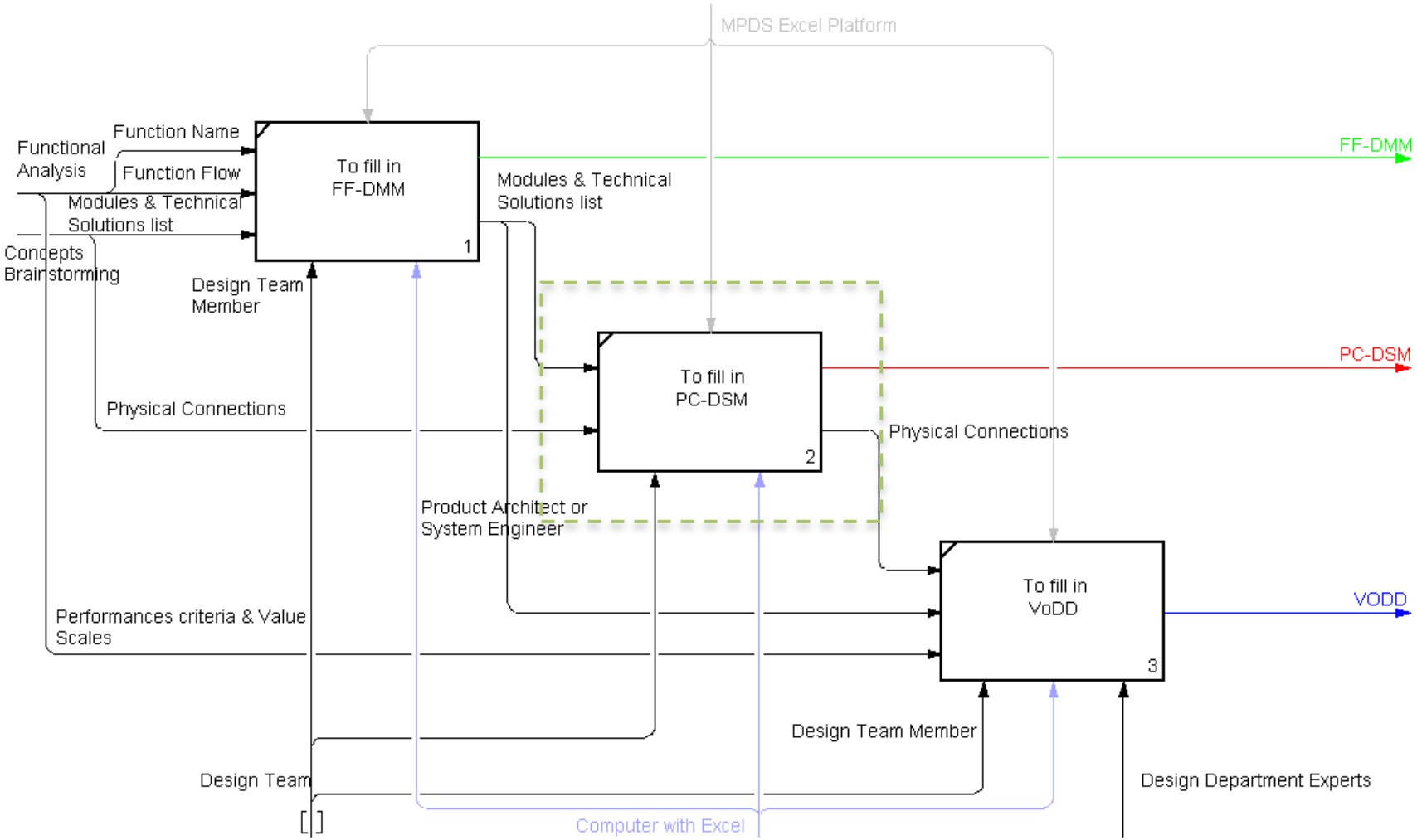


Figure 39: A11 SADT of MPDS method

The product architect or system engineer must fill in the PC-DSM matrix during the concepts brainstorming session done with the design team. The principal results defining concepts with named modules and technical solutions are automatically imported from the FF-DMM matrix into the PC-DSM matrix.

We propose the following process in order to populate the PC-DSM matrix (see Figure 22):

0. Module and technical solution names imported from the FF-DMM matrix are automatically filled in by the MPDS platform (see "0").
1. Fill in physical connections describing the brainstormed concepts as well as all physical connections possible between two or more independent technical solutions not part of the brainstormed concepts (see "1").

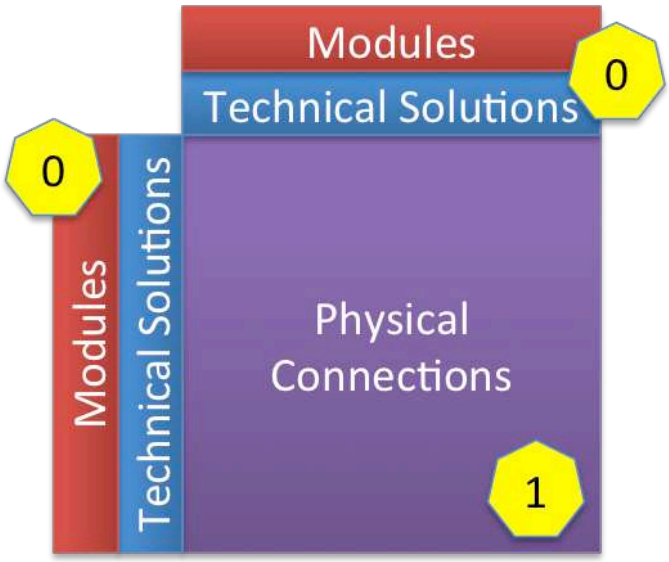


Figure 40: PC-DSM formalism

Both rows and columns ("0" in Figure 40) list modules and their technical solutions (concept breakdowns as well as other possible alternatives). The PC-DSM matrix is symmetric. Data concerning physical connections represent the body of the PC-DSM matrix ("1" in Figure 22). The rule-based formalism used to describe connections and alternatives is as follows:

- An alternate way (OR) to assemble two technical solutions is described by letters separated by a comma: "XX, YY".
- An association (AND) of two physical connection types in one physical connection is described by letters separated by a comma, all enclosed in brackets: "{XX, YY}".
- Both alternate and associative types of assembly are described by letters separated by a semicolon: "XX; YY".

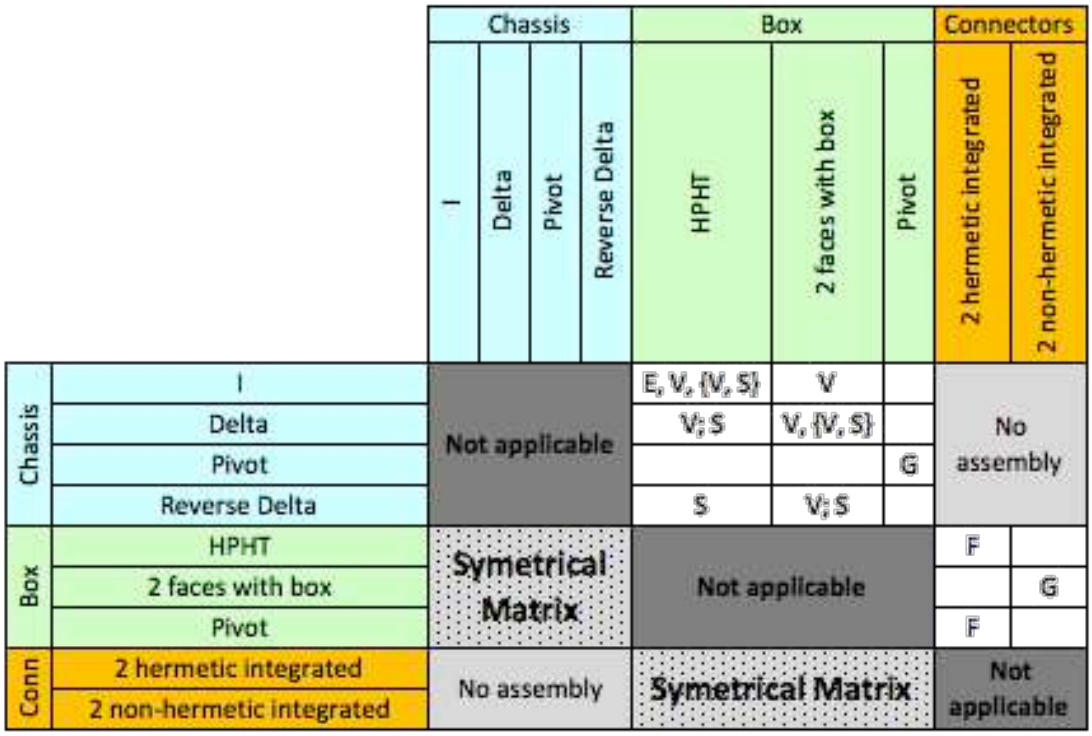


Figure 41: PEC PC-DSM matrix

Cells that read “Not applicable” in Figure 23 stress that it is not possible to assemble two technical solutions of the same module. “No assembly” cells indicate modules that are not physically connected.

Letters given in the matrix characterize physical connections:

- “E” means an elastomeric physical connection between the two technical solutions: in this case, the “I” chassis and “HPHT” box
- “V” represents physical connection by screws
- “S” corresponds to silicon
- “G” corresponds to glue
- “F” represents fitting

Thus, the cell entry that is the intersection of “I” chassis with “HPHT” box, filled in with “E, V, {V, S}”, describes the three possible types of physical connections between these technical solutions. The “E” corresponds to an elastomeric physical connection, the “V” to a physical connection by screws, and the “{V, S}” to the combination of screw and silicon physical connections.

Rows and columns can easily be added to the PC-DSM matrix as the design converges to detailed low-level technical solutions. The PC-DSM matrix remains clear and as simple as possible to understand by hiding columns in function of the convergence of the initial set of ideas.

5.1.3. Deployment of design department constraints through technical performance analysis

A multi-physics design process also requires the ability to identify potential design conflicts and find compromises. In order to achieve this, the Voice of Design Department (VoDD) matrix gathers data concerning design constraints and correlations between technical performances. The data model and related ontology is represented in Figure 24:

- *Design Team* represents the team in charge of the design of the product. It is identified by its project name and its project chief name.
- *Product* represents what the design team must design to achieve client needs. It is identified by its name.
- *Design Department* represents the department in charge of the design of a module of the system. A design department is identified by its name and the names of its engineers.
- *Design Team* groups the engineers collaborating on the design of the system (all modules). The design team is associated with the project name and the engineers' names.
- *Engineer* defines the person in charge of the design of a module. An engineer has a name and is associated with an area of expertise.
- *Moderator* represents the person in charge of data from the expert evaluations. It is identified by its name.
- *Evaluation* represents evaluations of technical performance criteria based on value scales. An evaluation is identified by a technical performance criterion name and a technical solution name.
- *Expert* refers to the person who evaluates technical performance. An expert has a name and is associated with area of expertise.
- *Module* designates a part of the system that must exist in order to perform a function. A module has a name.
- *Technical Performance* refers to technical performance criteria expected to be fulfilled in the evaluation of the product, a function, a module, or a technical solution. Independent technical performance scores are listed for each of these. A technical performance criterion has a name.
- *Technical Solution* represents a design solution for a module. A technical solution has a name.
- *Value Scale* contains the value scales for the evaluation of technical performance criteria. A value scale is specific to the technical performance: the technical performance has its own value scale for its evaluation. A value scale is attached to a technical performance criterion name, numerical values, and a value description.

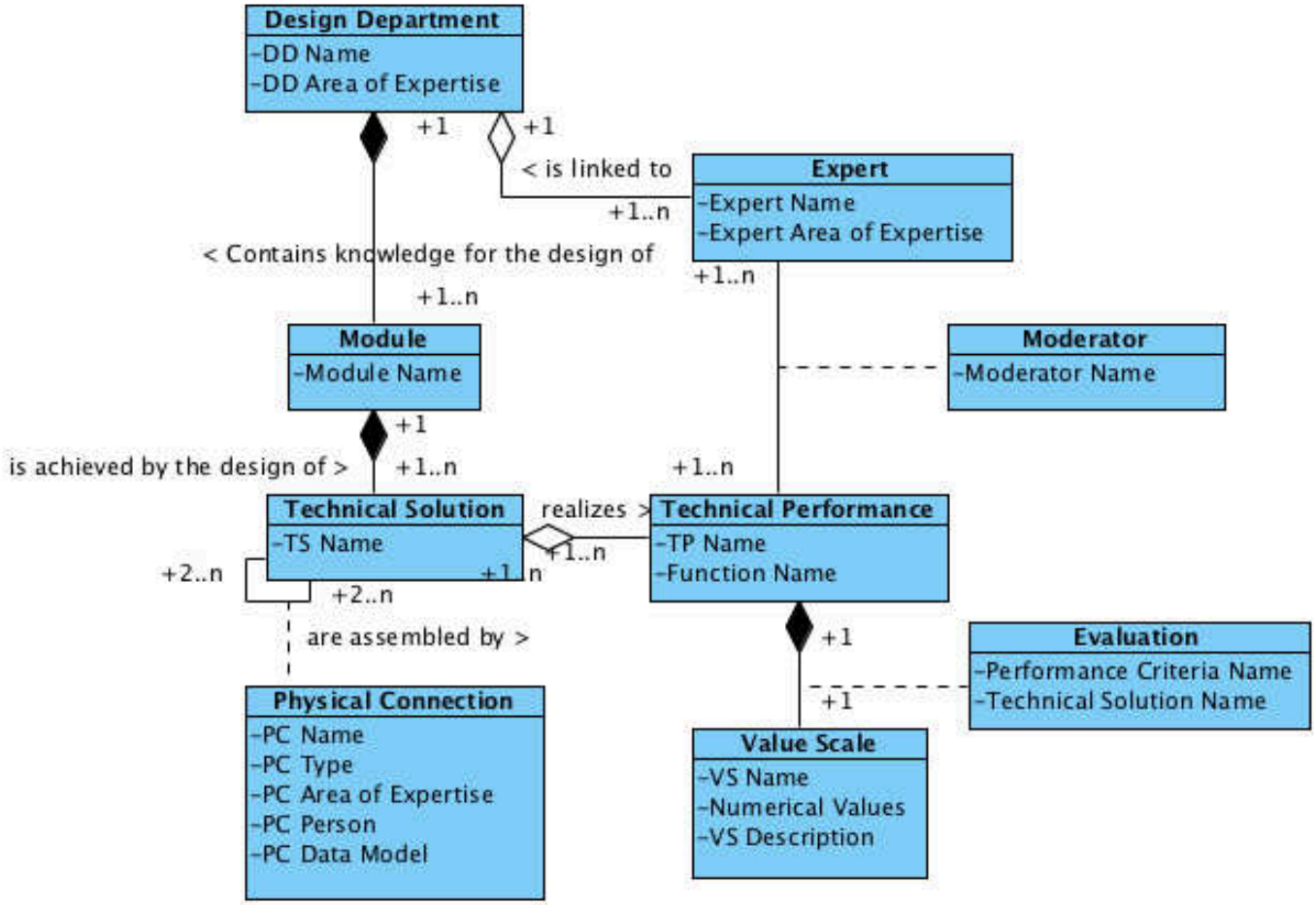


Figure 42: VoDD Model Ontology

The design department is composed of engineers and experts representing areas of expertise required for the design of one or several modules. It is in charge of the module, which is dimensioned by engineers and whose performance is evaluated by experts. As such, the *Design Department* class has aggregation relationships with the *Module* class, the *Engineer* class, and the *Expert* class.

A module's objectives are achieved by the design of technical solutions. Therefore, the *Module* class is an aggregate class composed of the *Technical Solution* class. The *Module* class has an association relationship with the *Engineer* class, as engineers design modules.

An assembly of technical solutions constitutes a concept. The *Technical Solution* class has an association relationship with itself through the *Physical Connection* class. The physical connections represent every possible mating pair of technical solutions. A technical solution fulfills a module's requirements by satisfying the technical performance criteria of the associated function(s). Therefore, the *Technical Solution* class has an association relationship with the *Function* class and an aggregation relationship with the *Technical* Performance class.

Experts evaluate technical performance. Therefore, the *Expert* class is in an association relationship with the *Technical Performance* class.

The moderator drives the brainstorming session during which experts debate about technical solutions evaluations. As such, the moderator has an association relationship with experts. The moderator is defined by a name.

Technical performance evaluates both the realization of functions and advantages of technical solutions. Thus, the *Technical Performance* class is an aggregate class composed of the *Technical Solution* and *Function* classes.

The value scale is intended to support the evaluation of technical performance by giving references. The *Value Scale* class has a composition relationship with the *Technical Performance* class. A value scale is defined for each technical performance criterion. The value scales cover the full range of technical performance values that might be attained by the concepts.

Figure 43 shows the interaction of the VoDD matrix with the other two matrices and how it is built based on data extracted from the functional analysis and the concepts brainstorming.

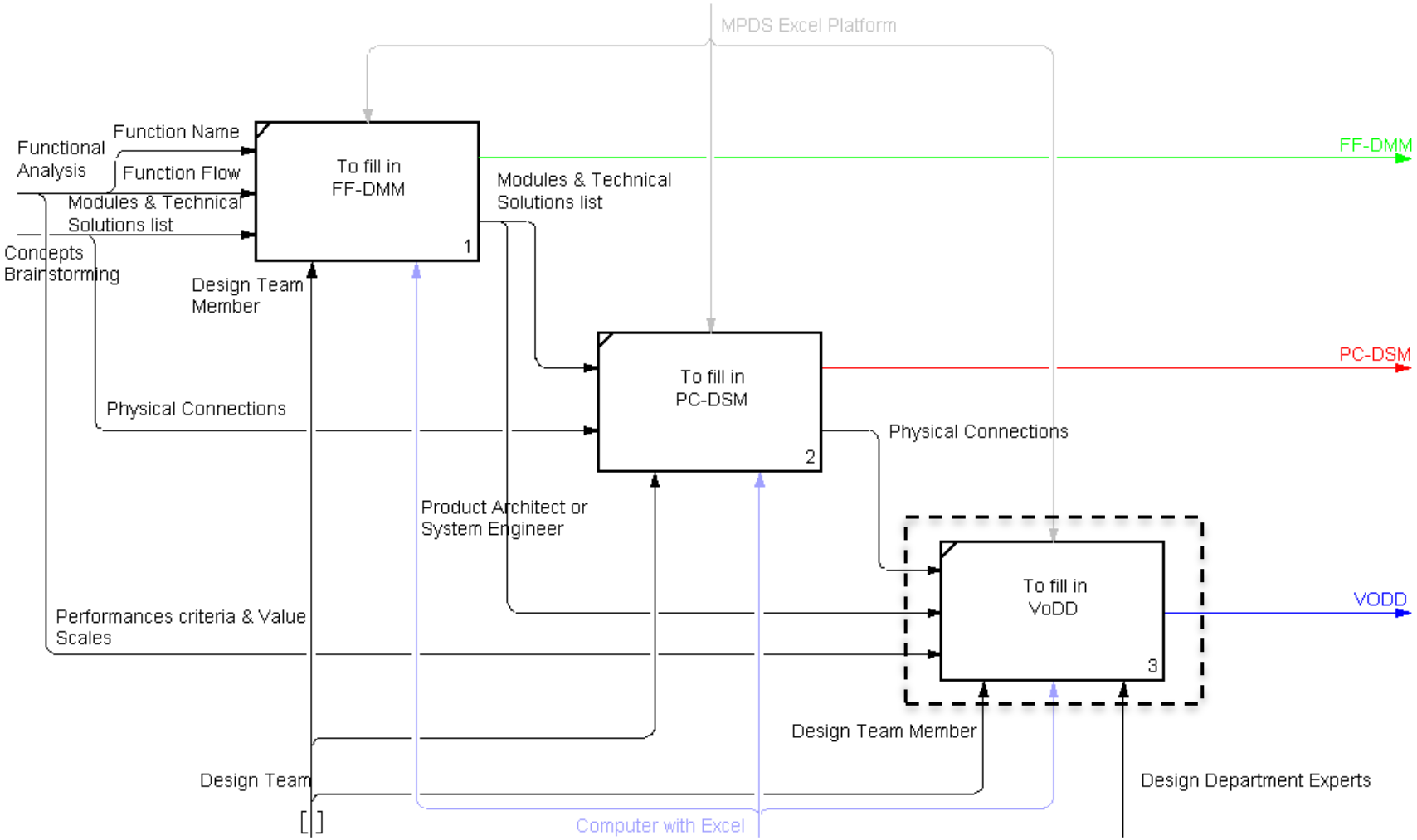


Figure 43: A11 SADT of MPDS method

Design team members and design department experts collaborate to populate the VoDD matrix with data extracted from the functional analysis, the FF-DMM matrix, and the PC-DSM matrix. The results used from the functional analysis are defined functions with identified technical performance criteria and value scales. The data extracted from the FF-DMM and PC-DSM matrices are defined concepts with modules, technical solutions, and physical connections.

We propose the following process in order to fill in the VoDD matrix represented in Figure 44:

0. Modules, technical solutions ("0a"), and their physical connections ("0b") are automatically filled in based on the PC-DSM matrix.
1. List technical performance criteria ("1") that permit evaluation of functions as well as differentiation of technical solutions.
2. Define value scales for the technical performance criteria of each function.
3. Fill in the body of the matrix ("2") with experts' evaluation of technical solutions' contribution to technical performance. In order to capitalize on the experts' discussions, we recommend documenting the workshop via audio and video recordings (this is further detailed later in this section).
4. Fill in the correlation between the technical performance criteria ("3").
5. Define a min, max, avg, or sum function ("4") for technical performance of the concept.

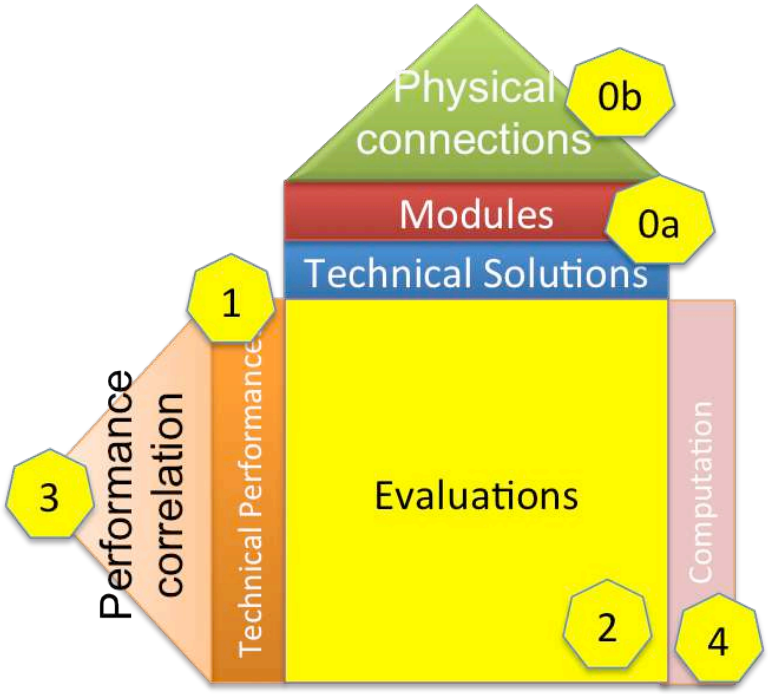


Figure 44: VoDD matrix

Columns correspond to modules and their technical solutions ("0a" in Figure 44). Rows list the technical performance expected in order to evaluate functions as well as to differentiate each technical solution ("1"). The contribution of technical solutions to the fulfillment of technical performance criteria represents the body of the matrix in the form of scale-based evaluations ("2"). Evaluation scales are defined and adapted for the technical performance criteria associated with each function. In general these value scales are set so that the highest value of the scale corresponds to the target set by the project. The left side of the VoDD matrix ("3") defines the correlation between technical performance criteria, either positive or negative:

- "+1" describes a positive correlation between the two technical performance criteria,
- "0" means that technical performance criteria are not influencing each other,
- "-1" corresponds to a negative correlation.

The right side of the matrix ("4") specifies the manner of evaluating a function, based on evaluation of the technical performance of the associated concepts. Each technical performance is associated with one of the following:

- "Min" indicates that the technical performance of the given concept is defined by the minimum value of the contribution of its technical solutions.
- "Max" indicates the maximum value of its contribution to technical solutions.
- "Avg" indicates the average value of its contribution to technical solutions.
- "Sum" indicates the sum of its contribution to technical solutions.

The top of the matrix ("0b") contains data regarding the assembly of technical solutions extracted from the PC-DSM matrix. This automated extraction leads to a choice among {0, 1, *void*} for any matrix intersection:

- "0" represents no physical connection possible between two technical solutions,
- "1" corresponds to a possible assembly between them, whatever the typology of the connection,
- A void entry corresponds to technical solutions that are not connected.

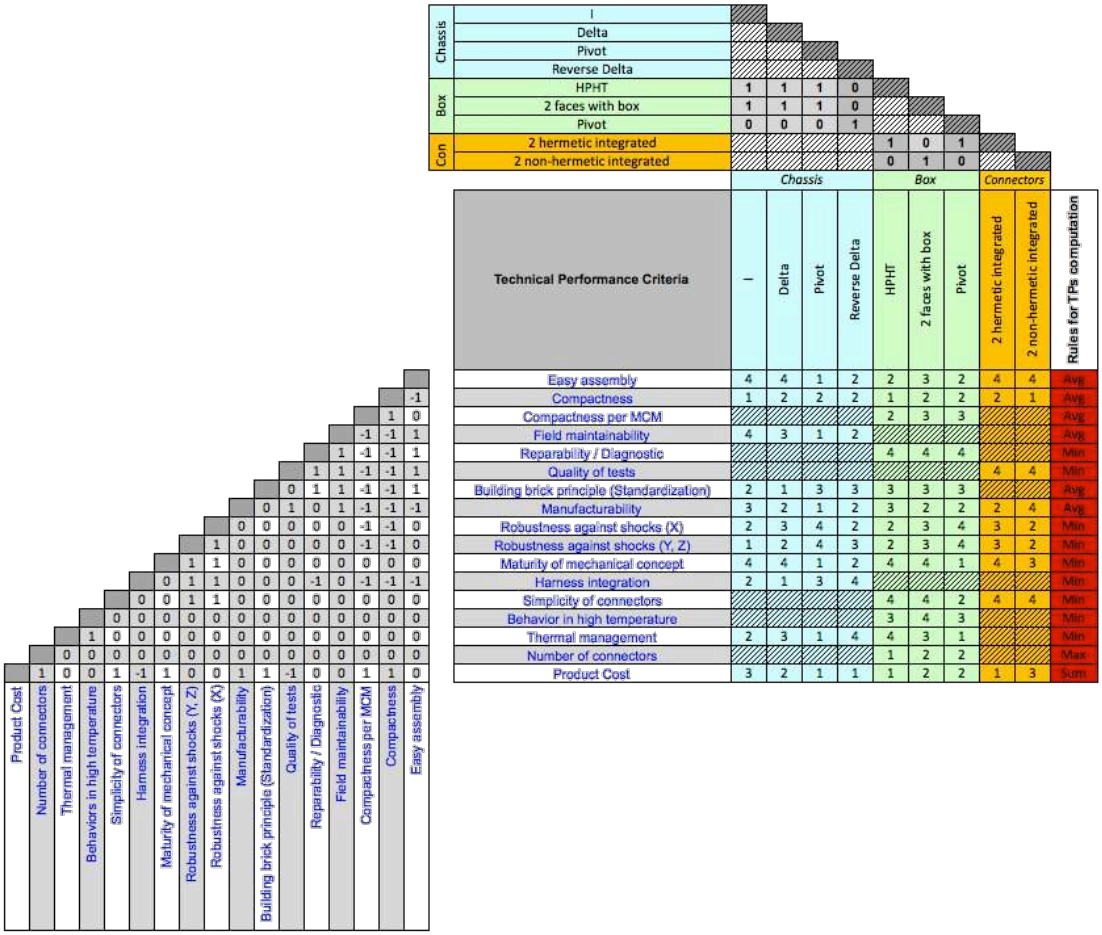


Figure 45: PEC VoDD matrix

We provide some examples from the PEC to fill in region "2" as indicated in Figure 44. There are two types of technical performance: one that gives a basis for evaluation of a function and one that highlights particular advantages of a given technical solution; both types can be either qualitative or quantitative.

"Robustness against shocks (x-direction)" is a technical performance criterion evaluating the function "resist shock", broken into a four-point qualitative scale:

- "1" means that shocks over 1G are not tolerated
- "2" means that shocks over 5G are not tolerated
- "3" means that shocks over 10G are not tolerated
- "4" means that shocks over 15G are not tolerated

In contrast, the technical performance criterion "number of connectors" is used to point out an advantage of a technical solution based on a quantitative scale:

- "1" indicates the need for 4 connectors
- "2" indicates that the need for 2 connectors
- "3" that only one connector is needed
- "4" indicates that the box has no connector

We recommend capturing audio and video recordings of the experts' debates, which are the basis for data extraction to populate the VoDD matrix. This makes it easier to verify the exhaustiveness of the data gathered and of the verification process. It is also recommended that experts evaluate technical solutions by comparing all possible technical solutions in a given module against one technical performance criterion (see Figure 46). For instance, the "chassis" module has been evaluated to find that its technical solution "pivot" (given a "4") is more "robust against shocks (x-direction)" than "delta" (given a "3") and than "I" and "reverse delta" (both given a "2").

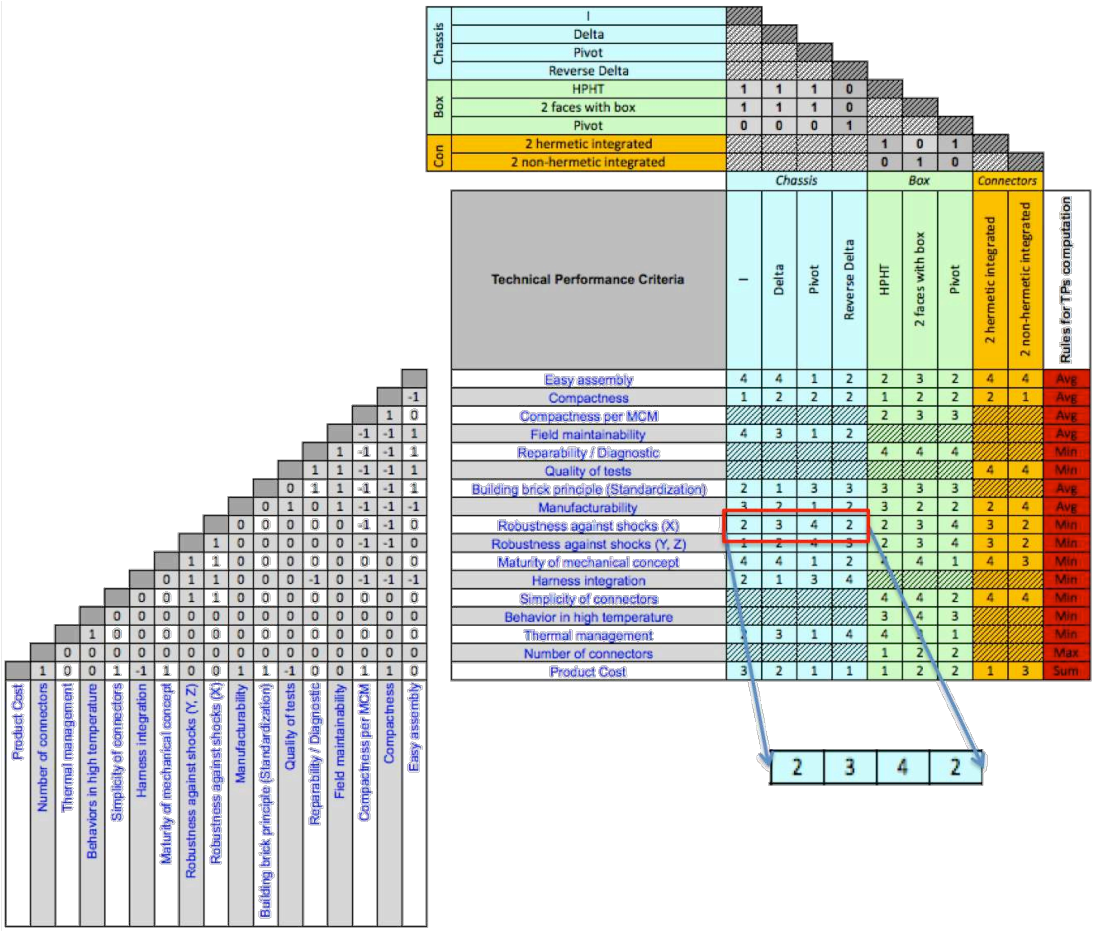


Figure 46: VoDD matrix expert validation example

The Voice of Design Department matrix is filled based on expert assessment. In order to consider that an expert can be wrong in his assessment and that a new product can be assessed based on filling more than on experiences, we develop a sensitivity analysis. The sensitivity analysis is considered from a mistake of one design scale on few technical performances.

Even if sensitivity analysis is not propagated in the following connectivity maps, it must be considered in decision-making based on design assessment cards.

5.1.4. A multi-physics data risk model to capitalize on design feedback

- Design Team represents the team in charge of the design of the product. It is identified by its project name and its project chief name.
- Product represents what the design team must design to achieve client needs. It is identified by a concept name.
- Product Design Parameter describes the product with a list of its design parameters. It has a design parameter name as an attribute.
- Design Department represents the department in charge of the design of a module of the system. The design department is identified by its name and those of its engineers.
- Module designates a part of the system that must exist in order to perform a function. Each module has a name.
- Module Design Parameter describes a module with a list of its design parameters. It is identified by a design parameter name.
- Technical Solution represents a potential solution to the design of a module. Each technical solution is assigned a name.
- Technical Solution Design Parameter describes a technical solution with a list of its design parameters. It is described by a design parameter name.
- Physical Connection describes assembly between technical solutions that have the possibility of being physically assembled. It is used to achieve interface objectives. It has a name and a type and is associated with an area of expertise, a data model, and the person who designs it.
- Physical Connection Design Parameter describes a physical connection with a list of its design parameters. It has a design parameter name.
- Design Constraint defines constraints of the project, design, design department, etc. It is defined by its name, design spaces, physical principles, physical domains, equations, and rules.
- Design Objectives challenge the design by the definition of targets for the design parameters to reach. It is defined by functions and technical performance criteria.
- Design Resolution Process capitalizes on the best practices in the design of physical connection design parameters. It is defined by mitigation plans and tasks, resources, and a duration.
- Risks summarize risks in the design of a physical connection. It is defined by a name, an owner, a description, its probability of realization, its potential impact, and its criticality.
- Design Interface Manager corresponds to the manager in charge of the risks in the design of physical connections based on the design resolution process. It is defined by a name, associated engineers, and associated design departments.

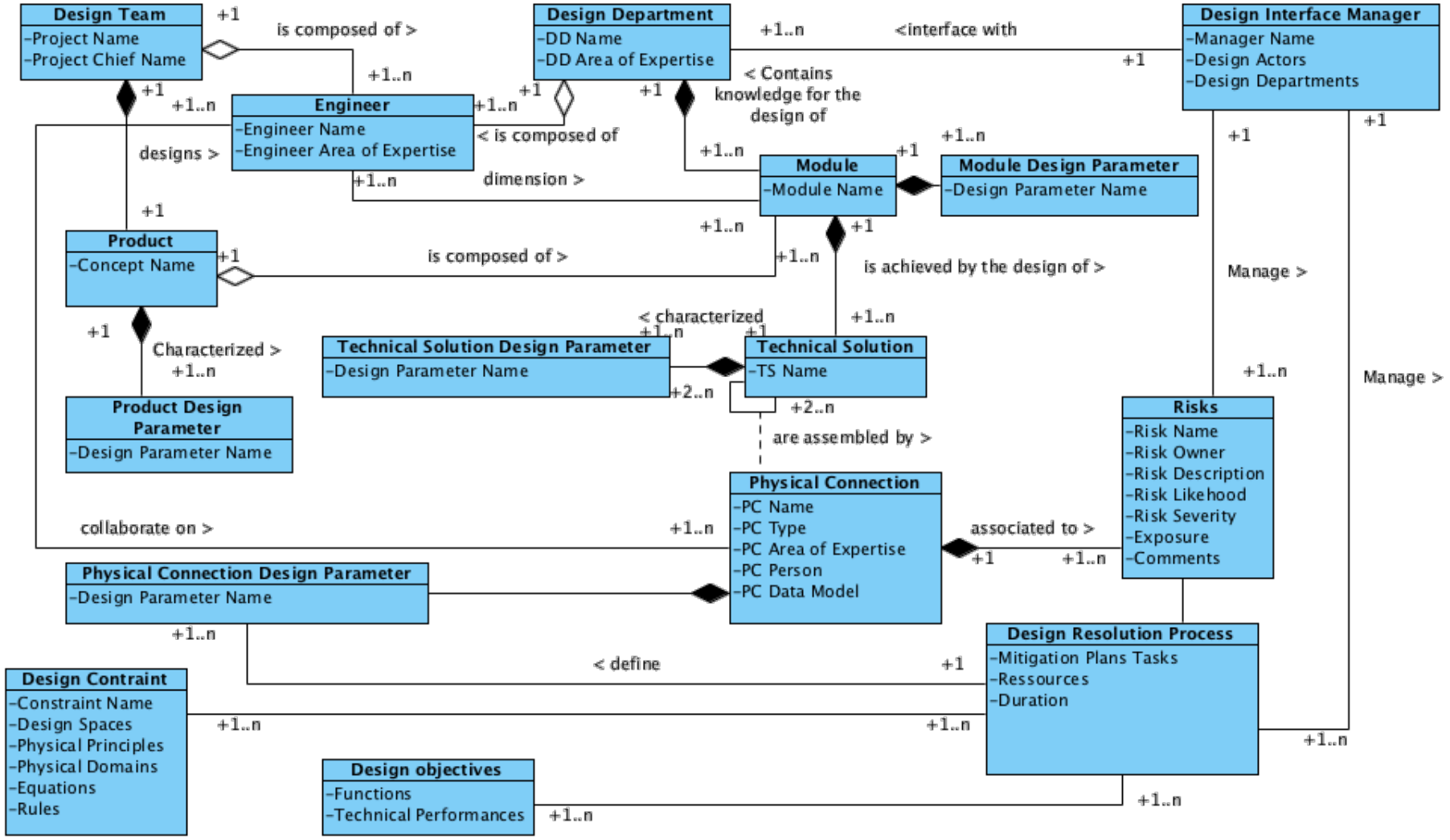


Figure 47: Collaborative risk data model ontology

The design team is composed of as many engineers as necessary to cover all of the domains required by the project. Therefore, the *Design Team* class has an aggregation relationship with the *Engineer* class. As a design team is in charge of the design of a product, the *Design Team* class has a composition relationship with the *Product* class. As an engineer dimensions modules and collaborates on the design of physical connections, the *Engineer* class has an association relationship with the *Module* class and the *Physical Connection* class.

The design department is composed of engineers and experts representing areas of expertise required for the design of one or several modules. It is in charge of the module, which is dimensioned by engineers and whose performance is evaluated by experts. As such, the *Design Department* class has aggregation relationships with the *Module* class, the *Engineer* class, and the *Expert* class. The design department is defined by its name and its knowledge.

The product is broken down into modules. Therefore, the *Product* class has an aggregation relationship with the *Module* class. A product is characterized by high-level design parameters; it therefore has a composition relationship with the *Product Design Parameter* class.

A module's objectives are achieved by the design of technical solutions. Therefore, the *Module* class is an aggregate class composed of the *Technical Solution* class. The *Module* class has an association relationship with the *Engineer* class, as engineers design modules. A module is characterized by its design parameters; it has a composition relationship with the *Module Design Parameter* class.

An assembly of technical solutions constitutes a concept. The *Technical Solution* class has an association relationship with itself through the *Physical Connection* class.. Physical connections represent every possible mating pair of technical solutions. Physical connections are characterized by their design parameters; they therefore have a composition relationship with the *Physical Connection Design Parameter* class.

A technical solution fulfills a module's requirements by satisfying the technical performance criteria of the associated function(s). Therefore, the *Technical Solution* class has an association relationship with the *Function* class and an aggregation relationship with the *Technical* Performance class. As a technical solution is characterized by its design parameters, it has a composition relationship with the *Technical Solution Design Parameter* class.

The design interface manager defines the organization between design departments, the design resolution process, and risks.

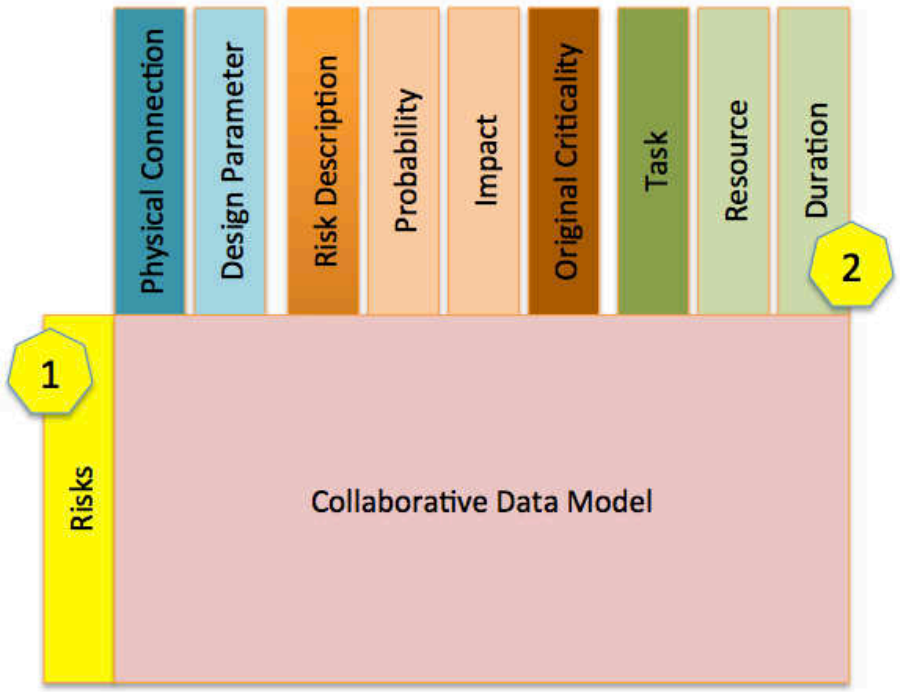


Figure 48: Collaborative risk data matrix

Collaborative risks are listed in rows ("1" in Figure 48) and characterized in columns ("2"):

- "Physical connection" identifies risk originating in physical connections
- "Design parameter" designates the design parameters of the physical connections that have an influence on collaborative risk
- "Risk description" describes the risk
- "Probability" is the likelihood of risk occurrence:
  - 1: Improbable
  - 2: Unlikely
  - 3: Possible
  - 4: Likely
  - 5: Probable
- "Impact" is the impact of the realized risk on project cost, timing, and success, from 1: Low to 5: High.
- "Original criticality" gives information about the criticality of the risk.
- "Task", "resource", and "duration" give an overview of the mitigation plan, the anticipated resources to be engaged, and the time needed to reduce risk criticality.

Such a data model must be completed each time a collaborative design problem arises during the design of a physical connection (interface) in the system being designed. An example of such a preliminary risk table for connections is given in Figure 30.

Physical Connection	Design Parameter	Risk Description	Probability	Impact	Original criticality	Mitigation Plan	Resource	Duration
Glue	Surface area	In a glue physical connection, shearing strength and pull-off strength vary a lot following the management of these desing parameters: Surface area between technical solution, Roughness of surface, viscosity coefficient and thickness of glue. See design guideline number: 100236239	5	5	25	Look equations and target values extrated from empirical approach on the design guideline number: 100236239	Contact the Houston center and the glue specialist	1 week
	Roughness							
	Viscosity coefficient							
	Thickness							

Figure 49: Example of Risk Data Model

Shear and pull-off strengths are critical in the design of a “glue” physical connection (see Figure 49). This interface dimensioning must take into account the “surface area” of contact between technical solutions, the “roughness” of these contacts, the “viscosity coefficient”, and the “thickness” of the glue between contacts. Probability is “probable” (”5”) because, in our design feedback, every time a design team dimensioned a glue interface, it failed during initial testing of shear or pull-off strengths. The impact is also considerable because the interface broke without prior reduced functionality (i.e., no forewarning). Design recommendations were summarized in an in-house referenced guideline; one week was deemed necessary to optimize design parameters with the support of a specialist in the center of Houston.

Rows can be added to the data model as the project progresses in order to run the collaborative risk analysis.

6. Seven design assessment cards of the two design quality vectors

Connectivity maps are the heart of our approach; they are necessary in order to get exploitable results for collaborative design. In this section, we introduce the defined generation of design assessment cards using connectivity maps and their link with the collaborative-FMEA (see Figure 50). In order to represent the mathematical aspects of the MPDS method, we use the following notations that serve as the basis for our explanation of connectivity maps:

The FF-DMM matrix: $A = (a_{ij})$

The PC-DSM matrix: $B = (b_{jj})$

The body of the VoDD matrix: $V = (v_{kj})$

The computation side of the VoDD matrix: $R = (r_k)$

The technical performance correlation side of the VoDD matrix: $P_a = (p_{kk})$

Where,

Table 4: Mathematical notations description

Designation	Description
h	represents the number of concepts composing the initial set
i	represents the number of functions that the product has
j	represents the total number of technical solutions, taken independent of their associated modules
k	represents the number of technical performance criteria evaluating the product
n	represents the number of modules comprising the product
s	represents the number of interfaces (where a physical connection is required)
z	represents the number of design departments (scientific fields) involved in the design of the product

In this section, we address the mathematical computation proposed in the MPDS method. The mathematical approach is described using SADT modeling language and connectivity maps.

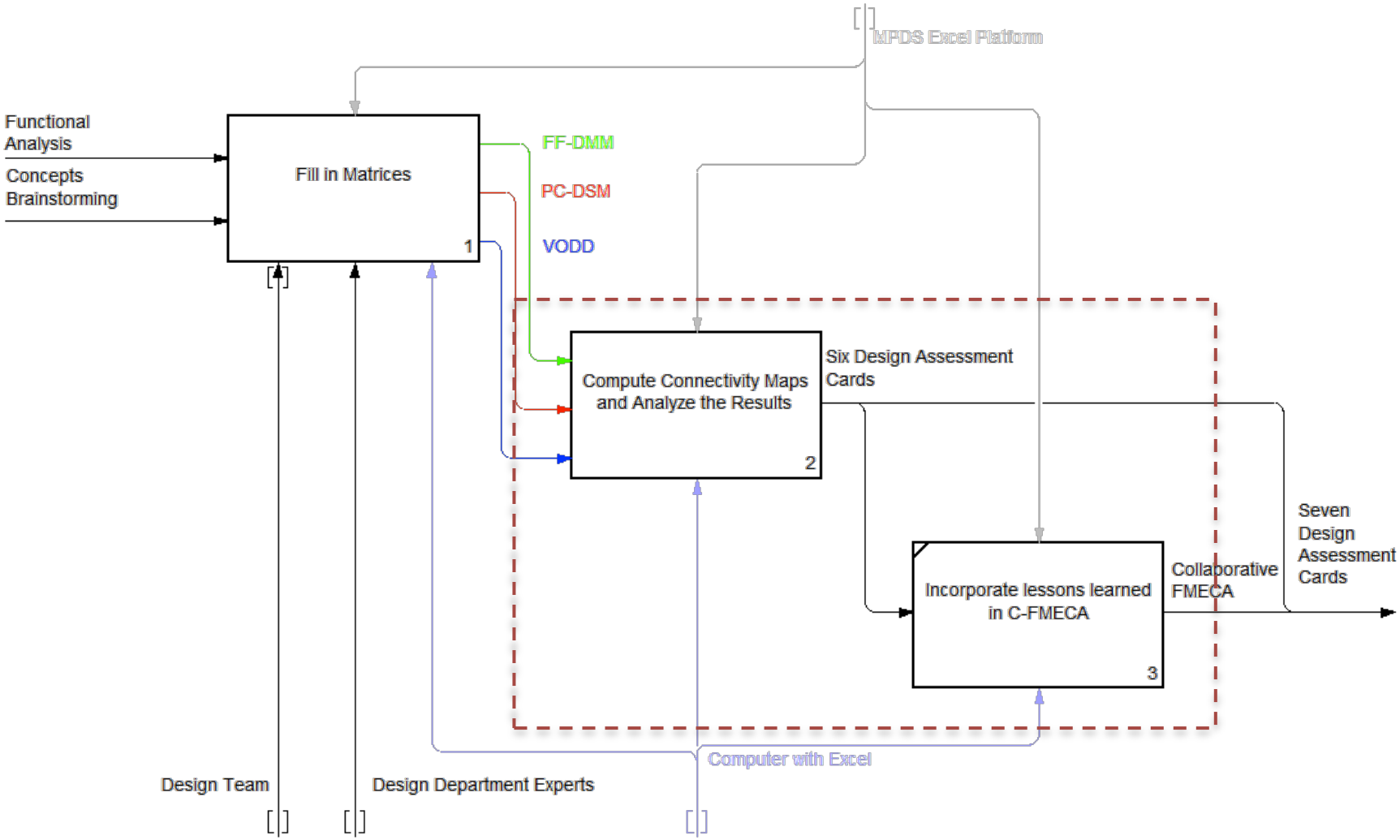


Figure 50: A1 SADT of MPDS method

The computation of connectivity maps is intended to analyze the FF-DMM, PC-DSM, and VoDD matrices by using a combination of the three in a way that is presented in this section. The six design assessment cards obtained are then used to constitute parts of the vectors and to select relevant information to be incorporated into the C-FMEA analysis, considered to be an additional design assessment card, for a total of seven These seven design assessment cards are aligned with ambition and constraint vectors (further introduced in section 6.1.1).

6.1. Design conflict management: identification of difficult interfaces through indicators

Data gathered within the FF-DMM, PC-DSM, and VoDD matrices are used as a basis for identification of potential difficulties and conflicts concerning interfaces of parts designed in collaboration with different design departments. Connectivity maps are used to extract adequate indicators for follow-up on conflicts and their management. In order to summarize interface design risks, the data model is used in a collaborative-FMEA (C-FMEA). Figure 51 shows the interaction between the FF-DMM, PC-DSM, and VoDD matrices and connectivity maps.

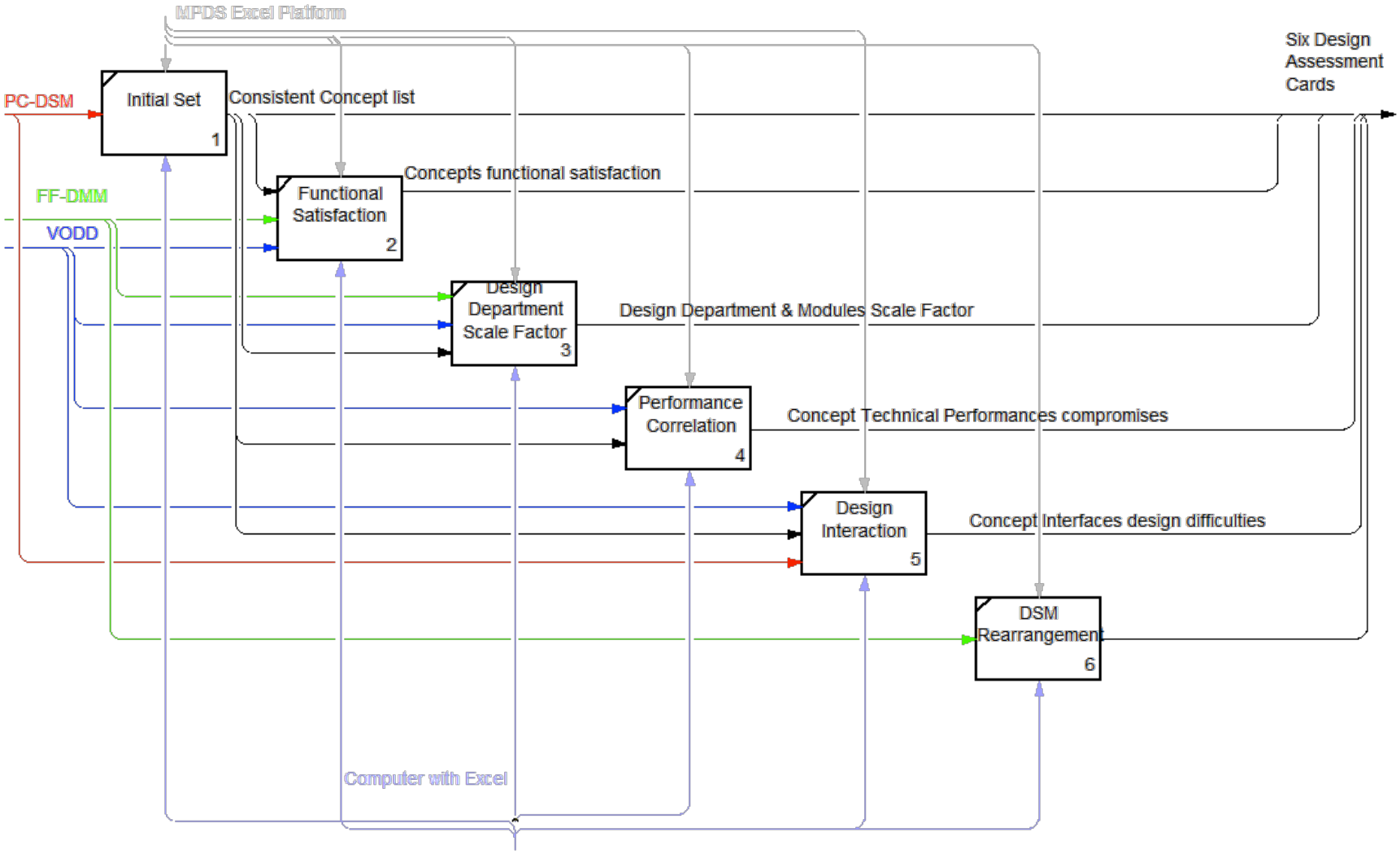


Figure 51: A21 SADT of the MPDS method

Application of the connectivity maps is illustrated through the PEC design experimentation.

6.1.1. Ambition and constraint collaborative vectors

The main objective of the MPDS method is to identify potential difficulties and conflicts in multi-physics design processes. To this end, we propose seven design assessment cards. These assessment cards constitute 2 design vectors that represent the balance within the design process: the ambition vector and the constraint vector. The ambition vector defines how far the design team reaches for project success: how many concepts they want to explore, as well as how far they aim to achieve client satisfaction. The constraint vector defines how difficult it will be to achieve project objectives: how technical performance criteria are correlated, as well as how difficult it will be to find a satisfactory equilibrium incorporating the wishes of all of the collaborating parties.

Table 5: Ambition and constraint vectors and their design assessment cards

	Indicator name	Description	Mathematical notation
Ambition vector	Definition of the initial set	This indicator defines the initial set of concept designs that are a result either of the brainstorming workshop or of the MPDS generation.	
	Functional satisfaction	This indicator measures client satisfaction based on the achievement of concept functionalities and their correlation with technical performance criteria.	$E_h = \left[e_h\right]_{ik}$
	Design department scale factor	This indicator calculates the potential contribution of design departments to the overall technical performance.	$E_{hzn} = \left[e_{hzn}\right]_{ik}$
Constraint vector	Technical performance trade-offs	This indicator shows the difficulties in achieving the trade-offs of different technical performance criteria.	$F_h = \left[f_h\right]_{kk}$
	Design interaction objectives	This indicator sets design targets for the co-design of interfaces.	$P_h = \left[p_h\right]_{ks}$
	DSM matrix rearrangement	This indicator rearranges the PC-DSM matrix based on functional and interfacial dependencies.	$G = \left[g\right]_{jj} = \left(g_{rt}\right)$
	Collaborative-FMEA	This indicator summarizes collaborative risks in a C-FMEA.	

6.1.2. Definition of the initial set

The initial set indicator is a matrix based upon the use of the consistency algorithm on the PC-DSM matrix. A consistency algorithm permits identification of all possible combinations of technical solutions for one design concept. We consider one design concept to be "consistent" when there is a possible physical connection between the chosen technical solutions. The consistency algorithm is possible because the typology of possible physical connections and their constraints are gathered in the PC-DSM matrix. The proposed algorithm generates all of the possible architectural combinations of technical solutions by identifying the physical connections possible between the technical solutions. Results of the consistency algorithms applied to the PC-DSM matrix for the PEC experiment are presented in Figure 52.

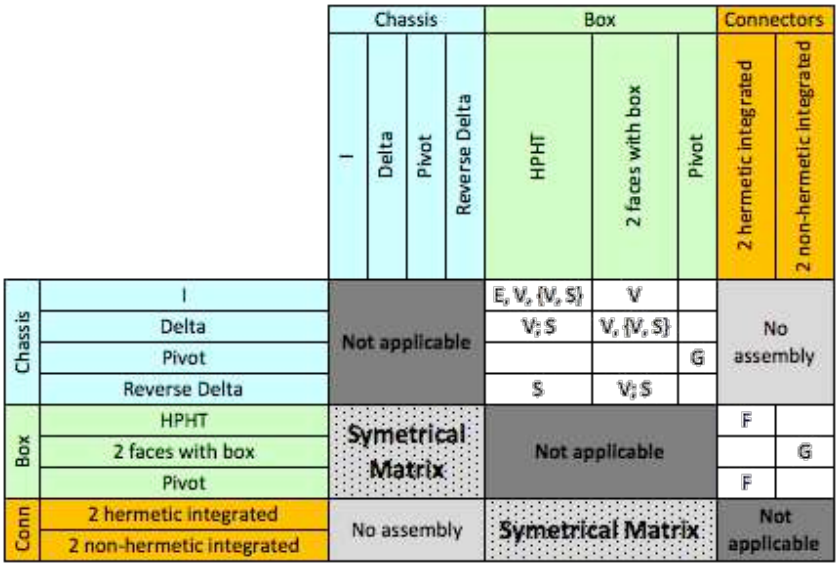


Figure 52: PEC PC-DSM matrix example

If we consider the "I" technical solution for the "chassis" module (the first row), the algorithm goes through the first entry in the row: using "E, V, {V, S}" to create an assembly of the "I" chassis with the "HPHT" technical solution for the "box" module, using either "E" – elastomer, "V" – screw, or "V, S" - screw and silicon physical connections. The concept list contains three potential concepts (rows) at this point. Then the algorithm goes through the remaining entries and generates a list of additional potential concepts; the number of rows of concepts generated is equal to the number of alternative assemblies of one technical solution with another via a physical connection. When the algorithm has finished generating all possible assemblies with the "I" chassis and box technical solutions, it adds the possible connector technical solutions to the "2 faces with box" and "HPHT" boxes, respectively. For instance, the "2 hermetic integrated" connectors are added to the "HPHT" box using "fitting" as a physical connection. Concepts are considered "consistent" if they are based upon the same technical solution for each module assembled with physical connections. From Figure 52, generation of 14 concepts is possible; these concepts are shown in Table 6.

Table 6: PEC consistent concepts list

Concept Name	Technical Solution for "Chassis"	Physical Connection Between "Chassis" and "Box"	Technical Solutions for "Box"	Physical Connection Between "Box" and "Connectors"	Technical Solutions for "Connectors"
1.01	I	E (Elastomer)	HPHT	F (Fitting)	2 hermetic integrated
1.02	I	V (Screw)	HPHT	F (Fitting)	2 hermetic integrated
1.03	I	{V, S} (Screw and Silicon)	HPHT	F (Fitting)	2 hermetic integrated
1.10	I	V (Screw)	2 faces with Box	G (glue)	2 non-hermetic integrated
5.11	Delta	V (Screw)	HPHT	Fitting	2 hermetic integrated
5.12	Delta	S (Silicon)	HPHT	F (Fitting)	2 hermetic integrated
5.13	Delta	V; S (Screw and Silicon)	HPHT	F (Fitting)	2 hermetic integrated
2.01	Delta	V (Screw)	2 faces with Box	G (glue)	2 non-hermetic integrated
2.02	Delta	{V, S} (Screw and Silicon)	2 faces with Box	G (glue)	2 non-hermetic integrated
8 - Pivot	Pivot	G (Glue)	Pivot	F (Fitting)	2 hermetic integrated
7 - Non Hermetic Chassis	Reverse Delta	S (Silicon)	HPHT	F (Fitting)	2 hermetic integrated
7.11	Reverse Delta	V (Screw)	2 faces with Box	G (glue)	2 non-hermetic integrated
7.12	Reverse Delta	S (Silicon)	2 faces with Box	G (glue)	2 non-hermetic integrated
7.13	Reverse Delta	V; S (Screw and Silicon)	2 faces with Box	G (glue)	2 non-hermetic integrated

These 14 concepts comprise the initial set of concepts and thus the scope of technical solutions that the design team will explore in depth in order to fulfill client requirements. These concepts will later be evaluated based on client satisfaction and technical correlation indicators.

6.1.3. Functional satisfaction

The functional satisfaction indicator correlates functions and technical performance criteria via product architecture. The objective is to evaluate the potential fulfillment of technical performance criteria for each design concept, taking into account the product architecture. The E matrix represents the functional satisfaction indicator. To evaluate the functional satisfaction of each concept independently, the FF-DMM and VoDD matrices are truncated into matrices representing only the technical solutions involved in the chosen concept. The matrix product of the FF-DMM and the VoDD matrices yields the E matrix (see Connectivity Map 1).

The mathematical model for Connectivity Map 1 is defined as:

The FF-DMM matrix: $A = \left(a_{ij}\right)$

The body of the VoDD matrix: $V = \left(v_{kj}\right)$

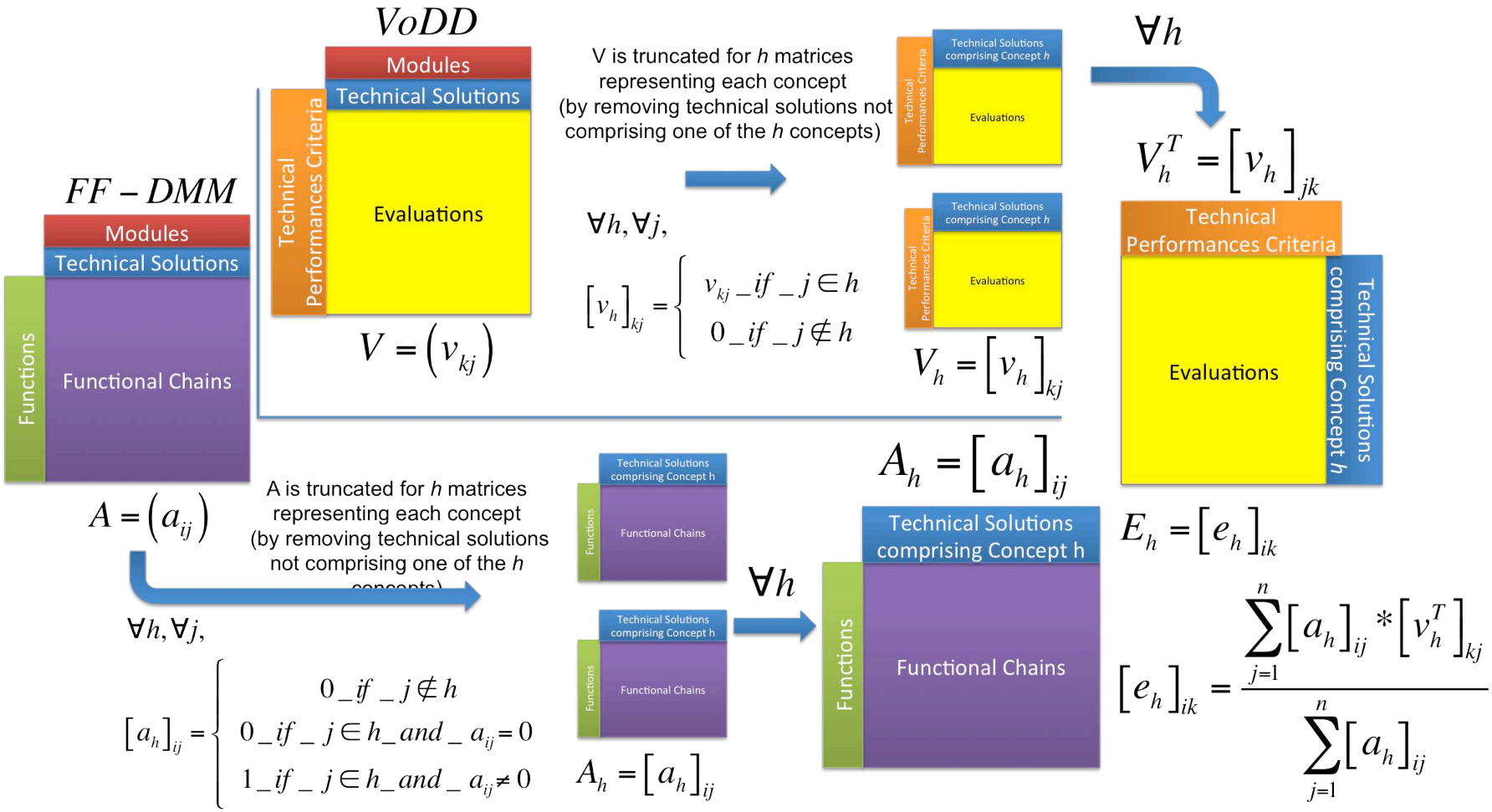
In which:

Table 7: Mathematical notation for Connectivity Map 1

Designation	Description
h	represents the number of concepts comprising the initial set
i	represents the number of functions that the product has
j	represents the number of technical solutions of which the product is composed
k	represents the number of technical performance criteria used in evaluating the product
n	represents the number of modules that comprise the product

The design scorecard matrix obtained (functional satisfaction of a concept) is as follows:

$$E_h = \left[e_h\right]_{ik}$$



Connectivity Map 1: E matrix functional satisfaction by concept

Connectivity Map 1 aims to evaluate functional fulfillment by concepts. Our objective is thus to map functions and technical performance criteria in a matrix representing each concept. The final design assessment card is denoted $E_h = [e_h]_{ik}$. In order to attain this assessment card, both the VoDD matrix ($V = (v_{kj})$) and the FF-DMM matrix ($A = (a_{ij})$) are duplicated into h matrices and then truncated (to eliminate the technical solutions that do not constitute the given concept), representing each concept independently. The $V_h = [v_h]_{kj}$ matrices obtained represent the correlation between technical performance criteria and technical solutions comprising each concept, and the $A_h = [a_h]_{ij}$ matrices correlate functions and technical solutions for each concept. The $V_h = [v_h]_{kj}$ matrices are then transposed to obtain $V_h^T = [v_h]_{jk}$. The $E_h = [e_h]_{ik}$ matrices are obtained via a matrix product between V_h and A_h, which is then normalized by the number of technical solutions involved in the evaluation (see equation in Connectivity Map 1).

Figure 53 shows an example of the E_h matrix for the concept: "7 – Non Hermetic Chassis" (see Table 6). Concept functionalities are listed in rows and technical performance criteria in columns.

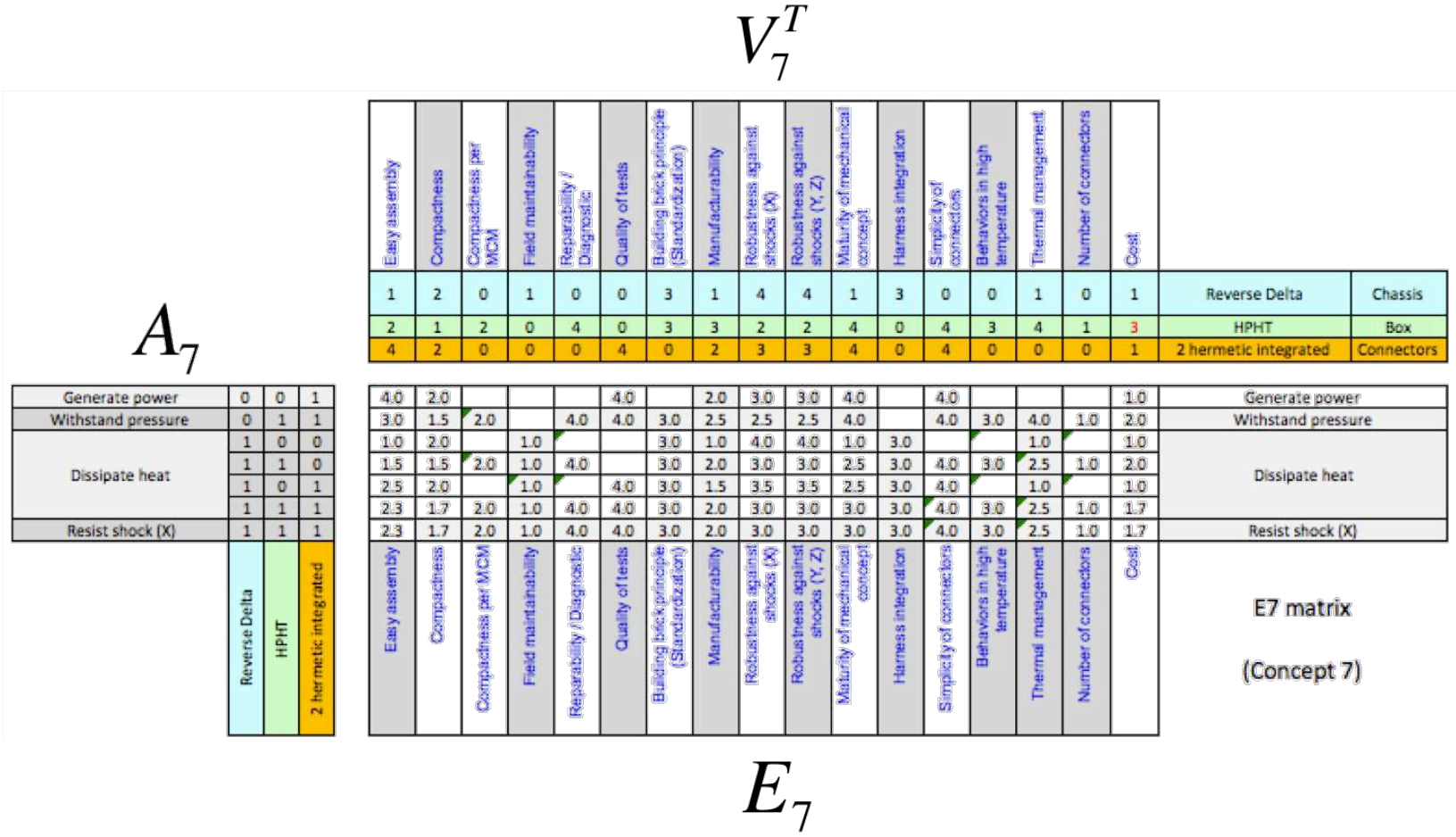


Figure 53: PEC example of E_7 matrix concept functional satisfaction

Part of the PEC example shown in Figure 53 is extracted in Table 8 to represent an analysis that can be done with this design assessment card. With this objective, we recall that the four rows concerning the function "dissipate heat" in Figure 53 are alternatives from which a PEC concept needed to be chosen, leading to two instead of the four alternatives for "dissipate heat" (one of the first two rows for the thermal bridge due to the air gap and one of the last two rows for the thermal bridge due to physical contact, see Functional Analysis in section 3). Table 8 shows the compromise between "thermal management" and "cost", two technical performance criteria that must be fulfilled in order to design this function.

Table 8: "Heat dissipation" functionality evaluation for the concept 7

Concept 7	Cost	Thermal management
High thermal technical performance (2^{nd} and 4^{th} rows of function "dissipate heat")	3.7 (= 2 + 1.7)	2 + 1.7
Low cost (1^{st} and 3^{rd} rows of function "dissipate heat")	2 (= 1 + 1)	1 + 0.5

Alternatives for the function "dissipate heat" can be 85% more expensive in order to achieve a "thermal management" technical performance that is 146% more efficient.

The comparison with concept 7.11 (see Table 10) shows a perceptible interest of this approach: the highlighting of design compromise. Cost is higher for concept 7.11 than for concept 7.

Table 9: $E_{7.11}$ matrix functional satisfaction for concept 7.11

4.0	1.0				4.0		4.0	2.0	2.0	3.0		4.0				3.0	Generate power
3.0	2.0	3.0		4.0		3.0	2.0	3.0	3.0	4.0		4.0	4.0	3.0	2.0	2.0	Withstand pressure
1.0	2.0		1.0			3.0	1.0	4.0	4.0	1.0	3.0			1.0		1.0	
2.0	2.0	1.5	0.5	2.0		3.0	1.5	3.5	3.5	2.5	1.5	2.0	2.0	2.0	1.0	1.5	Dissipate heat
2.7	1.7	1.0	0.3	1.3	1.3	2.0	2.3	3.0	3.0	2.7	1.0	2.7	1.3	1.3	0.7	2.0	
2.5	1.5		0.5		2.0	1.5	2.5	3.0	3.0	2.0	1.5	2.0		0.5		2.0	
2.7	1.7	1.0	0.3	1.3	1.3	2.0	2.3	3.0	3.0	2.7	1.0	2.7	1.3	1.3	0.7	2.0	Resist shock (X)
Easy assembly	Compactness	Compactness per MCM	Field maintainability	Reparability / Diagnostic	Quality of tests	Building brick principle (Standardization)	Manufacturability	Robustness against shocks (X)	Robustness against shocks (Y, Z)	Maturity of mechanical concept	Harness integration	Simplicity of connectors	Behaviors in high temperature	Thermal management	Number of connectors	Cost	E7.11 matrix (Concept 7.11)

Concept 7.11 has a different technical performance compromise for the "heat dissipation" function:

Table 10: "Heat dissipation" functionality evaluation for the concept 7.11

Concept 7.11	Cost	Thermal management
High thermal technical performance	3.5 (1.5 + 2)	2 + 1.3
Low cost	3 (1 + 2)	1 + 0.5

Table 7 shows that concept 7.11 costs more for equal technical performance for the "thermal management" criterion. The computation of $E_7 - E_{7.11}$ can bring out the strengths and weaknesses of the concepts (see Table 11).

Table 11: $E_7 - E_{7.11}$ concept functional satisfaction comparison

	1.0						-2.0	1.0	1.0	1.0						-2.0	Generate power
	-0.5	-1.0			4.0		0.5	-0.5	-0.5				-1.0	1.0	-1.0		Withstand pressure
-0.5	-0.5	0.5	0.5	2.0			0.5	-0.5	-0.5		1.5	2.0	1.0	0.5		0.5	Dissipate heat
-0.2	0.3	-1.0	0.7	-1.3	2.7	1.0	-0.8	0.5	0.5	-0.2	2.0	1.3	-1.3	-0.3	-0.7	-1.0	
-0.2	0.2	2.0	0.5	4.0	2.0	1.5	-0.5			1.0	1.5	2.0	3.0	2.0	1.0	-0.3	
-0.3		1.0	0.7	2.7	2.7	1.0	-0.3			0.3	2.0	1.3	1.7	1.2	0.3	-0.3	Resist shock (X)
Easy assembly	Compactness	Compactness per MCM	Field maintainability	Reparability / Diagnostic	Quality of tests	Building brick principle (Standardization)	Manufacturability	Robustness against shocks (X)	Robustness against shocks (Y, Z)	Maturity of mechanical concept	Harness integration	Simplicity of connectors	Behaviors in high temperature	Thermal management	Number of connectors	Cost	E7 compared to E7.11

The positive entries in Table 11 show advantages of concept 7, while the negative entries show advantages of concept 7.11. An empty entry signifies that the concepts do not differ with respect to the given technical performance.

6.1.4. Design department scale factors

This paragraph presents our Design department scale factors assessment card, used in order to involve design departments in the process of evaluation against functional satisfaction values. We apply a virtual variation to each technical performance criterion, on which design departments have an influence, in order to understand their effects on the results. With this approach, design department members can appreciate how different two concepts are by accounting for their particular influence on a given concept and how much they can improve it by improving their own technical performance by one value scale.

Mathematical model for Connectivity Map 2 is defined:

The FF-DMM matrix: $A = \left(a_{ij}\right)$

The body of the VoDD matrix: $V = \left(v_{kj}\right)$

The functional satisfaction of a concept: $E_h = \left[e_h\right]_{ik}$

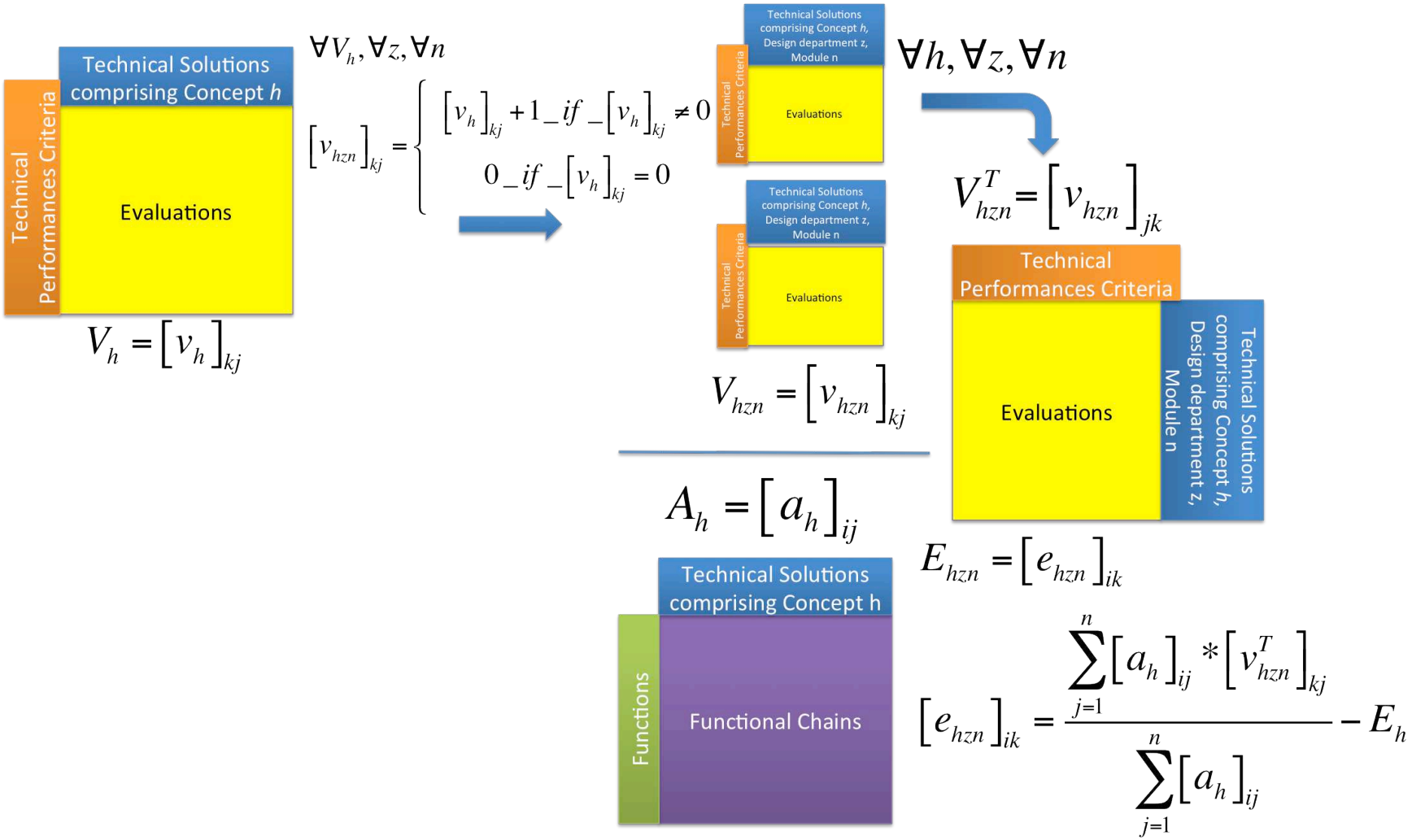
In which:

Table 12: Mathematical notation for Connectivity Map 2

Designation	Description
h	represents the number of concepts comprising the initial set
i	represents the number of functions that the product has
j	represents the number of technical solutions of which the product is composed
k	represents the number of technical performance criteria used in evaluating the product
n	represents the number of modules comprising the product
z	represents the number of design departments (scientific fields) involved in the design of the product

The proposed design scorecard matrix (design department scale factor) is as follows:

$$E_{hzn} = \left[e_{hzn} \right]_{ik}$$



Connectivity Map 2: E_{hzn} matrix design department scale factor

Connectivity Map 2 aims to evaluate the potential influence of design departments on functional satisfaction values for each concept and each module they design. Our objective is thus to map functions and technical performance criteria into a matrix representing each concept, each design department, and each module ($E_{hzn} = [e_{hzn}]_{ik}$). In order to do this, the $V_h = [v_h]_{kj}$ matrix (see Connectivity Map 1) is duplicated into n matrices each representing a single module (and its associated technical solutions; V_h only accounts for technical solutions comprising concept number h, and thus each associated design department is also represented independently, since modules are designed by a single design department), and each of them is modified by raising its associated technical performance criteria value by one. The $V_{hzn} = [v_{hzn}]_{kj}$ matrices thus obtained present a correlation between technical performance criteria and technical solutions designed by one design department. The $V_{hzn} = [v_{hzn}]_{kj}$ matrices are then transposed to obtain $V_{hzn}^T = [v_{hzn}]_{jk}$. The $E_{hzn} = [e_{hzn}]_{ik}$ design scorecards are the difference (see equations in Connectivity Map 2) between the product of the matrix V_{hzn} with the matrix A_h, normalized by the number of technical solutions involved in the evaluation, and E (extracted from Connectivity Map 1).

Figure 54 shows an example of the E_{hzn} matrix for "concept 7 – non hermetic chassis", the design department "mechanics", and their "chassis" module.

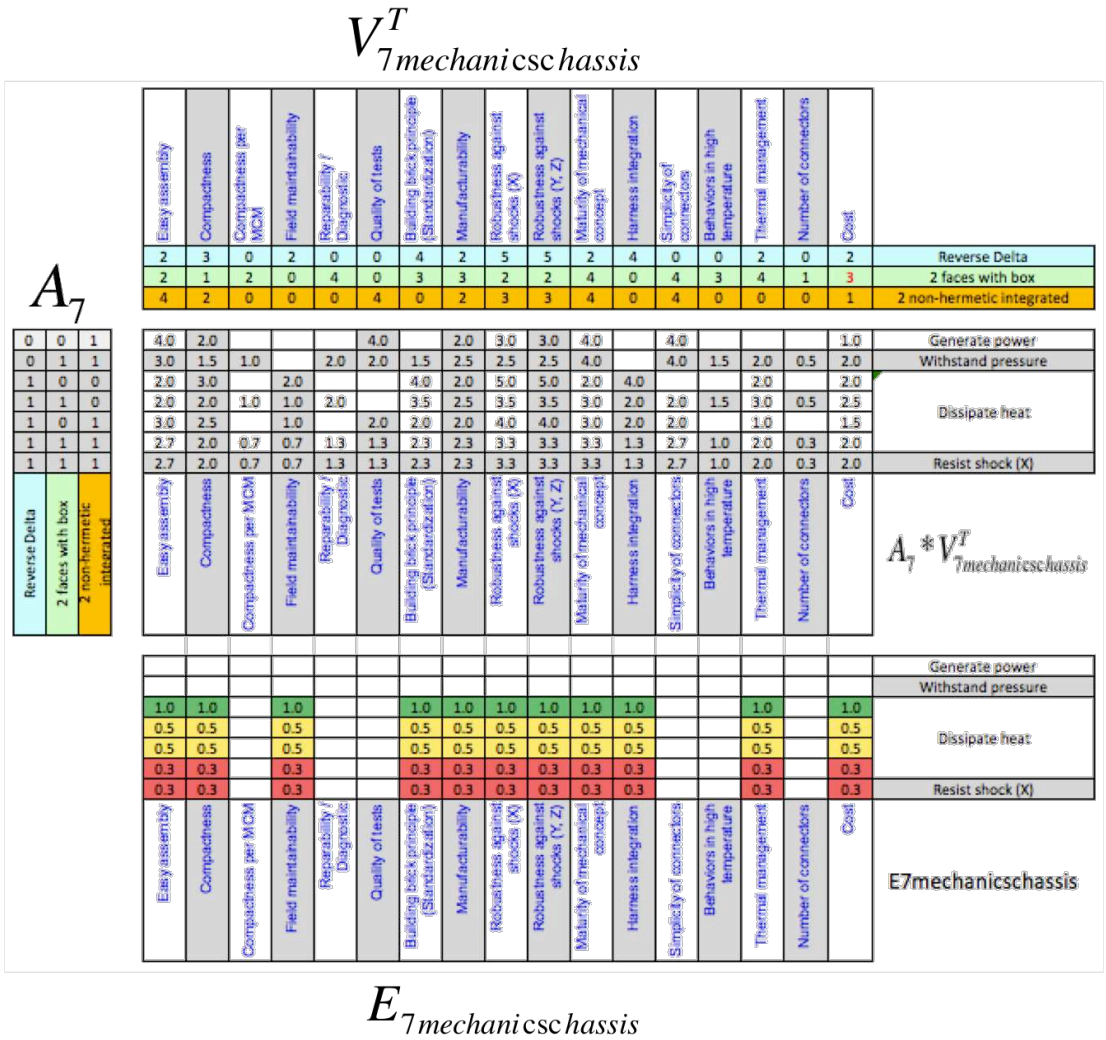


Figure 54: PEC example of $E_{7.mechanics.chassis}$ scale factor

Positive entries indicate that the mechanics design department can modify the technical performance:

- "1.0" entries mean that by raising the technical performance of the "chassis" design by one value scale, the design department will raise the associated functional satisfaction by one ("1.0") value scale.
- "0.5" entries mean that by raising the technical performance of the "chassis" design by one value scale, the design department will raise associated the functional satisfaction by half a value scale.
- "0.3" entries mean that by raising the technical performance of the "chassis" design by one value scale, the design department will raise the associated functional satisfaction by one third of a value scale. These values vary by concept. For instance, Table 13 shows that it is more difficult for the mechanics design department to improve the "cost" and "thermal management" technical performance values for concept 7 than it is for concept 7.11.

Table 13: Mechanics discipline scale factor

Mechanics discipline	Concept 7		Concept 7.1	
	Cost	Thermal management	Cost	Thermal management
"Dissipate heat" alternative 1 & 2	1	1	0.5	0.5
"Dissipate heat" alternative 3 & 4	1	1	0.3	0.3

Concepts evaluation brings the need to understand the contribution of design departments to the overall technical performance of the concept. With the last assessment card, team members are able to understand if the gap between concepts is significantly advantageous in favor of one, or if the re-design of modules will turn the advantage to the lower-ranked concept.

6.1.5. Technical performance design compromises

The re-design of modules can modify the distribution of the weight among the technical performance ratings assigned to the technical solutions of a given module. This section presents our approach to mapping technical performance ratings together to understand their complex dependencies (positive or negative correlations) in the creation of successful concepts. Connectivity Map 3 shows our mathematical approach.

The mathematical model for Connectivity Map 3 is as follows:

The body of the VoDD matrix: $V = (v_{kj})$

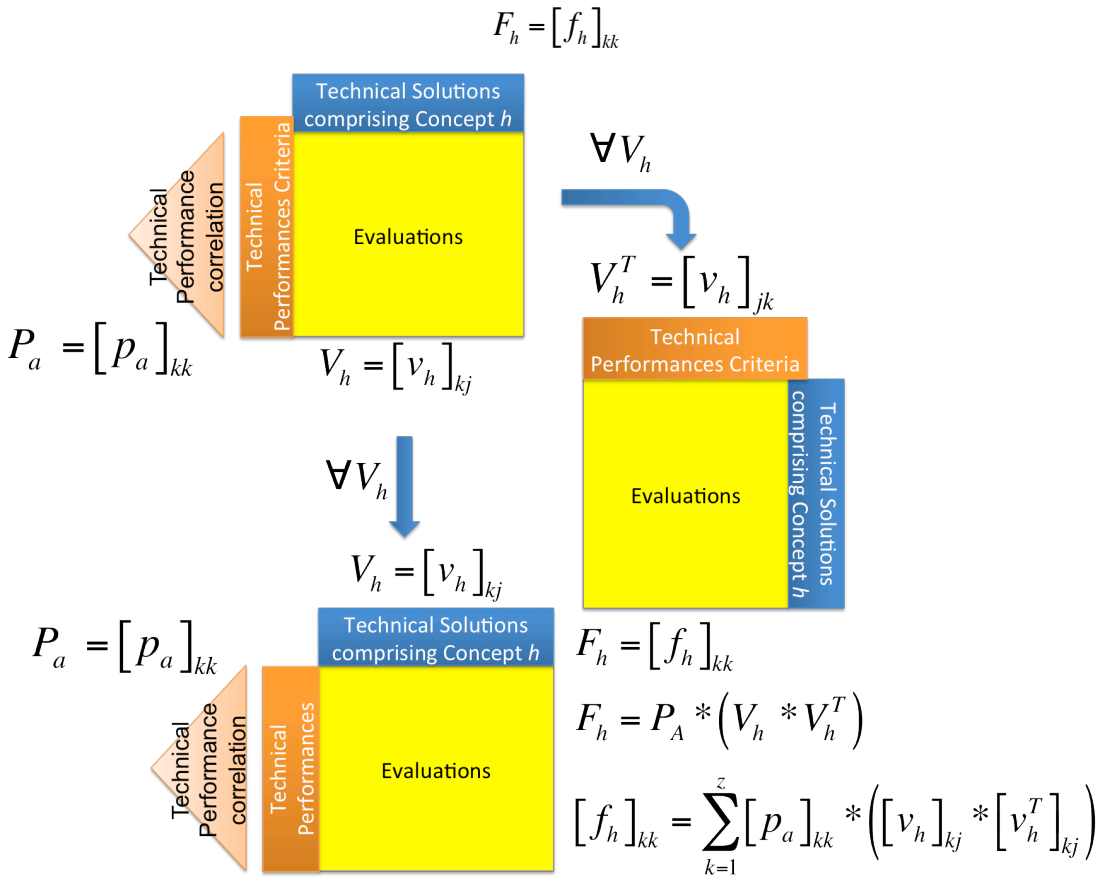
The technical performance correlation side of the VoDD matrix: $P_a = (p_{kk})$

In which:

Table 14: Mathematical notation for Connectivity Map 3

Designation	Description
h	represents the number of concepts comprising the initial set
j	represents the number of technical solutions of which the product is composed
k	represents the number of technical performance criteria used in evaluating the product
z	represents the number of design departments (scientific fields) involved in the design of the product

The proposed design scorecard matrix (technical performance design compromises) is as follows:



Connectivity Map 3: F_h technical performance compromises matrix

Connectivity Map 3 aims to highlight technical performance compromises. Our objective is thus to map technical performance values in a matrix representing each concept ($F_h = [f_h]_{kk}$). In order to do this, the $V_h = [v_h]_{kj}$ matrix (see Connectivity Map 1) is duplicated and transposed into $V_h^T = [v_h]_{jk}$. The $F_h = [f_h]_{kk}$ design scorecard is obtained by a matrix product between $V_h = [v_h]_{kj}$ and $V_h^T = [v_h]_{jk}$, with a correction factor $P_a = [p_a]_{kk}$, which indicates if the correlation is positive or negative.

Figure 55 shows an application of the F_h matrix to concept 7.

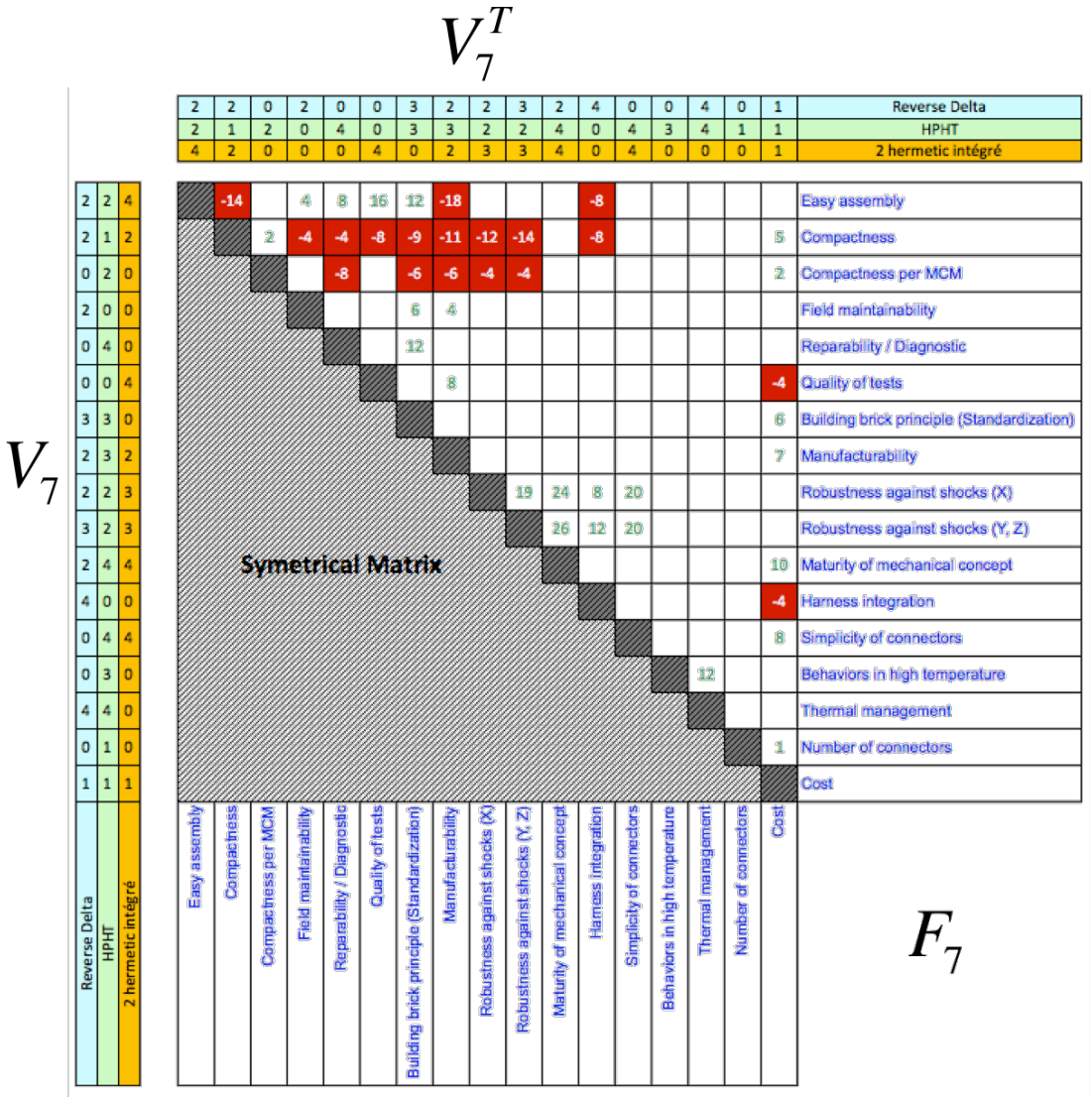


Figure 55: PEC example of F_7 matrix for concept 7

Positive entries are synonymous with no necessary compromise between technical performance criteria (both can be fulfilled at the same time). Negative entries indicate the need for a design compromise between technical performance criteria (both cannot be fulfilled at the same time). Empty entries mean no correlation between technical performance criteria. These cannot be interpreted with value scales. Figure 56 shows a comparison of concepts 7 and 7.11 with this assessment card.

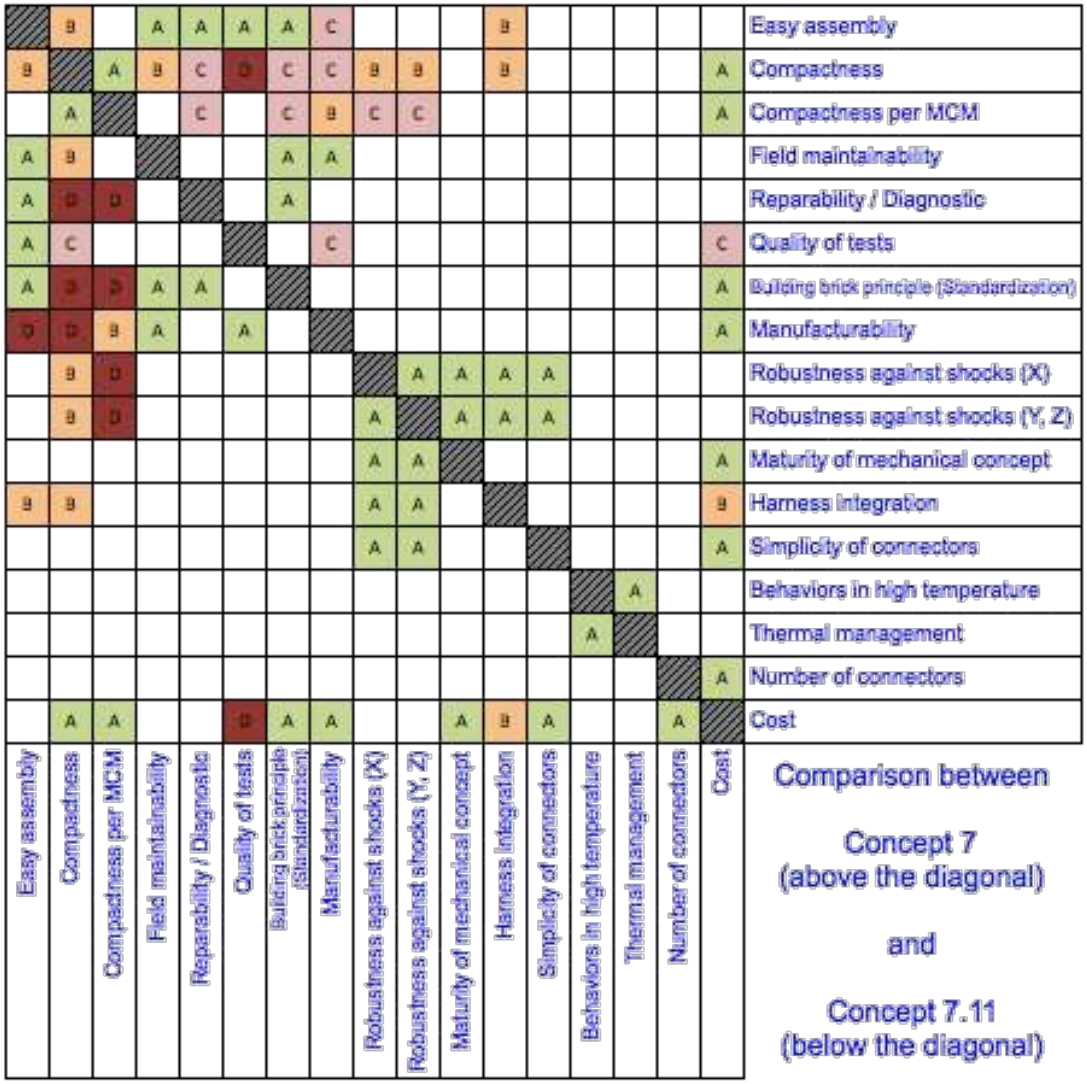


Figure 56: F_h matrix - technical performance compromises comparison for Concepts 7 and 7.11

The part of the matrix above the diagonal in Figure 56 represents concept 7, and the part below the diagonal represents concept 7.11. The shaded entries indicate the following:

- Empty entries (white) mean no correlation between technical performance criteria
- "A" entries (green) signify a correlation with no compromise necessary
- "B" entries (orange) indicate a compromise for both concepts being compared
- "C" (pink) and "D" (brown) entries indicate a more negative design compromise – "D" (brown) entries indicate a more negative compromise than C (pink) entries, in terms of effect on the concept

Design departments can validate their own compromise by analyzing the correlation between technical performance criteria; this analysis is executed using the same connectivity map by substitution of V_h with $V_{hz} = \left(v_{h\_kj}\right)$.

6.1.6. Design interaction objectives

Up to this point, concepts have been evaluated, the influence of the design departments has been understood, and design compromises have been mapped. It is of interest to set design interaction objectives to facilitate collaboration. This paragraph presents our approach to setting collaborative design targets. Collaboration dedicated to the co-design of physical connections by at least two design departments aims to maximize functional flows across their interfaces. Since functions have been evaluated based on technical performance criteria, definition of collaboration objectives consists of setting targets for technical performance values, based on the components on either side of the interfaces. Connectivity map 4 shows our mathematical approach.

The mathematical model for Connectivity Map 4 is as follows:

The PC-DSM matrix: $B = \left(b_{jj}\right)$

The body of the VoDD matrix: $V = \left(v_{kj}\right)$

The computation side of the VoDD matrix: $R = \left(r_{k}\right)$

In which:

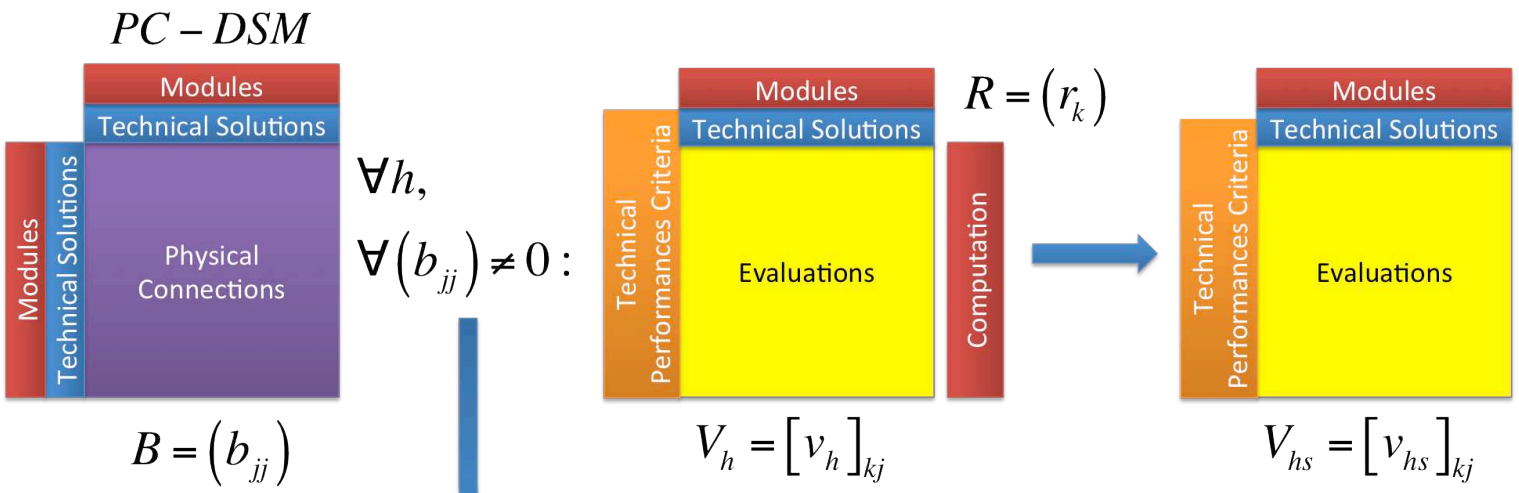
Table 15: Mathematical notation for Connectivity Map 4

Designation	Description
h	represents the number of concepts comprising the initial set
j	represents the number of technical solutions of which the product is composed
k	represents the number of technical performance criteria used in evaluating the product,
s	represents the number of interfaces (where physical connections are required)

The proposed design scorecard matrices (design interaction evaluation and design interaction objectives, respectively) are as follows:

$$V_s = \left[v_s\right]_{jk}$$

$$P_h = \left[p_h\right]_{ks}$$



$$P = [p_h]_k$$

$$[p_h]_k = \begin{cases} Min([v_{hs}]_{kj})\_si\_r_k = \min \\ Max([v_{hs}]_{kj})\_si\_r_k = \max \\ Moy([v_{hs}]_{kj})\_si\_r_k = avera \\ Sum([v_{hs}]_{kj})\_si\_r_k = sum \end{cases}$$

Connectivity map 4: V_s and P interface design difficulties matrices

Connectivity Map 4 aims to establish design interface objectives for the design of physical connections. Our objective is thus to map technical performance criteria to an interface for each concept. To this end, the $B = (b_{jj})$ matrix is used to detect interfaces: for all occupied entries, an empty $P = [p_h]_k$ matrix is generated. This matrix is filled with objectives for each technical performance criterion based on the $R = (r_k)$ matrix and the $V_h = [v_h]_{kj}$ matrix. The $R = (r_k)$ matrix indicates how to compute the technical performance of a concept based on the technical performance of its technical solutions. The $V_h = [v_h]_{kj}$ matrix gives the objectives to attain for dimensioning the interface of the physical connections. The equations used to fill in the $P = [p_h]_k$ design assessment card are given according to the $R = (r_k)$ values in Connectivity map 4.

$V_{7Chassis-Box}$ $P_{7Chassis-Box}$

Technical Performance Criteria	Reverse Delta	HPHT	Targets
Easy assembly	2	2	2
Compactness	2	1	1.5
Compactness per MCM		2	
Field maintainability	2		
Reparability / Diagnostic		4	
Quality of tests			
Building brick principle (Standardization)	3	3	3
Manufacturability	2	3	2.5
Robustness against shocks (X)	2	2	2
Robustness against shocks (Y, Z)	3	2	2
Maturity of mechanical concept	2	4	2
Harness integration	4		
Simplicity of connectors		4	
Behaviors in high temperature		3	
Thermal management	4	4	4
Number of connectors		1	
Product Cost	1	1	1

Figure 57: PEC example of V_7 and P_7 matrices for concept 7

Figure 57 presents the establishment of collaborative design targets for the chassis-box interface of concept 7. The $V_{7Chassis-Box}$ matrix shows the associated technical solutions, the evaluation of their technical performance criteria, and the associated design departments collaborating on the design of the interface. The $P_{7Chassis-Box}$ matrix represents technical performance targets in the design of the chassis-box for any physical connection chosen. Hatched entries show technical performance criteria that do not need to be fulfilled for concept functionalities.

6.1.7. DSM matrix rearrangement

After setting goals for the co-design of interfaces by different design departments, it is of interest to consider the design data flow between team members. In this paragraph, we present our approach to re-ordering the PC-DSM matrix to use classic algorithms for the organization of design tasks. To account for the fact that the design of a technical solution downstream of the functional flow requires data from upstream of the functional flow, internal functional analysis is used to rearrange the DSM matrix. Connectivity Map 5 presents our mathematical approach.

The mathematical model for Connectivity Map 5 is as follows:

The FF-DMM matrix: $A = \left(a_{ij}\right)$

In which:

Table 16: Mathematical notation for Connectivity Map 5

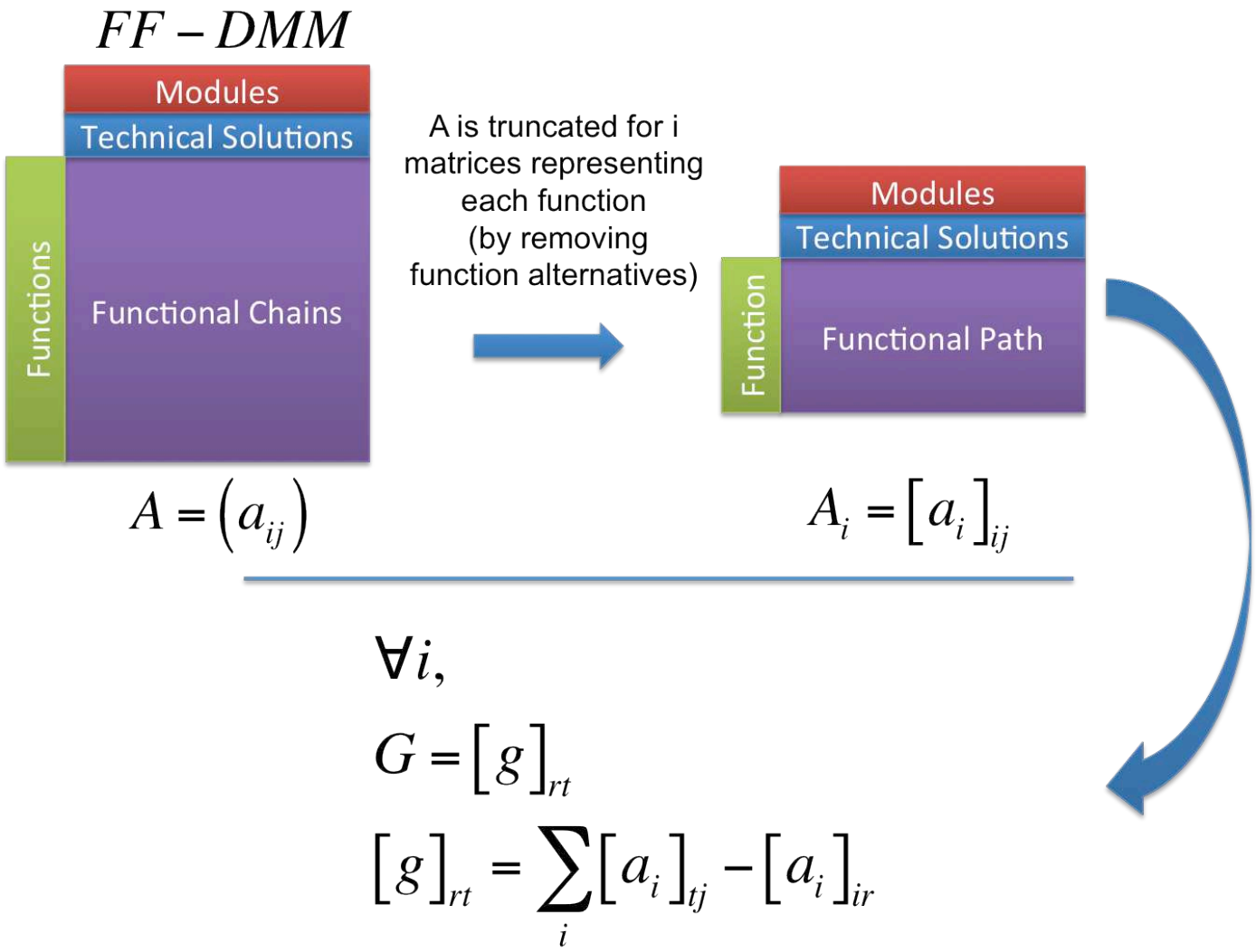
Designation	Description
i	represents the number of functions that the product has
j	represents the number of technical solutions which of the product is composed

The proposed design scorecard matrix (rearranged DSM matrix) is as follows:

$$G = \left[g\right]_{jj} = \left(g_{rt}\right)$$

Connectivity Map 5 aims to detect functions that are taken into account in the fulfillment of other functions of the product. Our objective is thus to order functions based on the FP-DMM matrix. In order to do this, we introduce the r and t variables to represent the number of technical solutions. These variables make the matrix operations that we do easier to understand. The $A = \left(a_{ij}\right)$ matrix is duplicated into A' and A", and the A" is then modified. All A" entries that are not empty or are equal to "0" are filled in with "1". This matrix is then transposed before being subtracted from A', leaving the $G = \left(g_{jj}\right) = (g_{rt})$ design assessment card (see Connectivity Map 5).

Figure 58 shows an example of the G matrix for the PEC.



Connectivity Map 5: G matrix - DSM matrix rearrangement

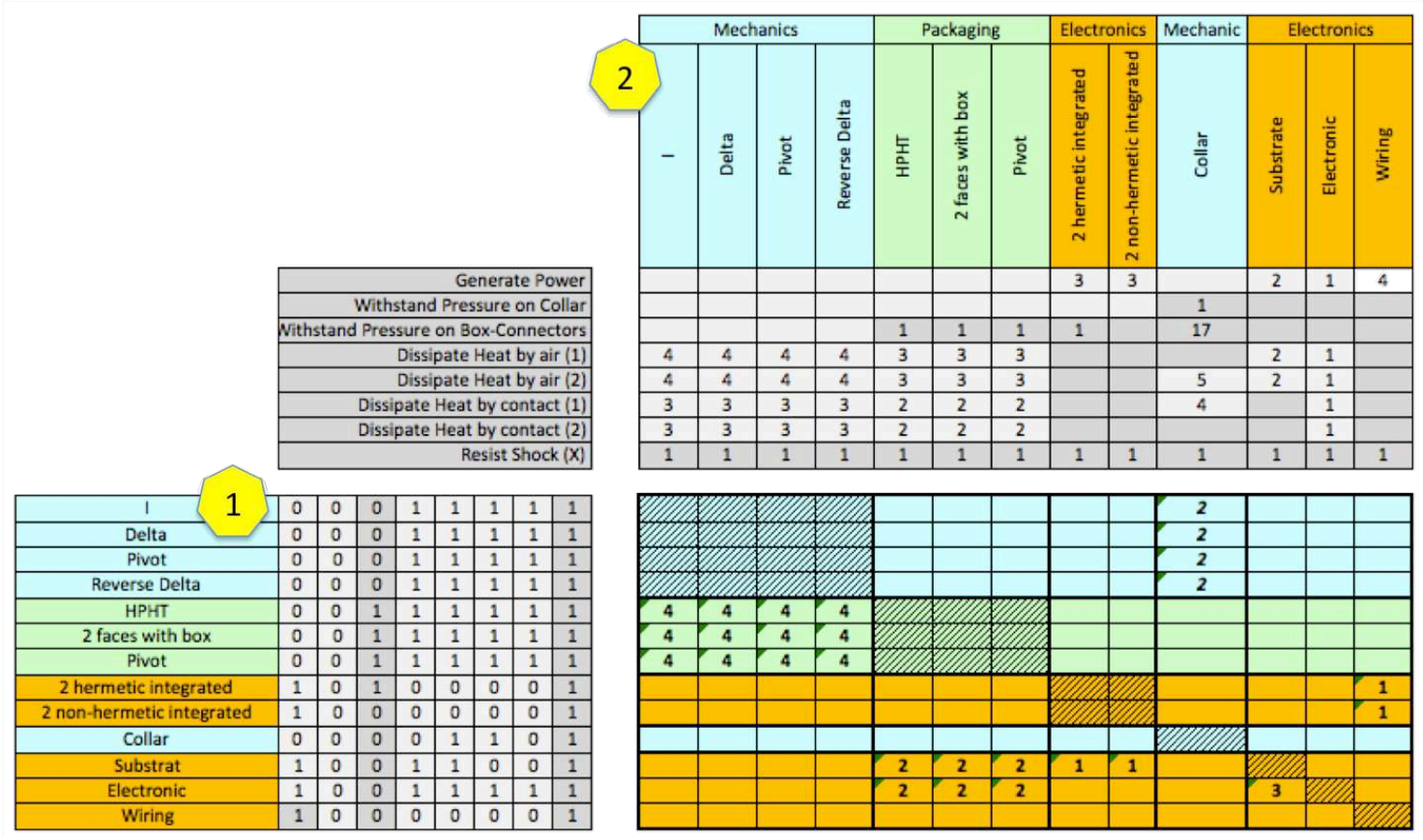


Figure 58: PEC example of the G matrix - DSM matrix rearranged

An entry in the G matrix signifies that the technical performance criterion listed in a row ("1" in Figure 58) sends design data to the technical performance criterion listed in the corresponding column ("2").

6.1.8. Collaborative-FMEA

Up to this point, our approach has only treated explicit areas of expertise; this section brings tacit data from the data model (introduced in section 0) into the framework of the project. In order to manage "difficult" points identified from the results of the six proposed design assessment cards, we propose to use these results as inputs for the collaborative-FMEA. This paragraph introduces our collaborative risk data model in the framework of the project: concepts, design departments, functions, technical solutions, and technical performance criteria are linked to the data model we introduced in section 0. The collaborative-FMEA is presented in the table that summarizes the risk feedback from the previous design and dimensioning of physical connections. Figure 59 presents the collaborative–FMEA as it is presented to design teams.

Filled in by MPDS Platform														Filled in by Design team			
Risk ID	Concept	Fonction	Technical Performance	Discipline	Module - Technical solution	Physical Connection	Design Parameter(s)	Risk Description	Mitigation Plan	Resource	Likelihood	Severity	Original exposure	Current Exposure	Owner	Expected date	Comments
56	8 - Pivot	Heat Dissipation	Easy assembly	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness	In a "glue" physical connection, shear strength and pull-off strength vary a lot with the variation of these desing parameters: Surface area between technical solutions, surface roughness, viscosity coefficient and thickness of glue. See design guideline number: 100236239	Look equations and target values extrated from empirical approach on the design guideline number: 100236239	Contact the Houston center and the glue specialist	5	5	25				
			Compactness	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Compactness per MCM	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Field maintainability	Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Reparability / Diagnostic	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Maturity of mechanical concept	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Harness integration	Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Simplicity of connectors	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Behaviors in high temperature	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Thermal management	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Number of connectors	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Cost	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
		Shock Resist	Easy assembly	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Compactness	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Compactness per MCM	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Field maintainability	Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Reparability / Diagnostic	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Maturity of mechanical concept	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Harness integration	Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Simplicity of connectors	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Behaviors in high temperature	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Thermal management	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Number of connectors	Packaging	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										
			Cost	Packaging & Mechanics	Chassis - Pivot, Box - Pivot	glue	surface area, roughness, viscosity coefficient, thickness										

Figure 59: PEC exemplary collaborative–FMEA in the framework of the project

The table shown in Figure 59 illustrates a collaborative risk (risk ID number 56, involving packaging and mechanics) for the design of a "glue" physical connection assembling the chassis and the box in "concept 8 –pivot". This risk can influence two functions, "dissipate heat" and "resist shock", by decreasing the value attained by thirteen technical performance criteria for these functions. Four design parameters must be accounted for during the design in order to lower the risk: contact surface area, surface roughness, viscosity coefficient, and thickness of glue. Filters are available for selection of the data type. The columns under the heading "Filled in by MPDS Platform" are automatically populated by our approach, while engineers must complete columns under the heading "Filled in by Design Team" in order to organize their tasks in reducing the risk. Traceability of this risk reduction is automatically ensured by recording the criticality profile over time.

6.2. An Excel platform for implementation of the method

This section introduces the current state of the MPDS Excel platform. This application will aim to automatically create MPDS connectivity maps using data from the FF-DMM, PC-DSM, and VoDD matrices. The platform returns the major design quality vectors and their design assessment cards.

The PC-DSM, FF-DMM, and VoDD matrices are filled in on different sheets. Redundant data are pushed into the other sheets to avoid inconsistency between them and to minimize the filling-in efforts. Each connectivity map is created on its own sheet using data from the three original matrices.

7. Experimentation case-study analysis and feedback

This section highlights key points from the results of the two case studies (referred to in this section as "PEC" and "Case Study #2") used to validate the MPDS methodology, both of which were in the same design stage: functional analyses had been carried out based on client expectations, and design teams were moving into the initial concept definition stage at the start of the design process.

Results are introduced with a presentation of the method implementation timeline, which is then further detailed. Then the brainstormed concepts, along with those generated by the MPDS process, are presented with their advantages and disadvantages. Finally, the influence of the MPDS outcome on the projects is summarized before presenting comments from the design teams.

7.1. PEC project

The experimentation was done during a three-day workshop. Schlumberger engineers joined engineers from our supplier for a total of eleven engineers (the project manager did not participate in this workshop). The schedule was as presented in Table 17.

Table 17: PEC experimentation planning

	Day 1	Day 2	Day 3: MPDS Method Implementation
Morning: 9h-12h	Problem framing	Concepts brainstorming	Gathering matrices
Afternoon: 14h-17h	Functional Analysis	Listing of technical performances	Results exploitation

Organization: The electrical engineer of the project led the workshop. The author was present during the workshop to guarantee the correct use of the proposed MPDS method.

Recommendations: During the brainstorming session, we recommend that there be one person dedicated to collecting the data and filling in the matrices in the correct format. The idea is to avoid unnecessary potential discussion about this part, in order to save time and focus directly on exploration of the results, etc.

Implementation process:

- Data collection and brainstorming: The first two days experienced progress as expected: workshop members implemented the problem framing steps: functional analysis, concepts brainstorming, and establishment of technical performance criteria. The author took notes and assembled data in the matrices in preparation for the subsequent steps of the method.
- Matrix development and exploration: the FF-DMM matrix was filled in with data from the functional analysis carried out the first day; the engineers validated it. We completed the PC-DSM matrix with the brainstormed concepts, and, in collaboration with the engineers, we extrapolated additional physical connections to assemble pairs of modules. A typology of physical connections,

their links to the data model, and the expertise required to design them were identified at the same time. We created performance scales to evaluate the technical performance of the modules present in the VoDD matrix. With these scales, the engineers performed 630 evaluations grouped into 130 blocks in two hours. The afternoon was dedicated to analysis and discussion of the results.

7.1.1. PEC starting point

The MPDS method began with nine concepts from the engineers' brainstorming session. Each of these concepts comprised six modules that have one to eight associated technical solutions (see Figure 60).

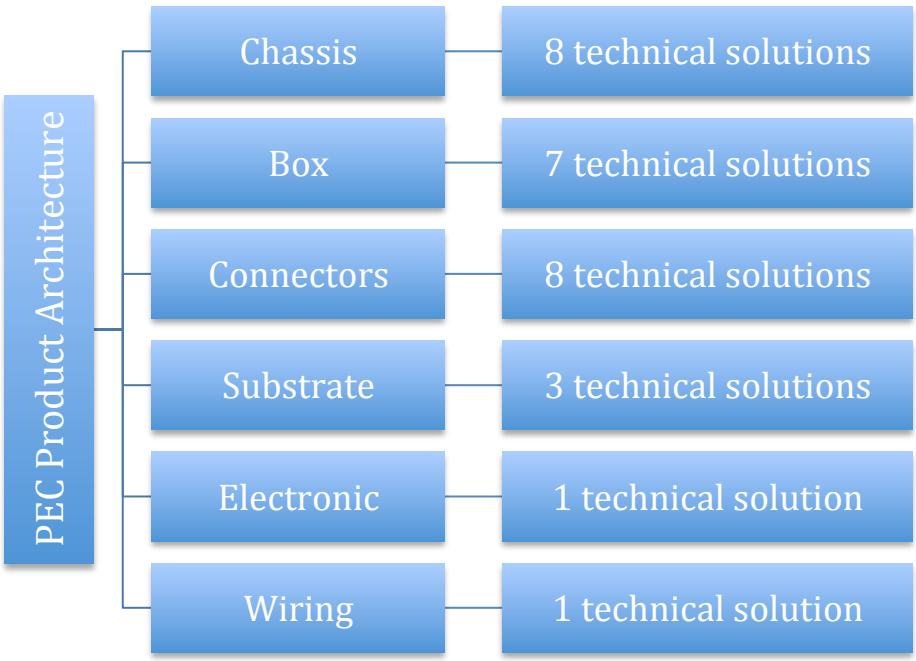


Figure 60: PEC architecture represented as a block diagram

All of the concepts created during the engineers' brainstorming session incorporated the chassis, box, connectors, substrate, electronics components, and wiring (each of which is referred to as a "module" in our approach). The nine concepts are described by 8 chassis solution alternatives (which means that two concepts use the same chassis solution), 7 box solution alternatives, 8 solution alternatives for the connectors, and 3 substrate solution alternatives. The nine concepts have identical electronics components and wiring (the alternatives are referred to as "technical solutions" in our approach). Figure 61 shows the technical solutions associated with the chassis and box modules.

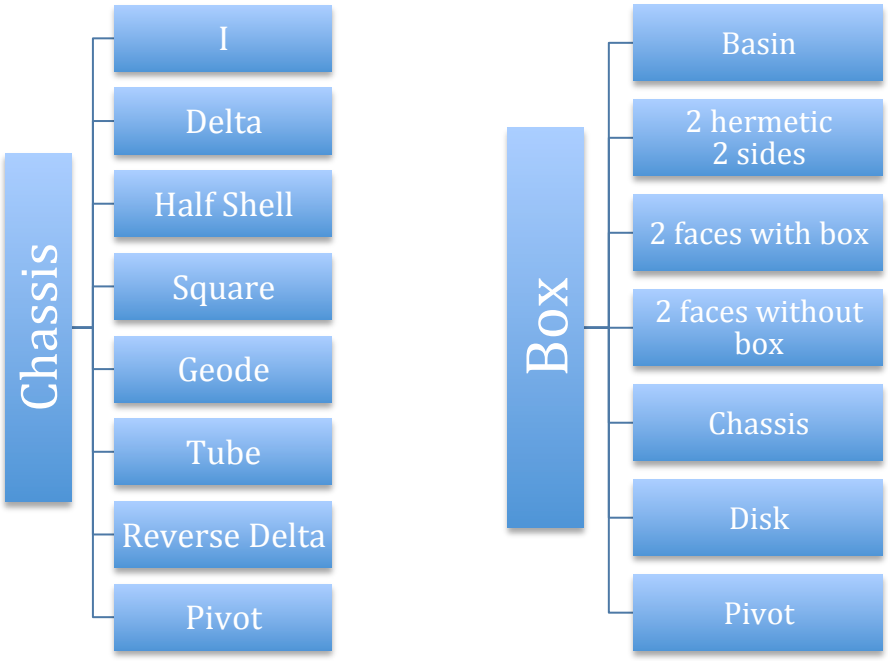


Figure 61: Decomposition of chassis and box modules and technical solutions for the PEC

7.1.2. MPDS implementation results: PEC

The process of filling in the matrices allowed the engineers to imagine three new alternatives:

- ✓ A new (conceived during the debate rather than the brainstorming session) substrate in assembly with a box from the brainstorming session, the "2 hermetic 2 sides" box. Advantages of this assembly are discussed in Table 18.
- ✓ Two new concepts, whose advantages are discussed in Table 19 and Table 20.

Table 18: Advantages of new substrate and box assembly

The assembly between the "2 hermetic 2 sides" box technical solution and a new substrate technical solution engenders certain advantages:
• Good thermal performance (box in contact with chassis) • Good versatility (large box space for large components) • Good access to test pins (side pins) • Simple assembly procedure (fastening with screws and local shock absorbers) • Good PEC effective area (passive components can be placed on the bottom face of the substrate) • Qualified connector • Excellent payload density (can include several PECs in one box)
And disadvantages:
• A very large box (130x30x15mm) can only be placed on a weak "I" chassis • Unqualified soft mounting • Current design is in Kovar; need to develop a box using a non-magnetic material with a low coefficient of thermal expansion

Table 19: Advantages of new concept #1

The box and substrate assembly discussed in Table 18 led to the concept discussed here. The advantages were highlighted during debates around the concept:
• Good PEC effective area (passive components can be placed on the bottom face of the substrate) • Uses standard 25-pin Micro-D connectors • Good thermal conduction (ceramic in contact with chassis) • Very good versatility (round shape with space for large components) • Good access to test pins (bottom pads) • Simple assembly procedure (fastening with screws and local shock absorbers) • Good payload density (minimum of three large PECs per cross section) • Low cost
Disadvantages:
• Unqualified brazing of the frame (qualified for Kovar only) • Unqualified flexible mounting • Unqualified connector • Unqualified use of ceramic in a structural component

Table 20: Advantages of new concept #2

This table shows another concept idea that arose during application of the method. Discussions among the engineers highlighted advantages of the modules of this concept:
• Very good thermal performance (ceramic in contact with chassis, close to the shock-receiving housing where heat is dissipated) => *chassis module* • Simple assembly procedure (fastening with screws and local shock absorbers) => *physical connection between chassis and box* • Very good versatility (round shape with space for large components) => *electronics component module* • Good access to test pins (bottom pads) • Low cost
But also disadvantages:
• Brazing of the frame unqualified (qualified for Kovar only) • Soft mounting unqualified • Connector unqualified • Use of ceramic in a structural component unqualified • High mechanical stress on the ceramic (ceramic placed in a high stress area) • Small effective area for PEC placement (one available face)

From the nine concepts brainstormed, the MPDS method returned nineteen concepts that were at least as good as the worst concepts devised by the engineers (see Table 6 for a partial list). The ranking of the nineteen concepts by the engineers shows that six of the ten best concepts were generated by our approach. However, the engineers had conceived three of the top four concepts. For political and company cultural reasons, the project was dedicated to what was felt to be the best concept, rather than continuing the

design process with the top four concepts proposed by the method. The project failed 18 months after this study due to an overlooked design parameter. Eventually, Schlumberger started a new design process with one of the other concepts from among the top four identified by our approach.

7.1.3. Lessons learned from PEC case study

Throughout the implementation process, the engineers noted several points:

- They found the approach gave structure to and helped with collecting data from their previous work
- They found it interesting to map the parameters of the functional analysis, concept, and technical performance representations. Some of them felt that "data collection and exploration alone represent an improvement in the design process"
- Some of engineers feared that the evaluation step could be time consuming. All of the engineers were surprised about the time spent in filling out the VoDD matrix: "pretty short for the capitalization made possible"
- The exploration and evaluation of the different concepts gave them clarity and induced general adherence of the engineers to the success of the project

7.2. Case Study #2 project

The study was carried out during a two-day workshop. Schlumberger engineers were mixed with a silent partner (internal to Schlumberger), project manager, and design department experts, for a total of about fifteen engineers. The planning of the workshop is presented in Table 21.

Table 21: Case Study #2 planning

	Day 1	**Day 2: Application of MPDS Method**
Morning: 9h-12h	Problem framing	Filling in matrices
Afternoon: 14h-17h	Presentation of concepts and their technical performance	Discussion and application of results

Organization: The mechanical engineer of the project in Case Study #2 led the workshop**.** The beginning of the workshop involved a presentation of the different aspects of the design process and the different challenges that were to be addressed. The second day of the workshop, the author led the meeting and its conclusions.

Recommendations: During the brainstorming session, we recommend that there be one person dedicated to gathering the data and filling in the matrices in the correct format. The idea is to avoid unnecessary potential discussion about this part, in order to save time and focus directly on exploration of the results, etc.

Implementation process: In this case study, the engineers carried out 288 evaluations and grouped them into 38 blocks in three hours.

7.2.1. Case Study #2 starting point

The process began with ten concepts from the engineers' brainstorming session (see Figure 62). Each of these concepts comprises five modules that have one to ten associated technical solutions.

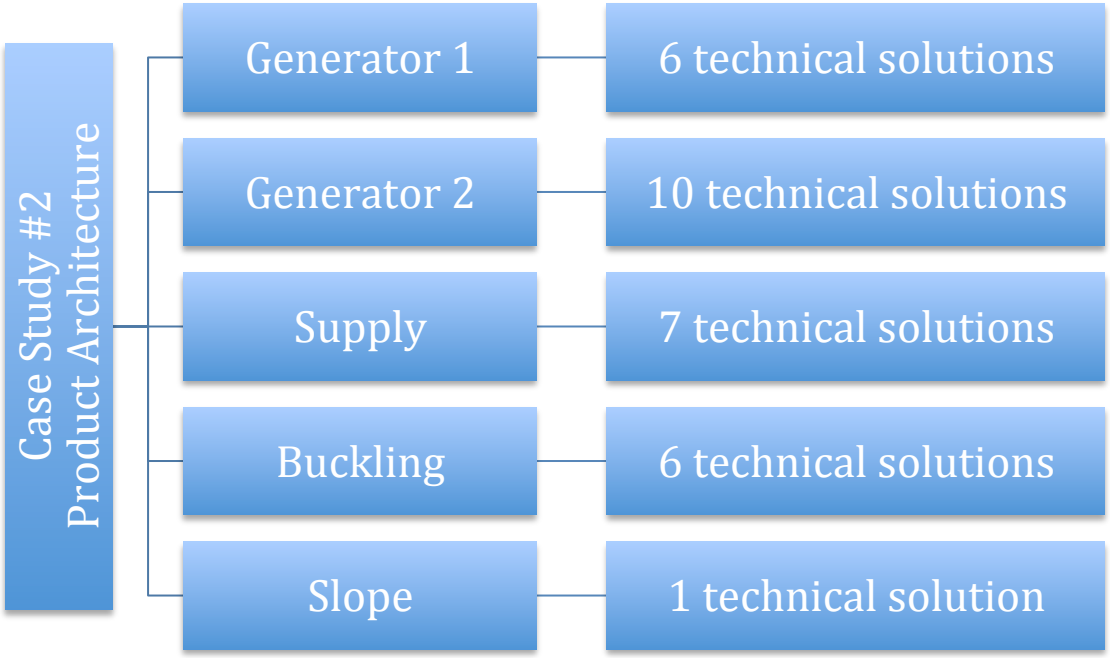


Figure 62: Case Study #2 architecture represented as a block diagram

7.2.2. MPDS implementation results: Case Study #2

The process of filling in the matrices allowed the engineers to imagine four new module alternatives. These new module alternatives can be combined to create two new concepts (advantages and disadvantages presented in Table 22).

Table 22: Debated advantages and disadvantages of the new concepts

Advantages:
• Length of product close to the useful drill length • Simple connection with bottom module
Disadvantages:
• For a majority of the new modules: technological design risks • Engineering development time

From the ten original concepts from the engineers' brainstorming session, before application of the MPDS method, the method generated thirty-eight new concepts that were ranked to be at least as good as the worst among those conceived by the engineers. This ranking showed that nine of the top ten concepts were generated by our approach. The design team proceeded with the fifteen "best" concepts, which were partitioned into three technological groups:

- Group 1 is composed of concepts created by the engineers before application of the method. The main advantage is that they use existing modules; the disadvantages are that the concepts are not all multifunctional, and their motions are discontinuous.
- Group 2 mixes concepts created by the engineers with those generated by the method. These concepts have the advantages of being compact, having a small diameter, and being continuous in their motions, but they involve technical risks and take a long time to develop (engineering).
- Group 3 is composed exclusively of concepts generated by our approach. Advantages: the forces are generated near where they are needed (reducing the need to transfer forces), there is no need for anti-buckling measures (more reliable); disadvantages: the concepts are new developments (time-consuming and risky), and they are characterized by discontinuous motions.

No other workshop was held before the project stopped in 2008 due to financial problems, but at this time, the project had not met with design difficulties that were not planned for in any of the three concept groups.

7.2.3. Case Study #2 lessons learned from engineers

The design team, which requested the application of the MPDS method, was pleased with the clear representations and results they obtained. They noted several points:

- "It is clear now that some concepts that we imagined are really better than the others; we did not see that before this workshop"
- The project manager was doubtful about the approach due to the fact that no industrial standard was involved and that his preferred concept was not highly ranked
- The silent partner was convinced about the progress made in the project using the method

7.3. Difficulty in the industrial application of the method

This paragraph presents the difficulties in applying such an approach in industry, based on three aspects: expertise, organization, and understanding of results.

From a methodological point of view, our approach introduces known tools: functional analysis, architectural breakdown, and performance analyses modeled in DSM, DMM, and QFD matrices. Connectivity maps that can be difficult to manipulate are computed by an Excel platform in an automatic process. The process of filling in matrices influences the results of the approach and must be done while respecting the recommendations given in section 5.1.1.

From an organizational standpoint, the success of the MPDS method is dependent upon the panel of experts. Experts from all design departments at different levels of design

(from engineering to manufacturing) must be involved in the process. We recommend having a person outside the design team conduct execution of the MPDS method. In both case studies, we test the stability of the results based on the assumption that experts can be wrong in their evaluations. We apply a virtual variation of one value scale to the scores of 10% of the technical performance criteria. The results of this variation demonstrate that the final ranking of solutions was not changed; we therefore consider our approach to be robust against a small variation.

From our experience, the acceptance of results is the biggest difficulty in the application of such an approach in an industrial context. The engineers and architects continue to try to push their preferred solution forward. The results of the MPDS method must be stable, considering that experts can be biased in their evaluation. We demonstrate this stability by modifying a few of the evaluations performed by the experts by one value scale and finding an unchanged overall result.

7.3.1. Integration of method in current and future design processes

This paragraph introduces the integration of the MPDS method in both current (through 2010) and future (2011 on) Schlumberger design processes.

The MPDS process is in accordance with the Schlumberger design process (Product Life Cycle Process): the generation and the evaluation of concepts follow the functional analysis and structural product breakdown. Moreover, our approach is a support tool for design teams for the detection and resolution of multi-physics design problems identified in our analyses (HOLLEY ; HOLLEY). This incorporation of design problem lessons learned into the design process is in line with the fundamental objective of Schlumberger's new design process (Collaborative Lifecycle Management System): to promote improved collaboration between engineers from different design departments.

7. Conclusion and perspectives

Highly constrained multi-physics systems involve multiple functional flows that share common flow pathways through the product architecture. Operation of these systems in severe conditions (high temperatures, high pressures, and shock and vibration conditions in limited dimensions) involving engineering designers in different design departments (mechanics, electronics, physics of sensors, etc.) introduces some challenging issues in the design process. One of the major concerns is that higher level technical performance may be too constrained and may block the design process. Moreover, in the design process, different design departments are more or less constrained depending upon the target technical performance criteria and the given concept architecture. We have already highlighted problems in the design process that can result in delays with dramatic consequences.

In order to address these issues, we propose the multi-physics design scorecard (MPDS) method and adopting conventional representation models: the design structure matrix (DSM) to represent admissible architecture connection and dependency configurations, the domain mapping matrix (DMM) to link functions and architecture, and quality function deployment (QFD) to evaluate technical performance criteria. However, we propose to enrich these representations. DSM matrix representation is to be enriched with the connection typology, allowing a range of choices at an early design stage. For a given connection, some related data about the natures of probable difficulties is known. DMM matrix representation is to be enriched with the flow along the architectural modules.

We believe that this ontological enrichment of design data can permit new and useful design assessments for multi-physics systems. In our approach, we presented **seven design assessment cards** aimed at supporting the design team as meaningful tools in the process of choosing from among different potential concept configurations. This process is driven by the necessity to avoid highly constrained constrainable objects and then by balancing and spreading out the design challenges within the system. The assessment cards are organized into **two major design quality vectors**: the **ambition vector** and the **difficulty vector**. The ambition vector defines the degrees of opportunities that are available at a given point in the design process. The difficulty vector aims to identify different difficulties and their impact in realizing given concepts.

This MPDS method has been applied to two case studies with our industrial partner, Schlumberger. The method allowed us to generate and analyze concepts and immediately generated data highly relevant in the design process. The ranking of the concepts in the first study demonstrated that the design team had found the best concepts. All of the concepts were analyzed, and this analysis predicted design problems the engineers had not known to think of. The second study was very valuable in the generation of concepts: starting with ten concepts brainstormed by the design team, the method generated thirty-eight new concepts that were evaluated to be better than the worst concepts envisioned by the engineers. Moreover, nine concepts generated by the MPDS method were ranked in the top ten.

Both design teams appreciated this application of the MPDS method: the method is quite easy to understand and apply. Results concerning the identification of collaborative design difficulties (the C-FMEA) were handicapped by the lack of incorporation of results by our industrial partner.

7.1. Future work

The MPDS method generates consistent concepts and analyzes them based on design scorecards. The next improvement should be to rank concepts by the difficulties that engineers would prefer to resolve, in order that a pairwise comparison might be made.

The MPDS method is supported by an Excel platform. This application is not yet fully automated: data must be filled in by hand, inviting possible mistakes, and connectivity maps must be computed manually. Our platform must be improved for faster and more reliable results, using menu trees for data entry and Visual Basic for Applications (VBA) for computation of connectivity maps.

Based on our proposed typology, the MPDS method only manages physical connections. It may be of interest to manage more than physical connections to be able to cover the overall collaborative design difficulties. The first step is to extend the class of connections managed by the MPDS method to the five types of dependencies identified by Sosa et al. (SOSA, EPPINGER et al. 2003): spatial, structural, energy, material, and data. The data model must be adapted to these different dependencies, and both ambition and constraint vectors must be redefined based on the potential expansion of the connectivity maps.

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