Developing a Use Case for implementing Modular Engineering at Portfolio Companies

by

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Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management
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Abstract

Modular engineering allows the creation of a product architecture that prepares the product families of companies for a fast response to changes in technology and customer demand. This thesis will focus on developing and proposing a methodology for implementing modular engineering at AIP's portfolio companies and ensure that the implementation is replicable in any other of its companies. AIP companies are from very diverse industries and offer multiple heterogeneous products. The proposed methodology will make it possible to target companies and products that are good candidates for the implementation of modularity from the standpoint of cost benefit.

One AIP portfolio company is currently implementing modular engineering. This project was the base for creating a use case. This thesis explores the methodology used by the portfolio company for designing a modular architecture and proposes an automated approach using machine learning techniques. This will allow a faster creation and evaluation of the modular architecture. In addition, the modular project benefits are: fewer unique part numbers, less assembly time, lower direct purchasing costs, fewer suppliers, faster time to market, shorter lead-time and more market offerings. The bottom line benefit is a streamlined operation that would add value to the company. Finally, this thesis summarizes the lessons learned of the modular engineering implementation to serve as a guide for future implementations on portfolio companies.

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Chapter 1

Introduction

This chapter presents the reason for the project and it aims to define the problem that this thesis addresses. In additions it presents a brief summary of what is discussed in every chapter.

1.1 Project Motivation

Once AIP acquires a control position on a company, in order to add value, it starts developing an operating agenda in collaboration with the company's management team. Often times, it is the case that the portfolio companies carry integrated product lines. These product lines usually have complex supply chains and manufacturing operations, sometimes determined by legacy and often times by add-on acquisitions of other companies that carry similar products. These product lines have the potential to be modularized in order to achieve some of the following benefits:

- Reduction of the part numbers: as the product development evolves on the companies, frequently, more unique parts are added to the designs. In addition, the complexity of the organizations sometimes prevents the multiple design teams from doing checks and balances for streamlining the designs.

- Decrease the assembly time: when a product is dis-integrated in modules, it enables the different modules to be assembled in parallel and even at different facilities, being closer to the final customer.

- Decrease the purchasing costs: by consolidating multiple parts on fewer unique part numbers it gives the organization an opportunity to achieve economies of scale and therefore power of negotiation with suppliers.
- Reduction on the number of suppliers: when fewer parts are required, there is an opportunity to consolidate the number of required suppliers, allowing the organization to focus more on the suppliers with the same or even less resources.
- Reduced time to launch into the market: once a good modular design is established, it is relatively simple to fit the market needs with different variants of the same base product and even adapt to technology evolutions.
- Decreased lead-time: not only because the assembly time is being shortened, but also by having fewer parts to procure and fewer suppliers to deal with, it removes complexity from the value chain, allowing a faster order to delivery time.
- Increased number of configurations offered: as a result and by definition, modularity provides the opportunity to offer different configurations of a product as the market changes or technology evolves.

The bottom line benefit is a streamlined operation that would add value to the company.

1.2 Problem Statement

AIP acquires controlling interest in industrial businesses. Often times, these businesses carry product lines that vary in complexity. Given the niche segments on which AIP portfolio companies generally compete, it is important that the product architecture is flexible enough in order to be able to adapt to customer demand, changes in technology and multiple configurations.

Every new company that AIP acquires, comes with its own product development practices that have been structured in the companies in accordance with its background, the type of industry and products. However, some of these companies have had a slow adaptation to the ever-changing conditions of the market. In addition, the time to market is not fast enough preventing the companies from taking the advantages of being the first offer in the market. This thesis explores the creation of a modular architecture as a means to address the complexity of the products and better utilize internal resources and lever the external resources.

There is no universal methodology to divide a product into separate modules. There are rather developed methods that present different approaches to the task of conceptualizing a product and then dividing it into modules. It will also address the need of organizational change in order to support the modular product architecture and its derivations.

1.3 Thesis Overview

This thesis is based on the input gathered from the implementation of a modular engineering project at one portfolio company of AIP. It analyzes the method followed by the company, the expected results and the potential benefits.

Chapter 2 introduces a brief background on ground-breaking events that have shaped the industry as an explanation on the importance of the actual trends of the industry and a justification for the desire of modernization on the product development activities.

Chapter 3 presents a literature review and sets the basis for the language that will be used in the rest of the thesis. It shows the theory of the good design, the origins of modularity, its definitions and its limits.

Chapter 4 introduces the case of The Portfolio Company, presents its particular problem statement, its proposed solutions, the stake holders working on the project, the goals, the method used for developing the modular platform and finally it introduces the concept of *modular engineering*.

Chapter 5 explains the purpose of the thesis from the stand point of AIP and its portfolio companies, its goals and its limits.

Chapter 6 documents all of the implementation of the modular engineering project at The Portfolio Company. It goes through the method step by step and presents the data obtained and the tools used to finally present the resulting module concept. Then, it introduces the basis for an alternate method that could complement the MFD^{TM} (Modular Function Deployment) method.

Chapter 7 recapitulates the product development process and jumps into the application of the proposed alternate method. It goes step by step introducing clustering techniques and presents the results of the implementation.

Chapter 8 makes the case for implementing modular engineering by presenting a cost analysis that explores the savings and benefits of migrating to a modular platform and proposes an outsourcing model as a result.

Chapter 9 concludes with a few general remarks about the implementation of modular engineering and proposes future work that complements the proposed method.

Chapter 2

Background

This chapter discusses the advent of modular design in general, its origins and some study cases. It will also discuss the current trends of the industry and in particular, the trends in the portfolio companies focusing on one portfolio company that develops automated equipment.

2.1 Industry 4.0

The first industrial revolution took place in the 18^{th} and 19^{th} centuries, when the major shift in the manufacturing processes came about and the use of machines transformed the landscape in the industry. Then, by the end of the 19^{th} century - early 20^{th}, the Second Industrial Revolution, added great inventions like the assembly line and the concept of mass production[7]. The Third Industrial Revolution during the 1980s introduced the transition from analog electronics to digital technologies like computers, robots and automation in general. Thanks to the advancement of the digital technologies and the breakthrough of new ones, we are now in the edge of the beginning of the Forth Industrial Revolution (See figure 2-1). "Industrie 4.0" is a term coined in a project in the high-tech strategy on the German government, that refers to digitalization of manufacturing[3]. This term is now used to refer to a number of industry trends. Some of the main trends are as follows:

- Cloud computing
- Big data and analytics

- Additive manufacturing
- The Industrial Internet of Things
- Autonomous Robots
- Horizontal and vertical integration
- Modular Engineering

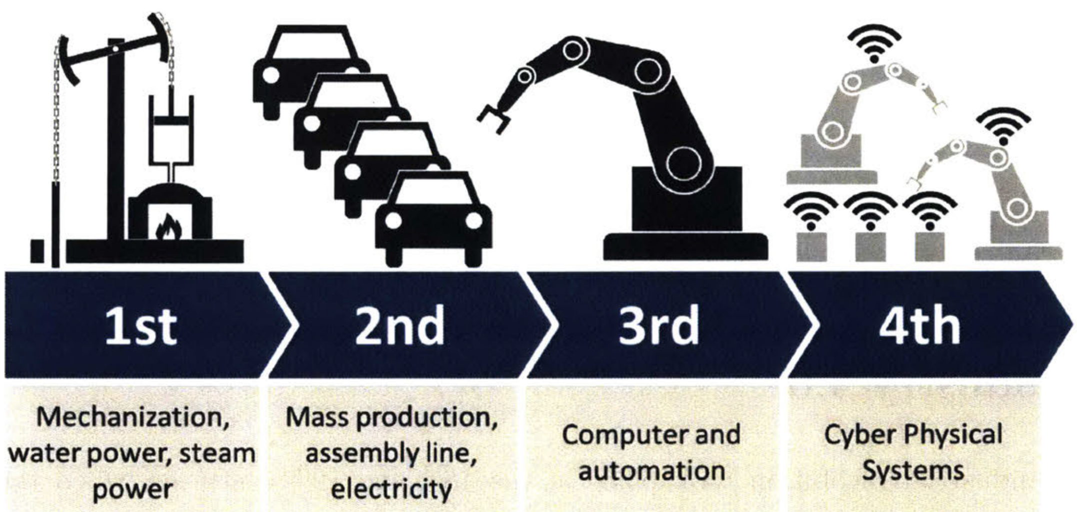

Figure 2-1: Industrial revolutions and future view[2]

2.2 Modular Architecture project at the portfolio company

In order to understand what are the potential benefits of migrating to modular design, as part of the project, it is necessary to research the latest modular engineering practices and technologies. This includes to research the state-of-the-art industry trends (IoT, big data and analytics, etc.) and adapt this methodology to AIP's needs. By the time that I stated my project, one of AIP's portfolio companies, which will be referred as "The Portfolio Company", was starting to work on a modular engineering project and I decided to consider it as the case study for this thesis. The Portfolio Company's project will provide data about best practices and lessons learned.

The project goal on The Portfolio Company is to develop a modular platform of one of their products which will be referred as "The product". As competitors entered the segment of this type of products with more technologically advanced products and competitive pricing, it is imperative for The Portfolio Company to come up with a modernized platform. This new platform should provide its customers with improved capabilities, renovated technology, improved lead-times and still keep its reliability.

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Chapter 3

Literature Review

New technologies make possible to develop new products that cover needs. This chapter discusses the design theories that give origin to some modularity concepts. It also addresses some of the most useful methods that aim to obtain and understand the customer needs. It explains the different types of modularity and finally, it addresses some of the limits to modularity.

3.1 Axiomatic Design

Developed by Dr. Nam P. Suh at the MIT, Department of Mechanical Engineering in the 1990s, Axiomatic Design (AD) is a design methodology whose ultimate goal is to provide scientific basis and improve the design process by providing theoretical tools and processes[12]. In addition, it proposes a criterion for good or bad design decisions early in the process, allowing the designers to focus on the good designs and discarding the less promising designs.

Concepts

The following concepts are the base language to understand the methodology:

Domains

Dr. Nam P. Suh, presents "a definition of design as a mapping between 'what we want to achieve' and 'how we want to achieve it'"[12] see Figure 3-1 below.

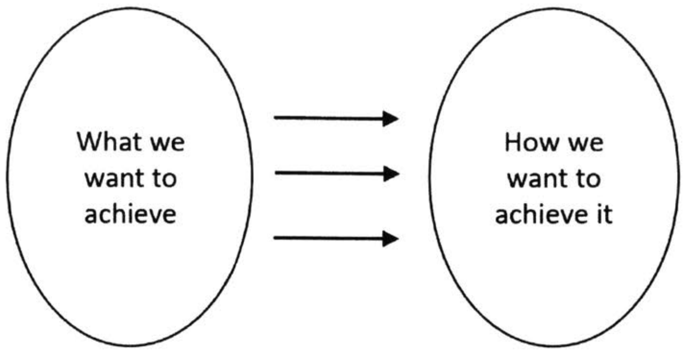

Figure 3-1: Definition of a design as a mapping between "what we want to achieve" and "how we want to achieve it."[12]

Building on this basic concept, then proposes the axiomatic design framework that consists of four domains: the *customer domain*, the *functional domain*, the *physical domain* and *process domain*.[12]

The *customer domain* represents the needs from the customer. Within the *functional domain* we have the *functional requirements* (FRs) and *constraints* (Cs). In order to satisfy the FRs, we generate the *design parameters* (DP) in the *physical domain*. Then in order to make the product, that is specified in terms of DPs, it is required to develop a process that has *process variables* (PVs) in the *process domain*.[12]

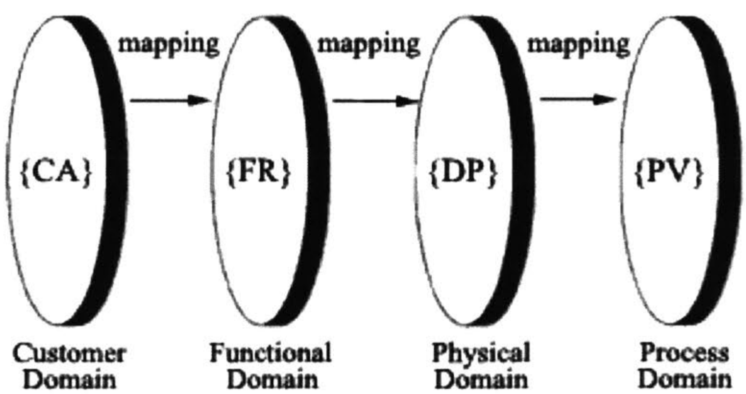

Figure 3-2: "Four domains of the design world. The {x} are the characteristic vector of each domain. During the design process we go from the domain on the left to the domain on the right. The process is iterative in the sense that the designer can go back to the domain on the left based on the ideas generated in the right domain."[12]

Functional Requirements

"Functional requirements (FRs) are a minimum set of independent requirements that completely characterizes the functional needs of the product ... in the functional domain. By definition each FR is independent of every other FR at the time the FRs are established"[12].

Constraints

"Constraints (Cs) are bounds on acceptable solutions. There are two types of constraints: input constraints and system constraints. Input constraints are imposed as a part of the design specifications. System constrains are constraints imposed by the system in which the design solution must function."[12]

Design Parameter

"Design Parameters (DPs) are the key physical variables ... in the *physical domain* that characterize the design that satisfies the specified FRs."[12]

Process variable

"Process variables (PVs) are the key variables ... in the *process domain* that characterize the process that can generate the specified DPs."[12]

Decomposing and hierarchy

As part of the design process, it is necessary to decompose the characteristic vectors FRs, DPs, and PVs. This process consists of digging down layer by layer from the highest level of FRs or DPs, toward a more detailed level until the design reaches the final stage, having as a result, a design that can be implemented. "Through this decomposition process we establish hierarchies of FRs, DPs, and PVs, which are a representation of the design architecture."[12]

Zigzagging

During the design process, when we map from the *functional domain* to the *physical domain*, we obtain the highest level conceptual design. Oftentimes, we need more details in order to complete the design; this is developed by decomposing the highest levels of FRs and DPs.[12] It is important to note that during the decomposing process it is not possible to find out what FR is required at the next level, until a DP has been chosen at the previous level. This is the reason why it is necessary to zigzag between domains. Let's suppose that it has been decided for a linear motion system to be rack-and-pinion and its DPs have been defined. The FRs at the next level, then would be in the rack-and-pinion environment. If the selection was in favor of a ball screw drive, then it would be necessary to consider FRs in the ball screw drive environment. It is not possible to just decompose FRs down to the bottom without making some DP decision along the way. We need to start out in the "what" domain and then we go to the "how" domain. See below in Figure 3-3, where we go from the FR in the *functional domain* to the *physical domain* in order to conceptualize a design and obtain its corresponding DP.[12]

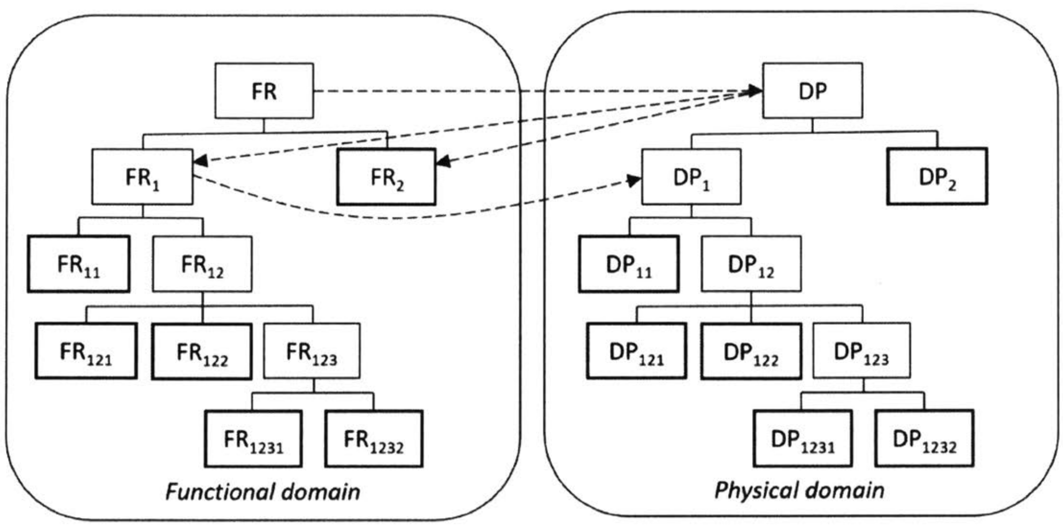

Figure 3-3: "Zigzagging to decompose FRs and DPs in the functional and the *physical domains* and to create the FR and DP hierarchies. Boxes with thick lines represent "leaves" that do not require further decomposition."[12]

Mapping process of Axiomatic Design

Dr. Suh acknowledges that sometimes it is difficult to define the customer needs but proposes an interesting rule for defining them: "to ask the right questions to the right customers at the right time."[12] There are multiple methods for defining the customer needs in a systematic fashion and some of them are addressed in this chapter, section 3.3.

Once the customer needs (in reference to a product's attributes) have been defined, then, a mapping process needs to happen with the objective of translating them into FRs. However, an important point is that this mapping has to happen within a "solution-neutral environment".[12] "That means that the FRs must be defined without ever thinking about something that has already been designed or what the design solution should be."[12] Otherwise, the process will introduce a personal bias that will lead to the specification of the FRs of an existing product therefore defeating the purpose of spurring creative thinking.[12]

The hypothesis of AD is that there are axioms that can help to distinguish good designs.[12] These are the two axioms of AD:

The Independence Axiom *(Axiom 1): Maintain the independence of the functional requirements* (FRs). As stated before, "the FRs are the minimum set of independent requirements that the design must satisfy"[12]. Therefore, "when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs".[12]

The Information Axiom *(Axiom 2): Minimize the information content of the design.* Since "there can be many designs that satisfy a set of FRs"[12], Axiom 2, "provides a quantitative measure of the merits of a given design"[12], making it easier to identify a superior design. Axiom 2, "states that the design with the highest probability of success is the best design".[12]

In this context, "information content I_i for a given FR_i is defined in terms of the probability P_i of satisfying FR_i."[12]

$$I_i = \log_2 \frac{1}{P_i} = -\log_2 P_i \tag{3.1}$$

"The mapping process between the domains"[12] (customer, functional, physical and *process domains*) "can be expressed mathematically in terms of the characteristic vectors"[12] (FR, DP) "that define the design goals and design solutions."[12] "The relationship between these vectors can be written as"[12]:

$$\{FR\} = [A]\{DP\} \tag{3.2}$$

"where [A] is called the *design matrix* that characterizes the product design."[12]. As an example, for a design with three FRs and three DPs, the design matrix would be as follows:

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{3.3}$$

"There are two special cases of the design matrix: the diagonal matrix and the triangular matrix. In the diagonal matrix, all $A_{ij} = 0$ except those where i = j.

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \tag{3.4}$$

In the lower triangular (**LT**) matrix, all lower triangular elements are equal to zero, as shown below.

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \text{"[12]} \tag{3.5}$$

This is important since in order to satisfy the independence Axiom, the design must be either diagonal or triangular.[12] In addition, if the matrix is diagonal or lower triangular, the equation can be easily solved for the first FR, since there is only one unknown. Then a waterfall method can be applied to solve for the second one and so on.

Modularity in Axiomatic Design

The concept of "module" is used in AD as it is relevant in system design. To avoid confusion, it is important to say that AD states that a module is not a piece of hardware even though in some instances, it might be the case. In addition, "it is important to note, that a module in a hardware system does not correspond to a physical component of the hardware. In a hardware component, there can be many DPs and, therefore, there can be many modules associated with a given piece of hardware system."[12] The definition of module in AD is as follows: "A *module* is defined as the row of the design matrix that yields an FR when it is provided with (or multiplied by) the input of its corresponding DP. For example, consider the following design equation:"[12]

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \end{Bmatrix} = \begin{bmatrix} \mathrm{a} & 0 \\ \mathrm{b} & \mathrm{c} \end{bmatrix} \begin{Bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \end{Bmatrix} \tag{3.6}$$

"M_1 is the module that corresponds to the combination of the first row of the design matrix and DP_1, i.e., when DP_1 is supplied as input to M_1, FR_1 results as the output. Similarly, FR_2 is obtained when DP_2 is provided as an input to the module M_2".[12]

3.2 Modularity concepts

The book "Design Rules: The Power of Modularity, Volume 1"[4] provides a succinct but deep definition of modularity: "modularity is a particular design structure, in which parameters and tasks are interdependent within units (modules) and independent across them".[4] In addition, the book mentions that modularity might occur in three different contexts: design, production and use.

Modularity in design: in this context the design task can be divided so it can be performed in parallel by multiple teams at the same time.[4] For example, the design of a landing gear. The electrical design team would be working on the electrical wire harnesses and connectors that will monitor the tires pressure, the hydraulics team would be designing the manifolds and routing of the metal tubes that will allow the landing gear to extend and retract and the structural mechanical team would be in charge of designing the structure of the landing gear that will integrate all of the systems. These teams would meet at milestones in order to review their design, however they enjoy some independency as long as the design rules have been well understood.

Modularity in production: this context refers to the situations when a manufacturing process is divided into process modules (or cells) in order to remove complexity.[4] For example, the manufacturing process of an aerospace grade connector, might require multiple processes: the machining of the part, which is done in a machine shop, then, tube bending (if it is a 90deg. elbow), welding, passivation process, etc. All of these processes are performed in separate cell in order to achieve the final product.

Modularity in use: in this case the consumers are enabled to mix and match the different parts in order to come up with the final product.[4] One example could be a car: the owners can change the tires for different types of tires, the rims from steel to aluminum, etc. This works as long as the manufacturers follow the standard sizes of the rims and tires that can work for a variety of cars. These standard sizes are the design rules.[4]

Modularity as an option

One of the business advantages of modularity is that it creates design "options" that can change the value of multiple designs.[4] The concept of "options" should be understood in the context of finance: "an option is 'the right but not the obligation' to purchase or sell something—a security, a contract, or a design—in the future."[4] In other words, the holder of the option can wait until the agreed date and, depending on the outcome, they can decide to purchase or sell at their convenience.[4] We can draw an analogy to the design context, by thinking of a modular design as an *option*. Since the design is created in modules, the stake holders have the *option* to further pursue the design of a module or cancel that specific module, if the outcome of the design was not as expected. On the other hand, if the design is not modular, as the design progresses, it becomes more and more costly to cancel a design since it often times becomes an all-or-nothing decision.

Just like the *options* in the context of finance, the design options can be valuated based on the work of Fischer Black, Myron Scholes, and Robert Merton[4], however, the valuation of design options, goes beyond the scope of this thesis.

In a modular design, designers can take decisions on their modules with no need to consult the designers of the other modules, as long as all of the designers respect the design rules. Figure 3-4 shows "the option structure of a design process before and after modularization"[4]

Design rules

In a modular system, in order for the modules to properly work in the system, it is a must that the designers follow a predetermined set of design rules. "Modular design rules establish

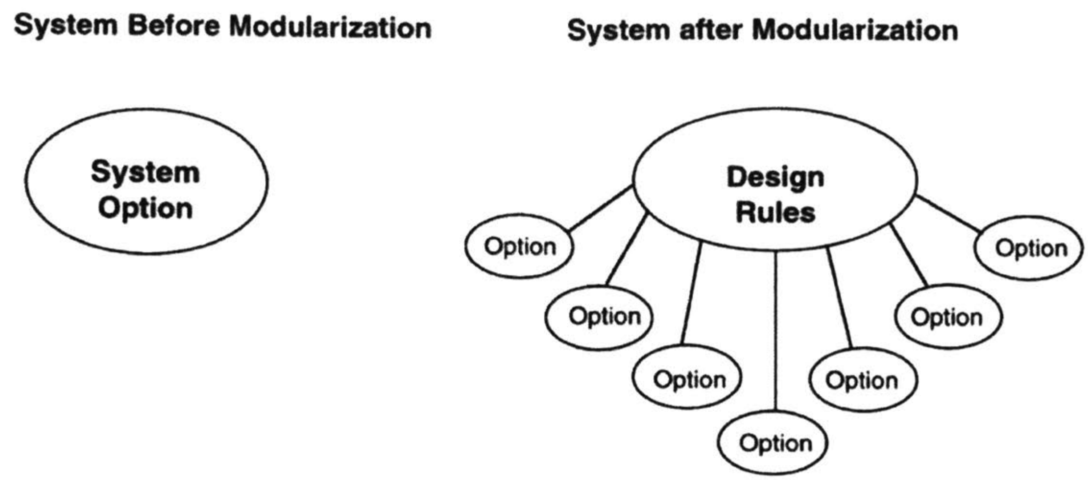

Figure 3-4: "Modularity creates design options."[4]

strict partitions of knowledge and effort at the outset of a design process. They are not just guidelines or recommendations: they must be rigorously obeyed in all phases of design and production. Operationally, this means that designers may not solve the problems of module A by tweaking parameters affecting module B."[4]

3.3 Understanding the customer needs or required product attributes

In product development, it is key for the designers to understand the customer needs in order to have a successful design. Even though this might sound obvious, often times this step of the process gets less attention from the designers and as a consequence some needs of the customers are overlooked. In order to avoid missing important needs from the customer, it is recommended to use a systematic way to capture the customer needs. There are some very useful tools that have been extensively used and have been proven practical. Let's introduce some of them.

Quality Function Deployment (QDF)

Created in Japan in 1996, QFD is a "method to transform qualitative user demands into quantitative parameters, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process."[1] In other words, QFD is a method for obtaining the CAs. A central method of QFD is the house of quality (See Figure 3-5), it identifies and classifies the customer needs and relates them to engineering characteristics, it compares them against the products of the competitors and from there it obtains the relevant engineering characteristics and selects the relevant areas of improvement.[12]

Pugh matrix

Created by Stuart Pugh, the Pugh matrix is a very useful and simple tool that can be used for evaluating several alternatives to a baseline[10]. It can be used for ranking the customer needs, however, we have to note that this tool is more useful at improving an existing product, but it is not very effective in developing new products.[12]

As an example, let's say that we want to decide among four different types of drives for the linear motion systems of a product to propose what would be the best type from the customer's stand point: ball screw, rubber band, rack-and-pinion and chain drive. Then, let's say that for evaluating them, we will consider four criteria that the customer cares about: precision, cost, noise level and maintenance requirement. We will take as our baseline the ball screw drive. The Pugh matrix will look as follows:

Table 3.1: Pugh matrix

Criteria	**Ball screw**	**Weight**	**Rubber band**	**Rack-and-pinion**	**Chain drive**
Precision	**0**	3	-3	0	-3
Cost	**0**	5	+5	+5	+5
Noise level	**0**	2	+2	0	0
Maintenance requirement	**0**	4	-4	0	-4
		Total	4	25	0

The baseline for benchmark is ball screw and has "0" in all of the criteria. The column weight allows us to give different weight to the criteria. The scores are "0" if it is close to

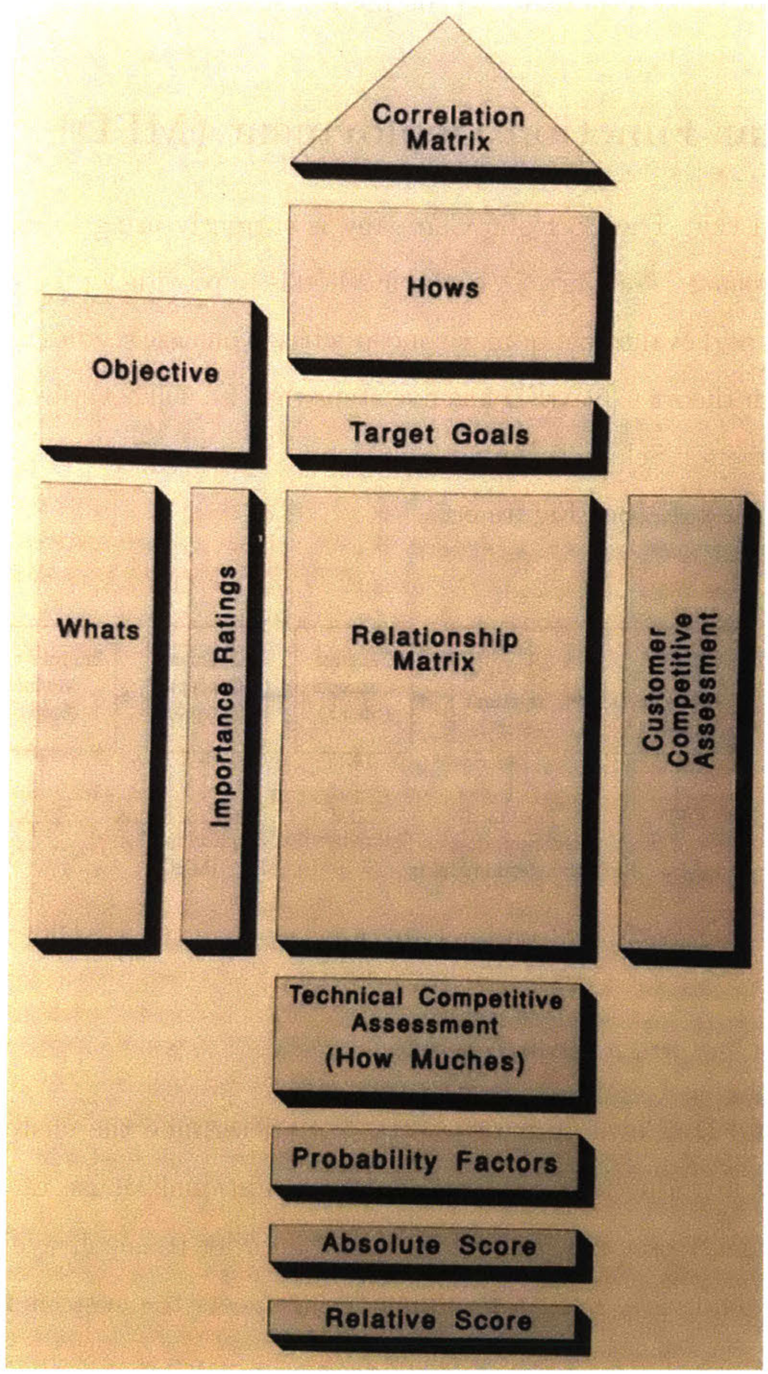

Figure 3-5: "Components of the QFD model."[8]

the baseline, "+1" if it is better, "-1" if it is worse. Then, the scores are multiplied by the weight column in order to get the result. As shown in this example, clearly rack-and-pinion is the best option of all, as it adds up to the highest score.

3.4 Modular Function Deployment (MFD)

This is the method that The Portfolio Company is currently using to develop the modular platform of *The Product*. The purpose of the method is to provide a procedure for developing a modular product and evaluate modular concepts based on case studies using empirical data and accepted design theories.[6] MFD has five steps that we will cover in this section: Clarify Customer Requirements, Select Technical Solutions, Generate Concepts, Evaluate Concepts and Improve each Module (See Figure 3-6).

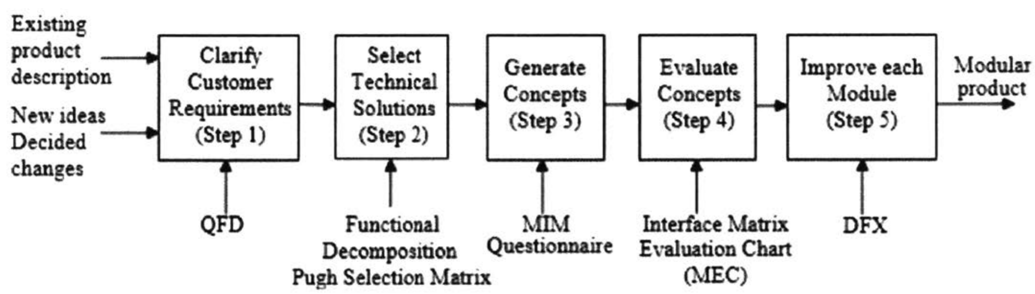

Figure 3-6: Modular Function Deployment, MFD[6]

Step 1: Clarify Customer Requirements

The method uses QFD (Covered in this section) to determine the customer needs and requirements. MFD introduces an addition to the traditional House of Quality Matrix, it includes a "modularity" column in the first "how" in order to encourage a mindset of modularity and understand early on if a modular design meets the customer needs or not (See Figure 3-7).[6]

Step 2: Select Technical Solutions

The output of the QFD are the customer requirements which are focused on the customer needs and generally have a market focus. In order to use this information for the technical

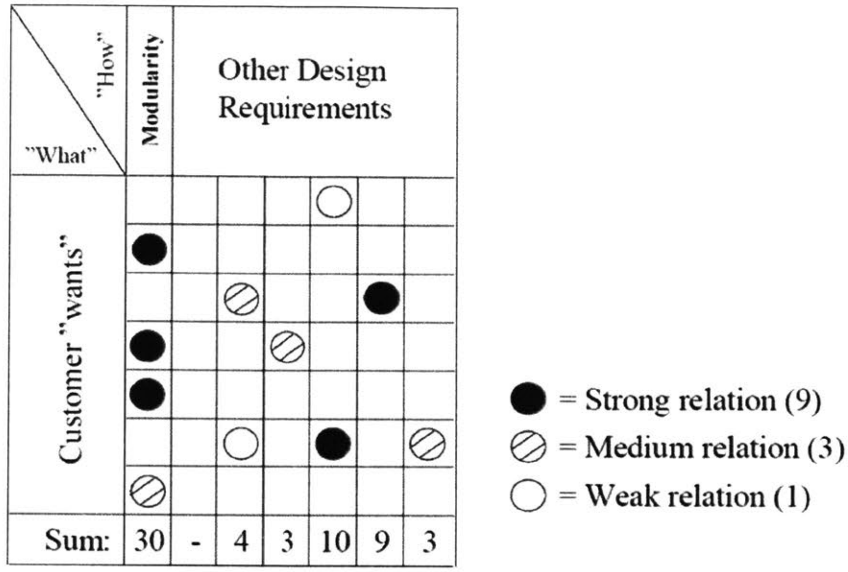

Figure 3-7: "QFD with "modularity" as the first design requirement."[6]

design, it is necessary to do a functional decomposition of the product. This consists of breaking down a product into function and corresponding technical solutions.[6] The tool borrows the design matrix from Axiomatic Design to perform the functional decomposition, please see the example below (Figure 3-8):

Since it is possible to have alternate technical solutions for the same function, the method suggests to use a Pugh matrix to select the best solution.

Step 3: Generate Concepts (Module Indication Matrix - MIM)

In this step, the method evaluates a few product characteristics that study cases have shown that are the driving forces for the creation of the modules. These characteristics are called "module-drivers" and can be found in the different stages of the lifecycle:
"Product development and design

- Carry-over
- Technological evolution / technology push
- Planned design changes / product planning

Technical solution

Function	Hub assembly	Spindel assembly	Brake assembly	Spring assembly	Schock absorber	Axle beam
Steer vehicle	X	X				
Allow rotation	X					
Brake vehicle	X	X	X			
Provide isolation				X	X	
Carry vehicle load	X	X		X		X

Figure 3-8: "Design matrix, according to Dr. Nam P. Suh for a vehicle front axle (simplified)"[6]

Variance

- Technical specification
- Styling

Production

- Common unit
- Process and/or organization re-use

Quality

- Separate testing of functions

Purchasing

- Supplier offers black box

After sales

- Service and maintenance
- Upgrading
- Recycling"[6]

All of the sub-functions that resulted from the functional decomposition, are to be evaluated against the module drivers in a Matrix that resembles the QFD matrix and it is called the Module-Indication-Matrix (MIM). See below:

Module driver		Sub-function 1	Sub-function 2	Sub-function 3	Sub-function 4	Sub-function 5
Company specific						
Development and Design	Carry-over					●
	Technology push			●		
	Product plan					
Variance	Technical spec.				●	
	Styling					
Prod.	Common unit	●			⊘	
	Process/Org.			●	●	
Quality	Separate test	○		⊘		
Purchase	Black-box eng.	⊘				
After sales	Service/maint.	⊘		●		
	Upgrading					
	Recycling				○	

Sub-function (techn. solution)

● = Strong driver (9)
⊘ = Medium driver (3)
○ = Some driver (1)

Figure 3-9: "Module-Indication-Matrix (MIM)."[6]

Matrix on Figure 3-9 helps us understand the potential of every sub-function to be a module and also the potential of merging sub-functions with one another in order to ultimately create the modules. There is a questionnaire that the authors of MFD™ use in support of the evaluation of the MIM. See Table 3.2.

Table 3.2: MIM questionnaire.[6]

Design and development

Carry over		
Are there	[ ] strong [ ] medium [ ] any	reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations?
Technology push		
Is it	[ ] a great risk [ ] a medium risk [ ] some risk	that this part[1] will go through a technology shift during the product life cycle?
Planned design changes (Product plan)		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module since it is the carrier of changing attributes that will be changed according a product plan?

Variance

Technical specification		
Is this part	[ ] strongly [ ] fairly [ ] to some extent	influenced by varying requirements?
Styling		

[1]For the purpose of this table, the word "part" refers to a sub-function (Technical solution)

Is this part	[ ] strongly [ ] fairly [ ] to some extent	influenced by trends and fashion in such a way that form and/or colour has to be altered, or should it be tied to a trademark?

Production

Common unit		
Can this function have the same physical form in	[ ] all [ ] most [ ] some	of the product variants?
Process/Organization		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module because: - a specific or specialised process is needed? - it has a suitable work content for a group? - a pedagogical assembly can be formed? - the lead time will differ extraordinary?

Quality

Separate testing		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module because its function can be tested separately?

Purchase

Black-box-engineering	

Are there	[ ] strong [ ] medium [ ] some	reasons for which this part should be a separate module because: - there are specialists that can deliver the part as a black box? - the logistics cost can be reduced? - the production and development capacity can be balanced?

After Sales

Service/maintenance		
Is it possible that	[ ] all [ ] most [ ] some	of the service repair will be easier if this part is easy detachable?
Upgrading		
Can	[ ] all [ ] most [ ] some	of the future upgrading be simplyfied if this part is easy to change?
Recycling		
Is it possible to keep	[ ] all [ ] most [ ] some	of the highly polluting material or easy recyclable material in this part (material purity)?

This questionnaire gives us the reasoning behind the scores that we select for the MIM. Once we fill out the MIM, it is necessary to interpret the result in order to understand what the proposed modules should be. The things to look at when grouping the sub-functions to create modules are as follows:

- In a per sub-function basis, observe the following about the applicable module drivers:
  - How many?
  - What score?

– What type?[6]

If many module drivers apply to a sub-function and they are highly scored, it is an indication that the sub-function has complicated requirements and therefore it is desirable that it forms a module or that it should be the base of a module.[6] To the contrary, if the sub-function scores low in multiple categories, this means that that sub-function should be integrated with other sub-functions to create a module.

Also, the proponents of the method, posit that there is an ideal number of modules for a design in order to have a balance between the time required to assemble the modules and the time required to assemble the finished modules to each other. See Figure 3-10.

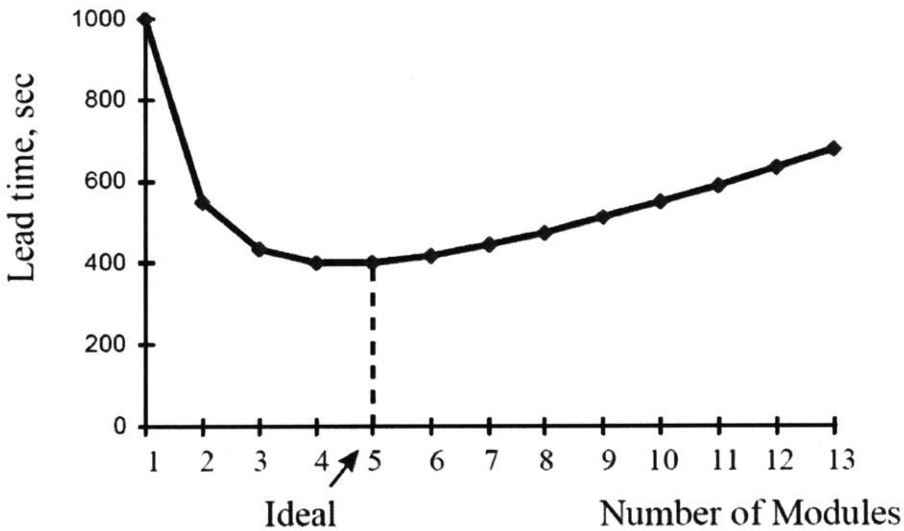

Figure 3-10: "Lead-time in assembly as a function of the average number of modules in every product. Minimum lead-time when the number of modules equals the square root of the number of assembly operations in the average product/assembly."[6]

Step 4: Evaluate Concepts

At this stage, the modular concepts have been created. An important factor to evaluate is the interfaces between the modules as this impacts the product and the flexibility within the assortment.[6] Figure 3-11 below, shows how to map the interface connections. "(E) stands for moving (energy transmitting) and media transmitting force, inertia, electricity etc. and (G) for solely geometrical specification in the connection. The assembly operation times may also be entered to complete the picture."[6]

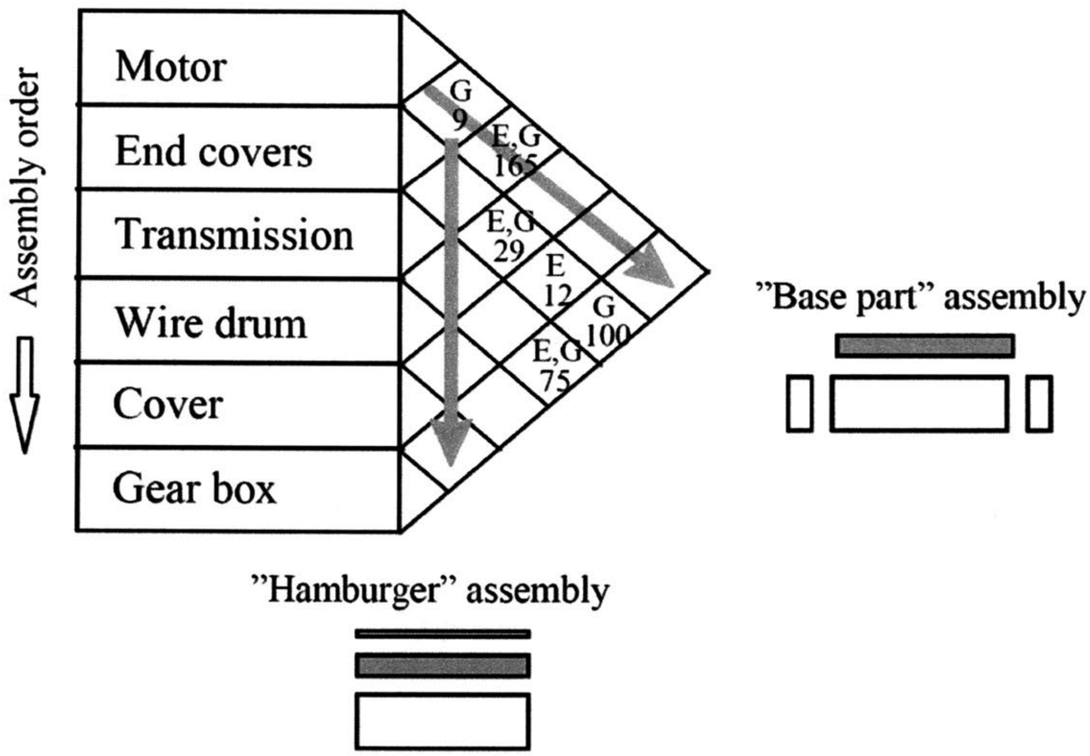

Figure 5.14 Evaluation of interfaces.

Figure 3-11: "Evaluation of interfaces."[6]

The "base part" and "hamburger" assembly types are ideal interface principles. They are considered ideal because they provide flexibility for simultaneous development and production[6] "the preferred interface principles have been marked with arrows."[6] Any interface outside the marked areas should be avoided as it is not a desirable connection.[6]

Then, it is time to evaluate the potential modules in multiple dimensions. The analysis goes deep and considers everything from number of modules and interfaces to the complexity of these ones. Some of the rules to be considered are as follows:

- "Lead Time in Development Depends on the Interface Complexity"[10]
- "Development Costs Depend on the Share of Carry Over"[10]
- "Development Capacity Depends on the Share of Purchased Modules"[10]
- "Product Costs Depend on the Assortment Complexity"[10]
- "System Costs Depends on the Share of Purchased Modules"[10]
- "Lead Time in Assembly Depends on the Number of Modules in a Product"[10]
- "Quality Depends on the Share of Separately Tested Modules"[10]
- "Variant Flexibility Depends on Multiple Use"[10]
- "Service/Upgrading Depends on the Functional Purity in Modules"[10]
- "Recyclability Depends on the Material Purity in Modules"[10]

Step 5: Improve Each Module

Since MFD™ is not a substitution of part level design improvement, this step focuses on every module separately with the purpose of improving it to better serve its purpose at the system level,[6] "e.g. a module that is chosen mainly for service and maintenance reasons should be designed to ease disassembly"[6]

3.5 Limits to modularity

In previous sections on this chapter, there is a review about how designers can strategically and theoretically divide a product into multiple modules. However, there hasn't been a discussion about any limits that the designers might face during the development process. To define the modules is ultimately the decision of the designers,[13] "However, physical phenomena intervene in many cases, with the result that 1) designers do not have freedom to choose the modules, or 2) that they will prefer not to subdivide their system into as small units as is possible."[13]Or as in the case of the Portfolio Company's project, the choice of what is in or out of the module.

Prof. Daniel E. Whitney from the MIT, Department of Mechanical Engineering in his paper "PHYSICAL LIMITS TO MODULARITY"[13] postulates that the absolute power needed to operate a system distinguishes the products that provide the ability to create modules from the ones that do not.[13] In that paper, he studies the possibility to replicate the design and manufacturing methods used in VLSI (Very-large-scale integration) systems to apply them to CEMO (Complex electro-mechanical-optical) products with the purpose of obtaining the same benefits.

VLSI

Even though these systems are extremely complex, they can be designed by few people as compared to the CEMO systems; in addition, the design can be done in modules in parallel, therefore saving design time.[13] The same manufacturing processes and even equipment can be used with multiple purposes.[13] Some of the benefits are that these product architectures can be customized at interest points during the product lifecycle.[13] Even more, these types of systems enable outsourcing allowing companies to share risk and gain access to outside capabilities.[13]

CEMO

The CEMO products can be classified as the "primarily signal processors" and the ones that "process and transmit significant power". We will focus the discussion on the second classification.

VLSI vs. Design

The following table, taken from the "PHYSICAL LIMITS TO MODULARITY" paper, can help us understand the fundamental differences between VLSI and CEMO:

We can highlight the following 5 points:

- "CEMO systems carry significant power"[13]: VLSI work from 0 to 5 volts, whereas CEMO systems could carry from kilowatts to gigawatts.[13]
- "VLSI systems are signal processors"[13]: The power levels are very low and what matters are the logical implications (digital logic and Boolean algebra)[13]
- "Single vs multiple functions per device"[13]: whereas VLSI's function is logic, mechanical components have multiple functions due to its physics nature. They transmit shear loads, rotational energy, etc.[13]
- "Ability or Inability to Separate Component Design from System Design"[13]: mechanical elements experience back-loading when connected to the system. They behave different as compared to isolation. On the other hand, VLSI products behave very similar in isolation and connected to a system.[13]
- "Ability or Inability to Define Interfaces"[13]: "VLSI systems transmit so little power that their interfaces can be designed based on other criteria." Since their main purpose is to transmit information, their interfaces are much larger than needed, this gives flexibility to design the interfaces and standardizing them without compromising their main function.[13] In the case of the high power systems, the interfaces must be designed specifically for every case in consideration of the physics to assure power transfer.

In conclusion, applying the design methods from VLSI in the CEMO systems will underestimate design time and using the same standard for evaluating the CEMO architecture would not pay attention to the valuable features of CEMO designs.[13] In addition, there are other reasons why achieving a modular design is a difficult task. In most cases the modules do interact with each other because they impose design or manufacturing constraints on each

Table 3.3: "Summary of Differences Between VLSI and Mechanical Systems."[13]

ISSUE	VLSI	Mechanical Systems
Component Design and Verification	Model-driven single function design based on single function components; design based on rules once huge effort to verify single elements is done; few component types needed	Multi-function design with weak or single-function models; components verified individually, repeatedly, exhaustively; many component types needed
Component Behavior	Is the same in systems as in isolation; dominated by logic, described by mathematics; design errors do not destroy the system	Is different in systems and in isolation; dominated by power, approximated by mathematics, subject to system- and life-threatening side effects
System Design and Verification	Follows rules of logic in subsystems, follows those rules up to a point in systems; logical implementation of main functions can be proven correct; system design is separable from component design; simulations cover all significant behaviors; main system functions are accomplished by standard elements; building block approach can be exploited and probably is unavoidable; complete verification of all functions is impossible	Logic captures a tiny fraction of behavior; system design is inseparable from component design; main function design cannot be proven correct; large design effort is devoted to side effects; component behavior changes when hooked into systems; building block design approach is unavailable, wasteful; complete verification of avoidance of side effects is impossible
System Behavior	Described by logical union of component behaviors; main function dominates	No top level description exists; union of component behaviors irrelevant; off-nominal behaviors may dominate

other. Designers often discover that they can't change one module without changing other ones.

3.6 Summary

This chapter presents the design theory and the terminology to understand modularity. Axiomatic Design introduces the concepts of domains and mapping across domains in order to achieve a design. It goes further to explain hierarchy as the levels that every domain can have as the design is more detailed. This hierarchy represents the design architecture. It also points out the importance of zigzagging across domains in order to decompose the highest levels of the domains layer by layer with the purpose of going from a conceptual design to a more detail and actionable design. All this activity must respect axioms that will enable the designers to create a good design. With all this, Axiomatic Design sets the criteria to distinguish a good design from a bad one and sets a good foundation to any design method that intends to do a good design. In general, for the purpose of this thesis, it sets the base for any modularity creation method in particular to MFD™.

In order to level the discussion on what do we mean by the word "modularity", the modularity concepts discussed define the multiple contexts on which modularity can be referred to. In addition, it mentions the options that conducting a modular design enables for the designers and introduces the concept of design rules, as the rules of the game that the designers must obey for a modular system to properly work.

Quality Function Deployment and the Pugh matrix are methods and tools that are practical and aim to systematize the work that is performed on the CA domain. These tools have proven to be valuable throughout its use in multiple companies for many years. In addition, QFD method has provided the input on the first step of The MFD™ and the mechanism for processing and relating qualitative data to quantitative in order to come up with a proposed design. All this reviewed material sets the base for QFD™, the method that aims to create modular designs that meet the customer needs and streamline the design and operations of the producer.

Some concerns arise about the limits to modularity mentioned in this section. MFD™

seems to not distinguish between low power and high power systems, therefore it tends to ignore the effect that the design of a module can have in another module. In addition, in high power systems, a modification of a module could have impact in other modules regardless of the designated design rules due to physical constraints. The product analyzed in the next chapter is not a low power system, therefore these considerations should be taken into account during the definition of the modules.

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Chapter 4

Modular Engineering and Product Development

The project at The Portfolio Company gives the opportunity to observe and study the implementation of a modular platform on an existing product. This chapter states the intent, the goals, the resources allocated and finally introduces the concept of *modular engineering.*

4.1 Portfolio company Case Analysis

As mentioned before, one of the portfolio companies was developing a modular platform in one of its product families. This product family has five different product lines with different applications by industry. Out of these five product lines, three are very similar and the other two have significant structural differences.

4.2 Problem Statement at The Portfolio Company

A recent assessment within the company has shown the need to speed the time to market of the products portfolio. It also revealed the existence of technology gaps and the need to find a way to better address each segment's demands.

4.3 Proposed solution

Develop a modular platform that replaces all of the five different product lines by dividing the functions of the product and assigning them to different modules to be connected by proprietary interfaces. This modular platform will provide a more flexible product by allowing more configurations to be offered according to the customers needs. It will also allow to streamline the design and the manufacturing process and ultimately provide a shorter development time as well as shorter lead-times.

4.4 Stake holders

The project had executive support since the beginning and involved the following departments in the company:

Key stake holders

Table 4.1 depicts needs and responsibilities of every area:

Table 4.1: Needs and responsibilities

Area	Needs	Supplies
Management	• Final Deliverable • Balanced Scope, Quality, Schedule, Budget, Resources, and Risks	• Authorization • Enterprise Environmental Factors

Engineering	• Defined Modular Requirements • Modular Platform Development Framework • Comprehensive Project Management Plans	• Sponsorship • Budget • Resource Assignments • Design Authority • Technical Baseline • Subject Matter Expertise
Operations	• Reduced Manufacturing Complexity & Cycle Time • Increased Reliability • Streamlined Procurement • Merge in Transit Capabilities (To be able to ship separate modules to a facility and perform the final assembly there or at the customers site)	• Quality Management • Procurement Management • Subject Matter Expertise

Sales, Service	• Modular Product Offering • Reduced Time to Market for New Products • Improved Serviceability • Sales Tools • Sales & Service Training Program	• Customer Requirements • Subject Matter Expertise
Aftermarket	• Recommended Service Intervals • Proprietary Suite of Consumables	• Customer Requirements • Subject Matter Expertise
Marketing	• Standardized Product Configuration • Marketing Collateral	• Customer Requirements • Branding • Subject Matter Expertise
Project Management	• Refinements to Project Management Process	• Organizational Process Assets • Subject Matter Expertise

Team

The project got assigned a team of more than 20 people from multiple disciplines, allocating up to 80% of their time as shown in Table 4.2.

Table 4.2: Team resources

Area	Role	%Time
Program Director	SME - SE	80%
Product Management	SME - PM	80%
Project Management	SME - PRJ	80%
Engineering	SME - ME	80%
Engineering	SME - EE	80%
Engineering	SME - APP	80%
Supply Chain	SME - SC	20%
Supply Chain	SME - SC	60%
Manufacturing	SME - MFE, QC	60%
Service	SME - SVC	80%

4.5 Goals and Key Performance Indicators (KPIs)

There were regular project reviews with the senior management team. Some of the aspects to be reviewed were:

- Project Milestones
- Team Personnel Updates
- Technical Development Updates
- Project Issues and Risks
- Reliability, Validation, and Demonstration Testing Feedback
- Marketing Updates
- Launch Checklist Status

Some of the KPIs to be considered to understand the outcome of the project are as follows:

- Annualized Failure Rate (AFR):
- First Pass Yield (FPY)
- Percentage of New Sales
- Average Selling Price (ASP)
- Aftermarket Sales Per Unit

After an initial review, some of the tangible goals were as follows:

- Reduce PNC (Part number count) by up to 50%
- Reduce direct material cost (On the long run)
- Reduce direct labor cost
- Reduce the number of suppliers by up to 50%
- Reduce time to Market to $\leq$ 6 months
- Increase the number of configurations offered

Some of the expected outcomes of the project are to streamline the value chain as well as explore the benefits of a "merge in transit" operation.

4.6 Method

The method employed by the team for the creation of the modular platform is the Modular Function Deployment (MFD™) method (See Figure 4-1), which is reviewed in section 3.4.

4.7 What is Modular Engineering?

Based on the review of the theory on design and product development from chapter 3, we now have the base of the necessary knowledge to answer this question in the context of the scope of this thesis.

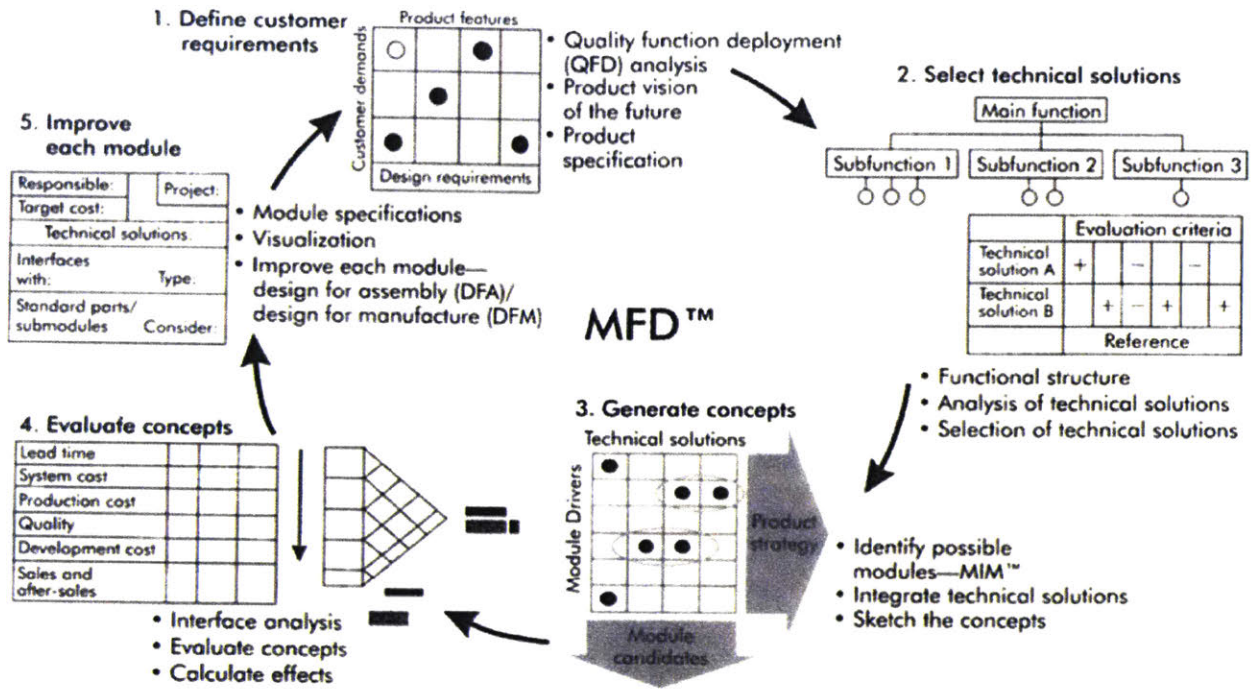

Figure 4-1: "The five steps of Modular Function Deployment™. The circle illustrates that design work is an iterative process."[5]

We mean by *modular engineering* a way of organizing all of the product development activities, across the value chain, that consists on structuring them in a way that the work of multiple modules can be performed in parallel and with independence. This independence can be achieved as long as the *design rules* have been properly established and are followed by all of the stake holders.

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Chapter 5

The purpose of this work

This thesis aims to level the understanding of the concepts of modularity and its relation to product design and development at AIP's portfolio companies. Then, it presents a case study performed in one of the portfolio companies with the purpose of sharing best practices, lessons learned and methods employed. Finally, it proposes alternative methods and tools to deal with the task of generating module concepts in a faster way.

5.1 Implementation at Portfolio Companies

The portfolio companies are from a very diverse panoply of industries and types of products. As such, it is not easy nor practical to propose a unified method for implementing modular engineering. Rather, it is more reasonable to display different methods and the theories that support them in order to understand the applicability of these to the design and operations of any determined portfolio company. In addition, the case study provides empirical knowledge about the implementation by using some of the methods. It also provides a sense of the problem that the company was intending to solve, the resources allocated and the nature of the interactions between stakeholders. Finally, it proposes KPIs and goals that address the status and impact of the project. All of this would be useful to understand in the future for any portfolio company that intends to implement a modular engineering project. It also can be used as an evaluation tool in order to understand if the problem that the company is trying to solve can be addressed with modular engineering.

5.2 Goals and Limits

More specific, the goal of this thesis is to create awareness on the portfolio companies of modular engineering practices, its benefits and limits. Being aware of the typical short timeframe that AIP's business model has, from the investment in the portfolio company to the exit of the investment, it is key for the implementation of any improvement project to be as fast as possible. That is precisely the intent of the proposed alternate methods, to dramatically decrease the implementation time. This will allow AIP not only to drive the implementation of the project, but also to be able to see its benefits. In addition, it is key to implement the project as early as possible. Some of the benefits have a waterfall effect, therefore, the sooner the project is implemented, the better. However, in the case of a modular engineering project, often times, the main constraints are not technical but organizational. Analogous to the implementation of a lean manufacturing project, a modular engineering project touches every department and activity on the company. In addition, the nature on the relations between departments changes and the same happens with the suppliers. Oftentimes new suppliers are brought to the table and some others no longer play a role in the companies.

Chapter 6

Method and Procedure

This chapter displays the implementation of MFD™ step by step on the modularization project of *The product* on The Portfolio Company.

6.1 Method and Procedure

The method MFD™ starts at the customer end. In this case, the team conducted a VOC (Voice of the Customer) survey that consisted of representatives of the company visiting several customers to obtain their feedback about the machines that they have and find out whether their needs were being met.

Step 1: Clarify Customer Requirements

VOC format

Approximately 40 interviews were conducted in all regions that the company covers in the world. The customers that participated were selected keeping in mind the diversity of industries where the existing products are sold.

The goals of the VOC are:

- To collect information from the customers in regard to their ownership experience, product needs, features, high points, shortcomings, competitive offerings, etc.

- To find out about any improvement suggestions

- To obtain information about the relationship that customers have with the company and benchmark it against their relationship with other suppliers

- To collect information about the consumables purchases

- Collect information about their future business direction

Teams of two people, one technical and one non-technical, were deployed at the customers' sites. One would ask questions and the other would take notes. Ideally the team would take a tour at the facility and will start asking open-ended question. The task was to gather as much information as possible but directed to find actionable data. Therefore, the use of 5 whys was encouraged. Figure 6-1 depicts the categories on which the customer's inputs were classified.

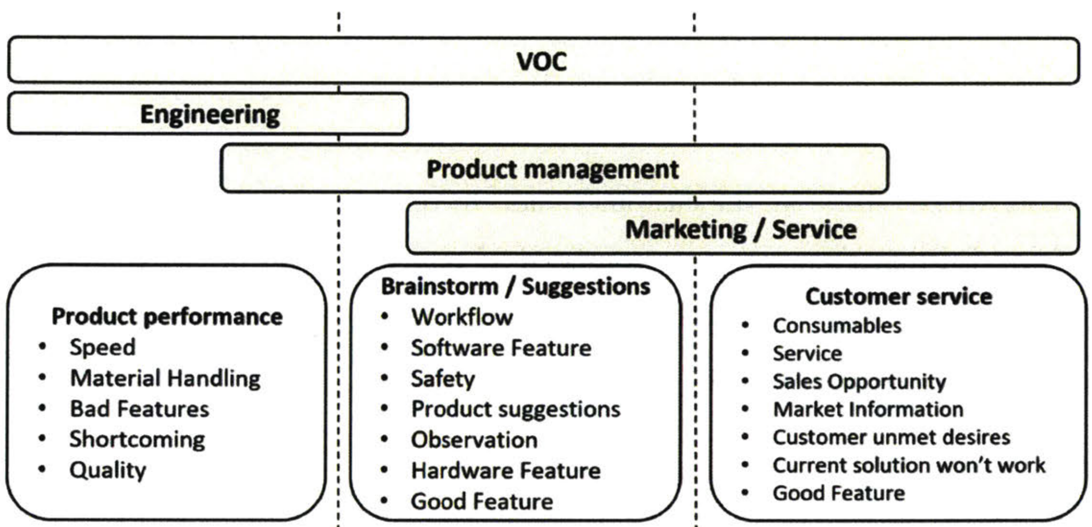

Figure 6-1: Classification of VOC

As explained in chapter 3, QFD method transforms the qualitative input from the customer into quantitative parameters that could subsequently be related to design parameters.

Step 2: Select Technical Solutions

All of the data from the VOC was processed and deployed into actionable functions required by the customer; during this step, the functional decomposition of the product was

Table 6.1: Design matrix of The Product

	Technical solution																														
Function	Technical Solution 1	Technical Solution 2	Technical Solution 3	Technical Solution 4	Technical Solution 5	Technical Solution 6	Technical Solution 7	Technical Solution 8	Technical Solution 9	Technical Solution 10	Technical Solution 11	Technical Solution 12	Technical Solution 13	Technical Solution 14	Technical Solution 15	Technical Solution 16	Technical Solution 17	Technical Solution 18	Technical Solution 19	Technical Solution 20	Technical Solution 21	Technical Solution 22	Technical Solution 23	Technical Solution 24	Technical Solution 25	Technical Solution 26	Technical Solution 27	Technical Solution 28	Technical Solution 29	Technical Solution 30	Technical Solution 31	Technical Solution 32
Position item																X															X	
Support item	X								X																							
Provide structure			X							X			X	X			X									X						
Provide interface			X							X			X	X			X									X						
Provide attachment				X																				X			X	X				
Distribute force						X																										
Generate force					X		X																									
Guide item																					X											
Provide force																																
Complement force																																
Move item																					X											
Control item															X							X										
Hold item											X																					
Process item																									X							
Drive item																													X			
Guide item2																														X		
Provide support		X																														
Secure item																							X									
Connect item								X																								
Connect system																				X												
Cover item																			X													
Change item												X																				
Control item2																		X														
Protect item																																X

performed. Functions desired from the customers in a product are then coupled to technical solutions proposed by the designers, see Table 6.1.

The design matrix displays the key functions that the product performs and the technical solutions that make them possible. As explained in Chapter 3, this is the time to explore alternative technical solutions and the tool that we can use to decide which is the best solution is the Pugh matrix.

Step 3: Generate Concepts (MIM)

The Module Indication Matrix helps to group the technical solutions into what eventually will become the modules. This is achieved by evaluating the technical solutions (*function carriers*) against the module drivers. The questionnaire from Table 3.2 in section 3.4 is a useful criterion to score the different *function carriers* in order to complete this process. See Table 6.2.

At this point, the assumption is that every *function carrier* is isolated in a separate assembly as a module.[6] In the MIM, we can see that each one of the *function carriers*

Table 6.2: Module Indication Matrix (MIM) for The product

Module driver \ Function carrier		Module Candidate 1	Module Candidate 2	Module Candidate 3	Module Candidate 4	Module Candidate 5	Module Candidate 6	Module Candidate 7	Module Candidate 8	Module Candidate 9	Module Candidate 10	Module Candidate 11	Module Candidate 12	Module Candidate 13	Module Candidate 14	Module Candidate 15	Module Candidate 16	Module Candidate 17	Module Candidate 18	Module Candidate 19	Module Candidate 20	Module Candidate 21	Module Candidate 22	Module Candidate 23	Module Candidate 24	Module Candidate 25	Module Candidate 26	Module Candidate 27	Module Candidate 28	Module Candidate 29	Module Candidate 30	Module Candidate 31	Module Candidate 32	Driver Subtotal
Design	Carry-over	●	◑	●	●	●	◑	●	○	●	●	●	◑	◑	◑	◑	●	●	●			●	●	●	●	●	●	◑	●	○		◑	○	189
	Technology push		◑	○	○								○						●		◑					◑				○			○	23
	Product planning		◑		○		◑		●				◑				○			◑	◑											○	◑	30
Variance	Diff specification	◑	●	◑	◑	◑	◑		○			●		○	○	◑	◑	○	◑	○	●		○	○	○	●		○		○	○	○	●	81
	Styling							○					○							●						○							○	13
Manuf.	Common unit	○		○	○	○		◑	○	●	●	○	◑	◑	◑	○	○	◑	○			◑	○	◑	◑		◑	○	◑	◑	◑	◑		68
	Process / Organization	●	○	●		●	◑					◑	◑				○			●		○			◑		○							52
Quality	Separate testing					◑			●			◑	◑	○	○				●		●				○	○				○				41
Purchase	Black-box engineering		●			◑	●	●	◑			○	○				◑		◑	◑		●	●	○		○	●		◑		○	○		78
After sales	Service / Maintenance		●		●	◑		◑	○			●	○	●	●	●	○		○	●		●	●	◑	○	●	●					◑		116
	Upgrading	○	●	◑	●	◑	○	◑	◑		○	●	●			○	◑	○	◑	○	●		○	●	◑	●						◑		94
	Recycling		○			○	○		○					◑	◑	◑			●	◑	◑					○		◑		◑		◑	●	47
● 9 ◑ 3 ○ 1	Weight of Driver vertically summarized	23	47	26	33	35	23	28	29	18	19	44	28	20	20	20	22	14	47	38	36	31	30	26	21	43	31	8	15	10	5	18	24	
	Module Rank	18	1	15	8	7	18	13	12	26	25	3	13	22	22	22	20	29	1	5	6	9	11	15	21	4	9	31	28	30	32	26	17	

has been evaluated in the scale shown: 9 (= strong driver), 3 (= medium driver), and 1 (= some driver) in accordance with the relevance of the reasons for being a module.[6] For instance, the *carry-over* on *"module candidate 1"* has been assigned a "9" since there are strong reasons (according to the designers) that indicate "that this technical solution should be a separate module because the new design can be carried over to coming product generations".[6] "The weighting scale is adopted from QFD. The irregular scaling is used in order to support the identification of the really strong driving forces."[6] If a *function carrier* has many module driver that are highly weighted that is an indication that it should either form a module by itself or it should be the basis of a module. On the other hand, if the *function carrier* presents low weighted module drivers, that means that it is a good candidate to be integrated with other *function carrier.* The MIM helps to understand which of the technical solutions are more suitable to form a module.

By observing the matrix and considering the suggestions from section 3.4 to interpret the MIM, we can proceed to the ranking by the assigned weight from highest to lowest in Table 6.3:

Table 6.3: Sub-functions by total weight

Function carrier	**Weight**
Module Candidate 18	47
Module Candidate 2	47
Module Candidate 11	44
Module Candidate 25	43
Module Candidate 19	38
Module Candidate 20	36
Module Candidate 5	35
Module Candidate 4	33
Module Candidate 26	31
Module Candidate 21	31
Module Candidate 22	30
Module Candidate 8	29
Module Candidate 7	28
Module Candidate 12	28
Module Candidate 3	26
~~Module Candidate 23~~	~~26~~
~~Module Candidate 32~~	~~24~~
Module Candidate 6	23
Module Candidate 1	23
Module Candidate 16	22
Module Candidate 24	21
Module Candidate 15	20
Module Candidate 14	20
Module Candidate 13	20
Module Candidate 10	19
Module Candidate 9	18

Module Candidate 31	18
Module Candidate 28	15
Module Candidate 17	14
Module Candidate 29	10
Module Candidate 27	8
Module Candidate 30	5

The process of generation of concepts is a multidisciplinary effort and after generating the MIM, it might be the case that some of the *function carriers* have to be separate modules for strategic reasons or have to be shipped in separate kits. For example, if one *function carrier* has a high weight but it can only be sourced from a strategic supplier, that *function carrier* had to be a module itself and it cannot be grouped with other sub-functions to create a module. That is the case of the *"Module candidate 2"*. In addition, notice that we crossed-out a couple of the *function carriers*. These are non-module *function carriers*. They do not constitute a module not it is desirable for them to take part of a module.

The next task is to group the remaining *function carriers* to create the modules. We can start by the ones with the highest weight and evaluate if they can be a module basis or a module by themselves. After this classification, we can see which one can be grouped with the ones that are module basis. For example, it has been determined by the team that *"Module candidate 18 (47)"* can be a module basis. After that, we start to analyze, physically and strategically, which of the remaining sub-functions can be joined with *"Module candidate 18 (47)"* and it turned out that *"Module candidate 20 (36)"* is a good candidate and we group them to create a module that we call the *"Module M"*. Subsequently, we continue with the other sub-function until the modular concept is created. The modular concept is in Table 6.4.

The modular concept table, proposes 14 potential modules and displays the *function carriers* that comprise every module. In the next step, these concepts will be evaluated according to a proposed criterion.

Step 4: Evaluate Concepts

Table 6.4: Modular Concept

Module	**Candidates combined**
Module A	Module Candidate 25
	Module Candidate 11
	Module Candidate 29
	Module Candidate 30
Module B	Module Candidate 24
	Module Candidate 28
	Module Candidate 27
	Module Candidate 4
	Module Candidate 22
	Module Candidate 15
	Module Candidate 19
Module C	Module Candidate 14
	Module Candidate 10
	Module Candidate 26
	Module Candidate 3
Module D	Module Candidate 17
	Module Candidate 13
	Module Candidate 21
Module E	Module Candidate 6
Module F	Module Candidate 1
	Module Candidate 9
Module G	Module Candidate 5
	Module Candidate 7
Module H	Module Candidate 16
	Module Candidate 31
Module J	Module Candidate 2
Module K	Module Candidate 8
Module L	Module Candidate 12
Module M	Module Candidate 18
	Module Candidate 20
Non-modules	Module Candidate 23
	Module Candidate 32

This step consists on evaluating the potential modules. In the previous stage, the MIM provided us with some "weight score" for every *function carrier*. This weight was the base for the formation of modules. A key element to evaluate is the interfaces, since as mentioned in chapter 3 they have a huge impact in the final product. It is also a good tool to display the complexity of the connections and any undesired connections.[6] Figure 6-2 shows the matrix for the evaluation of the interfaces.

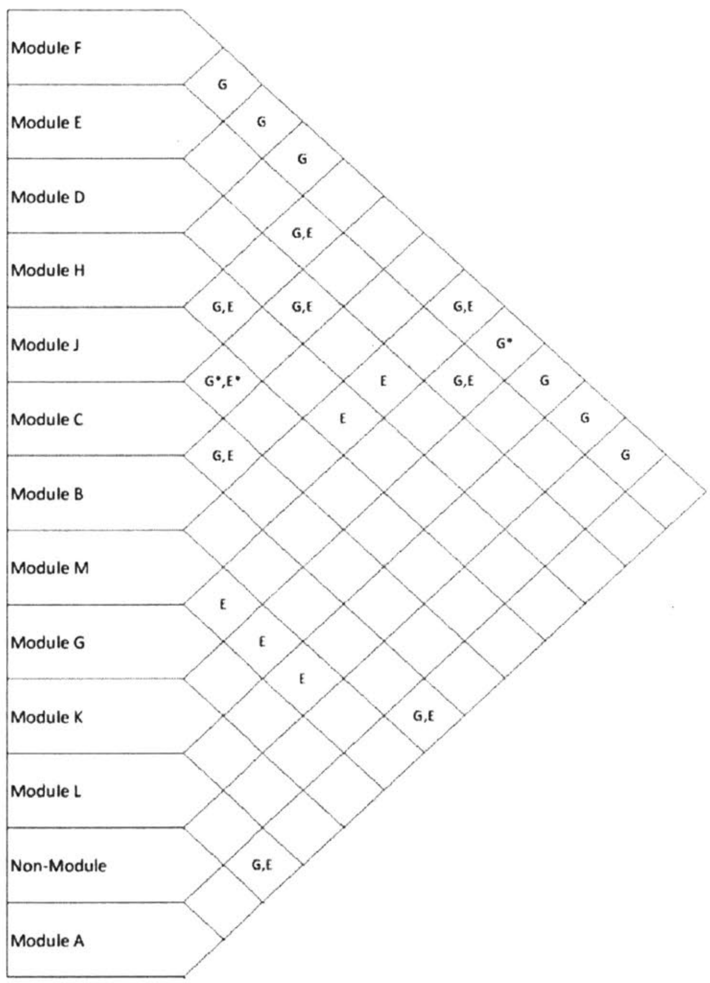

Figure 6-2: Evaluation Matrix for The Product

As explained in chapter 3, (E) means that there is "energy transmitting" between the modules (It could be force, inertia, electricity, etc.) and (G) means that there is geometrical specification in the connection.[6] For example, *"Module F"* is connected to *"Module F"* according to the geometry of these modules. On the other hand, there is an electrical connection between, *"Module M"* and *"Module G"*. This reminds us of the limits to modularity discussed in chapter 3 and the differences between VLSI and CEMO systems. We can see that there are some similarities to VLSI in the electrical connection as they transmit data as well. However, there needs to be a distinction for the (E) as to whether this (E) transmits power of data or both. An if it transmits both, how much leverage do we have for designing the interface as small and simple as possible.

Even though it is not considered on MFD™, a deeper analysis of the interfaces between modules can be performed by creating an Annotated Liaison Diagram as proposed by Prof. Whitney on the book "Mechanical Assemblies"[14]. See Figure 6-3 and Table 6.5 below.

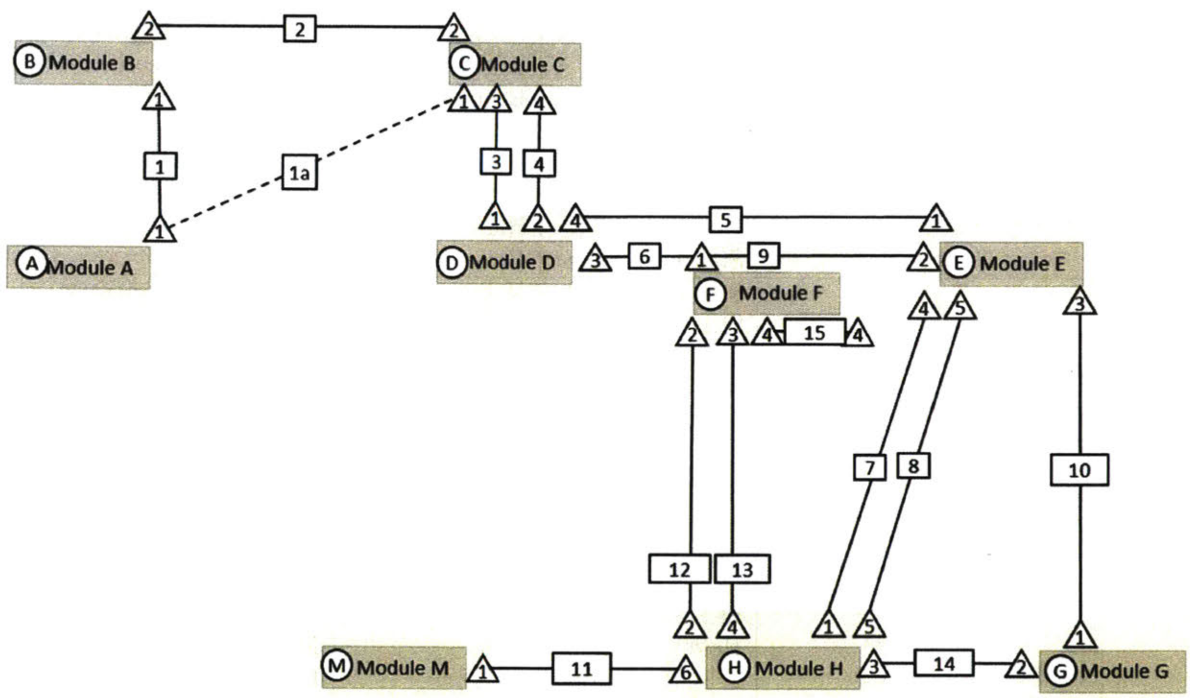

Figure 6-3: Annotated Liaison Diagram for The Product

Then, chapter 3 suggests several topics to cover with the team for the evaluation of the modular concepts. These include questions about potential lead time in development on the modules as a function of the complexity of the interfaces. The team went on to analyze other factors that impact costs, capacity, quality and variant flexibility which are in function of share of carry over, share of purchase modules, the assortment of complexity or share of separately tested modules and functional/material purity of the modules.

Step 5: Improve Each Module

Table 6.5: Modules, Assembly Features, Assembly Feature Classes and Interfaces of The Product

Module	Module Name	Feature	Feature Name	Feature Class	Interfaces with
A	Module A	1	Std. Interface A	Surface	Module B - Geometric Module C - Geometric
B	Module B	1 2	Std. Interface A Std. Interface A	Surface Surface	Module A - Geometric Module C - Geometric
C	Module C	1 2 3 4	Std. Interface A Std. Interface A Bearing Block Hole pattern A	Surface Surface Bearing Hole	Module B - Geometric Module D - Geometric
D	Module D	1 2 3 4	Bearing Block Hole pattern A Hole pattern B Std. Fastener 1	Bearing Hole Hole Hole	Module C - Geometric Module E - Geometric Module F - Geometric
E	Module E	1 2 3 4 5	Std. Fastener 1 Std. Fastener 1 Coupling Std. Fastener 2 Clearance Hole	Hole Hole Hole Hole Hole	Module D - Geometric Module F - Geometric Module H - Geometric Module G - Geometric
F	Module F	1	Std. Fastener 3	Hole	Module D - Geometric, Energy Module E - Geometric, Energy Module H - Energy
G	Module G	1 2 3 4	Std. Fastener 1 Hole pattern C Std. Fastener 2 Std. Fastener 3	Hole Hole Hole Hole	Module E - Geometric Module H - Geometric & Electric
H	Module H	1 2 3 4 5 6	Std. Fastener 1 Std. Fastener 3 Hole pattern D Std. Fastener 1 Clearance Hole Std. Fastener 1	Hole Hole Hole Hole Hole Hole	Module E - Geometric Module F - Geometric Module G - Geometric, Energy Module H - Energy
M	Module M	1	Coupling	Hole	Module H - Energy

MFD™ is intended to be an iterative process and as such, it encourages to constantly improve every module. The method suggests guidelines to revisit the modules once these are designed. The product can be improved at different levels: product range (assortment) level, product level and part level.[6] In particular, it suggests to pay attention to the number of different parts that are used to build up a product as it has been identified as an important cost driver in a company.[6]

6.2 Alternate Methods

After the functional decomposition of the product, the process for generating modular concepts that MFD™ proposes, could get convoluted. The idea of evaluating every *function carrier* in regard to the module drivers (Carry-over, technology push, product planning, etc.) is very practical since we want to be able to group the *function carriers* in modules in order to achieve the benefits of a modular platform. However, the way it is decided which *function carriers* are going to create the modules, is rather a cumbersome and ambiguous process. As explained in chapter 3, during the generation of concepts (MIM), every *function carrier* is given a weight number on every module driver that could be 0, 1, 3 or 9. There are twelve module drivers to evaluate per each *function carrier.* The idea behind the proposed method would be to consider every *function carrier* as a point in the Euclidean space[1] with as many coordinates as module drivers (at least twelve). Then, measure the Euclidean distances[2] among the points. The points that are closer (shortest Euclidean distance) to each other will create clusters of points that we will interpret as the defined modules. For the purpose of this method, proximity, as measured by the Euclidean distance, will define similarity of two given *function carriers.* This will ensure that the modules are comprised of sub-functions that are similar among them in their modularity characteristics. Let's review a few concepts in order to understand how this proposed method works and why it is applicable.

Clustering

[1]Defined as the space of real number $\mathbb{R}^n$

[2]Euclidean distances are defined as the distance between the point $P = (p_1, ..., p_n)$ and $Q = (q_1, ..., q_n)$ given by $d(P,Q) = \sqrt{(p_1 - q_1)^2 + ... + (p_n - q_n)^2}$[9]

Also called unsupervised classification or exploratory data, "the goal of clustering is to separate a finite, unlabeled data set into a finite and discrete set of "natural", hidden data structures, rather than to provide an accurate characterization of unobserved samples generated from the same probability distribution".[11] More specific, "in cluster analysis a group of objects is split up into a number of more or less homogeneous subgroups on the basis of an often subjectively chosen measure of similarity (i.e., chosen subjectively based on its ability to create "interesting" clusters), such that the similarity between objects within a subgroup is larger than the similarity between objects belonging to different subgroups."[11]. There are mainly two types of clustering: hierarchical and partitional.

Hierarchical Clustering

Hierarchical clustering groups the data in a hierarchical structure with a sequence of nested partitions.[11] This hierarchical structure is formed according to a proximity matrix.[11] "The results of hierarchical clustering are usually depicted by a binary tree or dendrogram, as depicted in..."[11] Figure 6-4. "The root node of the dendrogram represents the whole data set, and each leaf node is regarded as a data point. The intermediate nodes thus describe the extent to which the objects are proximal to each other; and the height of the dendrogram usually expresses the distance between each pair of data points or clusters, or a data point and a cluster. The ultimate clustering results can be obtained by cutting the dendrogram at different levels"...[11] (the dashed line in Figure 6-4). "This representation provides very informative descriptions and a visualization of the potential data clustering structures, especially when real hierarchical relations exist in the data..."[11] such as the data from a modular platform of a product.

Partitional Clustering

We mentioned before, that in clustering, the data is split up into groups according to how similar elements are, but, what does it mean for two data points to be similar? It is necessary to establish a criterion function. The most used criterion function in partitional clustering is the sum-of-squared-error criterion.[11]

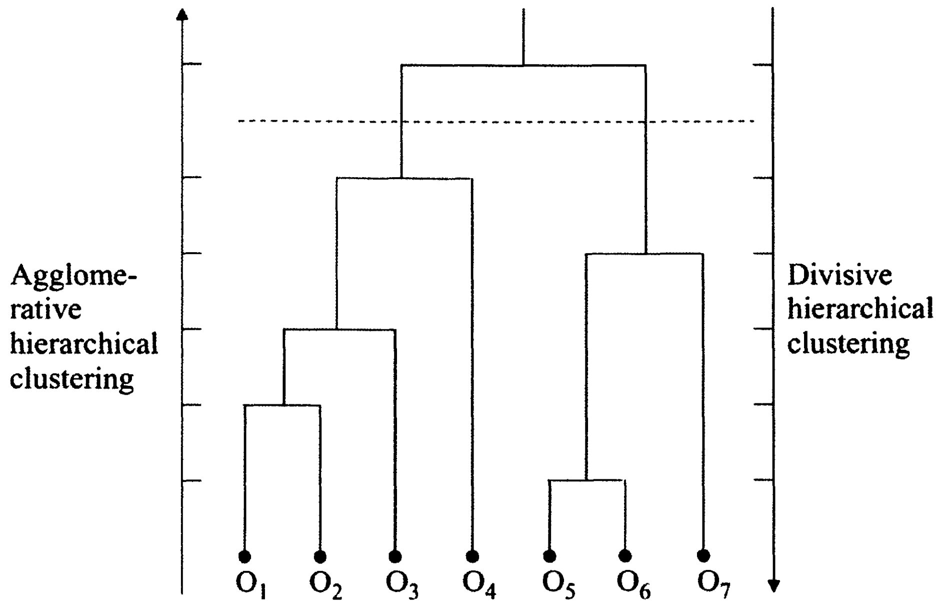

Figure 6-4: "Example of a dendrogram from hierarchical clustering. The clustering direction for the divisive hierarchical clustering is opposite to that of the agglomerative hierarchical clustering. Two clusters are obtained by cutting the dendrogram at an appropriate level."[11]

"Suppose we have a set of objects $x_j \in \Re^d, j = 1, ..., N$, and we want to organize them into K clusters $C = \{C1, ..., CK\}$. The sum-of-squared-error criterion then is defined as

$$\begin{aligned} J_s(\Gamma, M) &= \sum_{i=1}^{K} \sum_{j=1}^{N} \gamma_{ij} \parallel x_j - m_i \parallel^2 \\ &= \sum_{i=1}^{K} \sum_{j=1}^{N} \gamma_{ij} (x_j - m_i)^T (x_j - m_i), \end{aligned} \tag{6.1}$$

where

$$\Gamma = \{\gamma_{ij}\} \text{ is a partition matrix,} \gamma_{ij} = \begin{cases} 1 & \text{if } X_j \in \text{cluster i} \\ 0 & \text{otherwise} \end{cases} \quad with \sum_{i=1}^{K} \gamma_{ij} = 1 \forall_j; \tag{6.2}$$

$M = [m_1, .., m_k]$ is the cluster prototype or centroid (means) matrix; and

$m_i = \frac{1}{N} \sum_{j=1}^{N} \gamma_{ij} x_j$ is the sample mean for the i^{th} cluster with N_i objects"[11]

Partitional clustering "assigns a set of data points into K clusters without any hierarchical structure. This process usually accompanies the optimization of a criterion function. More specifically, given a set of data points $x_i \in \Re^d, i = 1, ..., N$, partitional clustering algorithms aim to organize them into K clusters $\{C1, ..., CK\}$ while maximizing or minimizing a prespecified criterion function J."[11]

K-means algorithm

"K-means seeks an optimal partition of the data by minimizing the sum-of-squared-error criterion... with an iterative optimization procedure..."[11]. "The basic clustering procedure of K-means is summarized as follows:

1. Initialize a K-partition randomly or based on some prior knowledge. Calculate the cluster prototype matrix $M = [m_1, ..., m_k]$;

2. Assign each object in the data set to the nearest cluster C_l, i.e.,

$$x_j \in C_l, \text{if} \parallel x_j - m_l \parallel < \parallel x_j - m_i \parallel \\ \text{for } j = 1, ..., N, i \neq l, \text{and } i = 1, ..., K; \tag{6.3}$$

3. Recalculate the cluster prototype matrix based on the current partition,

$$m_i = \frac{1}{N_i} \sum_{x_j \in C_i} x_j; \tag{6.4}$$

4. Repeat steps 2 and 3 until there is no change for each cluster."[11]

There are multiple software packages that can run this algorithm on the desired data. The desired result is that *K-means* will partition the data (list of sub-functions) into "K" number of clusters. Where "K" is a number determined by the designers. There are several factors that can be considered for taking this decision, as explained in section 3.4. These clusters represent the different modules .

Chapter 7

Applying the Method in Practice

This chapter put in practice the method proposed in the previous chapter using the same case study of The Portfolio Company. It proposes a different approach and shows different results.

7.1 Application Results and Experiences

In the previous section, a method was proposed for the partition of the product into modules. To recapitulate, here are a few points on what was discussed and proposed:

- First, obtain the customer's input. We work on the *customer domain* and use methods and tools like the VOC, to gather the data about the needs of the customer.
- Once we gather the data, we need to process it in order to display it in a quantitative form. We can use QFD for this purpose.
- Then, we use the quantitative form of the customer needs data to perform a functional decomposition of the product. *Zigzagging* between FRs and DPs and PVs would significantly improve the process. During this task, the designers propose technical solutions that would satisfy the functions required from the customer to the product to perform.
- At this point, we have a set of technical solutions that satisfy the functions required from customer needs. Then, we need to group the technical solutions in different

clusters that will eventually become modules. We will use the method proposed in section 6.2 for this.

- After assessing the number of modules that the product should have, the interfaces between modules have to be analyzed and defined.

- Evaluate the outcome from a hierarchical stand point. At every domain, CA, FR, DP and PV.

Clustering the technical solutions *(function carriers)*

As explained in section 6.2, the input for the *K-means* algorithm is a set of objects $x_j \in \Re^d, j = 1, ..., N$. In our case, this set of objects is represented by the *function carriers.* Every sub-function on the set of objects x_j is a data point. We will consider the scores of the *module drivers* as the Cartesian coordinates in Euclidean n-space of these data points. Therefore, every data point has as many coordinates as there are *module drivers* (twelve in our case).

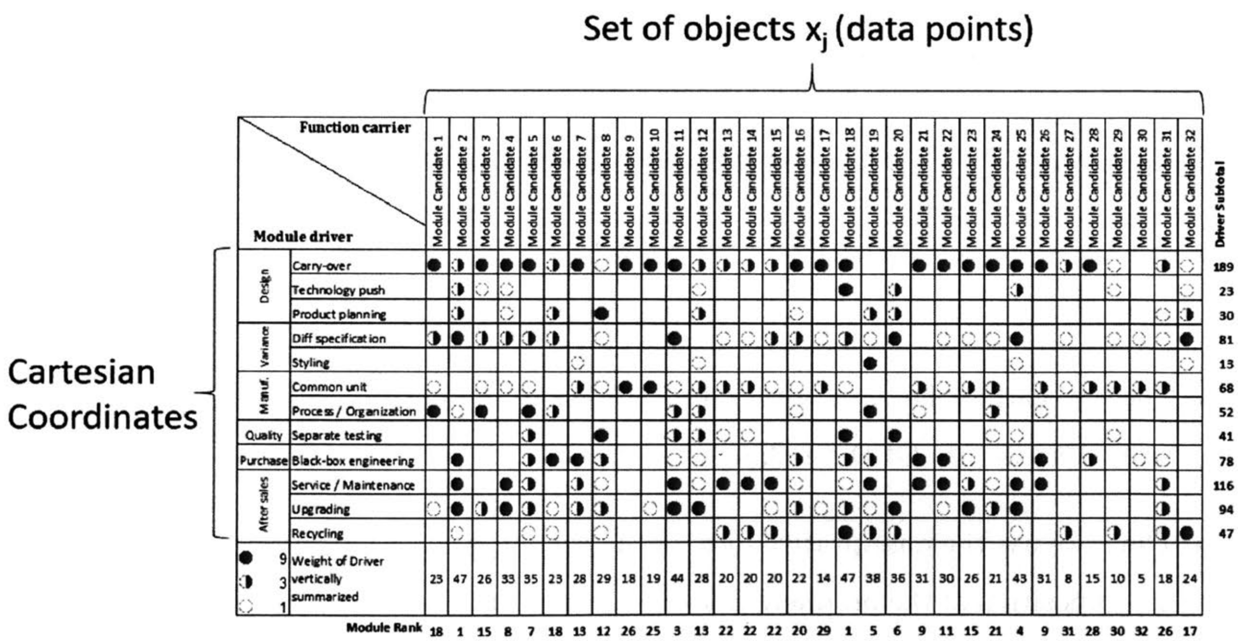

Figure 7-1: Interpretation of MIM for alternate method

Figure 7-1 depicts the MIM, which is the main input for the alternate method. We will use R software for running the *K-means* algorithm. The software requires to input the data in a matrix. Table 7.1 shows the data prepared to be used as the input, all of the weights from the MIM have been substituted by numbers and the data of the columns have been transposed.

Load data into R

The code below, depicts how we pull the data from a .csv file and load it into R.

```
#Load data from excel file
clust <- read.csv( file.choose(), header = T)
```

Normalize the data

The weight from the MIM are discrete values of 0, 3 and 9. This represents a scaling problem for data mining purposes. Since we are seeking for relations between the *function carriers*, in order to deal with the data, it is recommended to normalize it.

```
#Change scale of the data > normalize <- function(x)
+ return( (x - min(x)) / (max(x) - min(x)) )
```

Table 7.2 displays the normalized data.

Perform hierarchical clustering

I would recommend to start by performing hierarchical clustering since we can easily generate a dendrogram. The advantage of generating a dendrogram is that we can quickly start identifying the potential module concepts even if we do not have an idea of the number of modules that we will require. The code below show that we perform hierarchical clustering using Euclidean distance.

```
#Compute the Euclidean distance between the rows of the matrix
d <- dist(clust, method = "euclidean")
#Perform hierarchical cluster analysis
fit <- hclust(d)
#Plot dendogram
plot(fit)
```

As mentioned before, Figure 7-2 helps to have a visual understanding of all of the potential modules at different levels. The intermediate nodes describe the extent to which the *function carriers* are similar to each other (by using the sum-of-squared-error criterion

Cartesian Coordinates

Set of objects x_j (data points)

Module driver / Function carrier	Carry-over	Technology push	Product planning	Diff specification	Styling	Common unit	Process / Organization	Separate testing	Black-box engineering	Service / Maintenance	Upgrading	Recycling
Module Candidate 1	9	0	0	3	0	1	9	0	0	0	1	0
Module Candidate 2	3	3	3	9	0	0	1	0	9	9	9	1
Module Candidate 3	9	1	0	3	0	1	9	0	0	0	3	0
Module Candidate 4	9	1	1	3	0	1	0	0	0	9	9	0
Module Candidate 5	9	0	0	3	0	1	9	3	3	3	3	1
Module Candidate 6	3	0	3	3	0	0	3	0	9	0	1	1
Module Candidate 7	9	0	0	0	1	3	0	0	9	3	3	0
Module Candidate 8	1	0	9	1	0	1	0	9	3	1	3	1
Module Candidate 9	9	0	0	0	0	9	0	0	0	0	0	0
Module Candidate 10	9	0	0	0	0	9	0	0	0	0	1	0
Module Candidate 11	9	0	0	9	0	1	3	3	1	9	9	0
Module Candidate 12	3	1	3	0	1	3	3	3	1	1	9	0
Module Candidate 13	3	0	0	1	0	3	0	1	0	9	0	3
Module Candidate 14	3	0	0	1	0	3	0	1	0	9	0	3
Module Candidate 15	3	0	0	3	0	1	0	0	0	9	1	3
Module Candidate 16	9	0	1	3	0	1	1	0	3	1	3	0
Module Candidate 17	9	0	0	1	0	3	0	0	0	0	1	0
Module Candidate 18	9	9	0	3	0	1	0	9	3	1	3	9
Module Candidate 19	0	0	3	1	9	0	9	0	3	9	1	3
Module Candidate 20	0	3	3	9	0	0	0	9	0	0	9	3
Module Candidate 21	9	0	0	0	0	3	1	0	9	9	0	0
Module Candidate 22	9	0	0	1	0	1	0	0	9	9	1	0
Module Candidate 23	9	0	0	1	0	3	0	0	1	3	9	0
Module Candidate 24	9	0	0	1	0	3	3	1	0	1	3	0
Module Candidate 25	9	3	0	9	1	0	0	1	1	9	9	1
Module Candidate 26	9	0	0	0	0	3	1	0	9	9	0	0
Module Candidate 27	3	0	0	1	0	1	0	0	0	0	0	3
Module Candidate 28	9	0	0	0	0	3	0	0	3	0	0	0
Module Candidate 29	1	1	0	1	0	3	0	1	0	0	0	3
Module Candidate 30	0	0	0	1	0	3	0	0	1	0	0	0
Module Candidate 31	3	0	1	1	0	3	0	0	1	3	3	3
Module Candidate 32	1	1	3	9	1	0	0	0	0	0	0	9

Table 7.1: Preparation of data

Module driver / Function carrier	Carry-over	Technology push	Product planning	Diff specification	Styling	Common unit	Process / Organization	Separate testing	Black-box engineering	Service / Maintenance	Upgrading	Recycling
Module Candidate 1	1.00	0.00	0.00	0.33	0.00	0.11	1.00	0.00	0.00	0.00	0.11	0.00
Module Candidate 2	0.33	0.33	0.33	1.00	0.00	0.00	0.11	0.00	1.00	1.00	1.00	0.11
Module Candidate 3	1.00	0.11	0.00	0.33	0.00	0.11	1.00	0.00	0.00	0.00	0.33	0.00
Module Candidate 4	1.00	0.11	0.11	0.33	0.00	0.11	0.00	0.00	0.00	1.00	1.00	0.00
Module Candidate 5	1.00	0.00	0.00	0.33	0.00	0.11	1.00	0.33	0.33	0.33	0.33	0.11
Module Candidate 6	0.33	0.00	0.33	0.33	0.00	0.00	0.33	0.00	1.00	0.00	0.11	0.11
Module Candidate 7	1.00	0.00	0.00	0.00	0.11	0.33	0.00	0.00	1.00	0.33	0.33	0.00
Module Candidate 8	0.11	0.00	1.00	0.11	0.00	0.11	0.00	1.00	0.33	0.11	0.33	0.11
Module Candidate 9	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Module Candidate 10	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.11	0.00
Module Candidate 11	1.00	0.00	0.00	1.00	0.00	0.11	0.33	0.33	0.11	1.00	1.00	0.00
Module Candidate 12	0.33	0.11	0.33	0.00	0.11	0.33	0.33	0.33	0.11	0.11	1.00	0.00
Module Candidate 13	0.33	0.00	0.00	0.11	0.00	0.33	0.00	0.11	0.00	1.00	0.00	0.33
Module Candidate 14	0.33	0.00	0.00	0.11	0.00	0.33	0.00	0.11	0.00	1.00	0.00	0.33
Module Candidate 15	0.33	0.00	0.00	0.33	0.00	0.11	0.00	0.00	0.00	1.00	0.11	0.33
Module Candidate 16	1.00	0.00	0.11	0.33	0.00	0.11	0.11	0.00	0.33	0.11	0.33	0.00
Module Candidate 17	1.00	0.00	0.00	0.11	0.00	0.33	0.00	0.00	0.00	0.00	0.11	0.00
Module Candidate 18	1.00	1.00	0.00	0.33	0.00	0.11	0.00	1.00	0.33	0.11	0.33	1.00
Module Candidate 19	0.00	0.00	0.33	0.11	1.00	0.00	1.00	0.00	0.33	1.00	0.11	0.33
Module Candidate 20	0.00	0.33	0.33	1.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.33
Module Candidate 21	1.00	0.00	0.00	0.00	0.00	0.33	0.11	0.00	1.00	1.00	0.00	0.00
Module Candidate 22	1.00	0.00	0.00	0.11	0.00	0.11	0.00	0.00	1.00	1.00	0.11	0.00
Module Candidate 23	1.00	0.00	0.00	0.11	0.00	0.33	0.00	0.00	0.11	0.33	1.00	0.00
Module Candidate 24	1.00	0.00	0.00	0.11	0.00	0.33	0.33	0.11	0.00	0.11	0.33	0.00
Module Candidate 25	1.00	0.33	0.00	1.00	0.11	0.00	0.00	0.11	0.11	1.00	1.00	0.11
Module Candidate 26	1.00	0.00	0.00	0.00	0.00	0.33	0.11	0.00	1.00	1.00	0.00	0.00
Module Candidate 27	0.33	0.00	0.00	0.11	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.33
Module Candidate 28	1.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	0.00
Module Candidate 29	0.11	0.11	0.00	0.11	0.00	0.33	0.00	0.11	0.00	0.00	0.00	0.33
Module Candidate 30	0.00	0.00	0.00	0.11	0.00	0.33	0.00	0.00	0.11	0.00	0.00	0.00
Module Candidate 31	0.33	0.00	0.11	0.11	0.00	0.33	0.00	0.00	0.11	0.33	0.33	0.33
Module Candidate 32	0.11	0.11	0.33	1.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 7.2: Normalized data

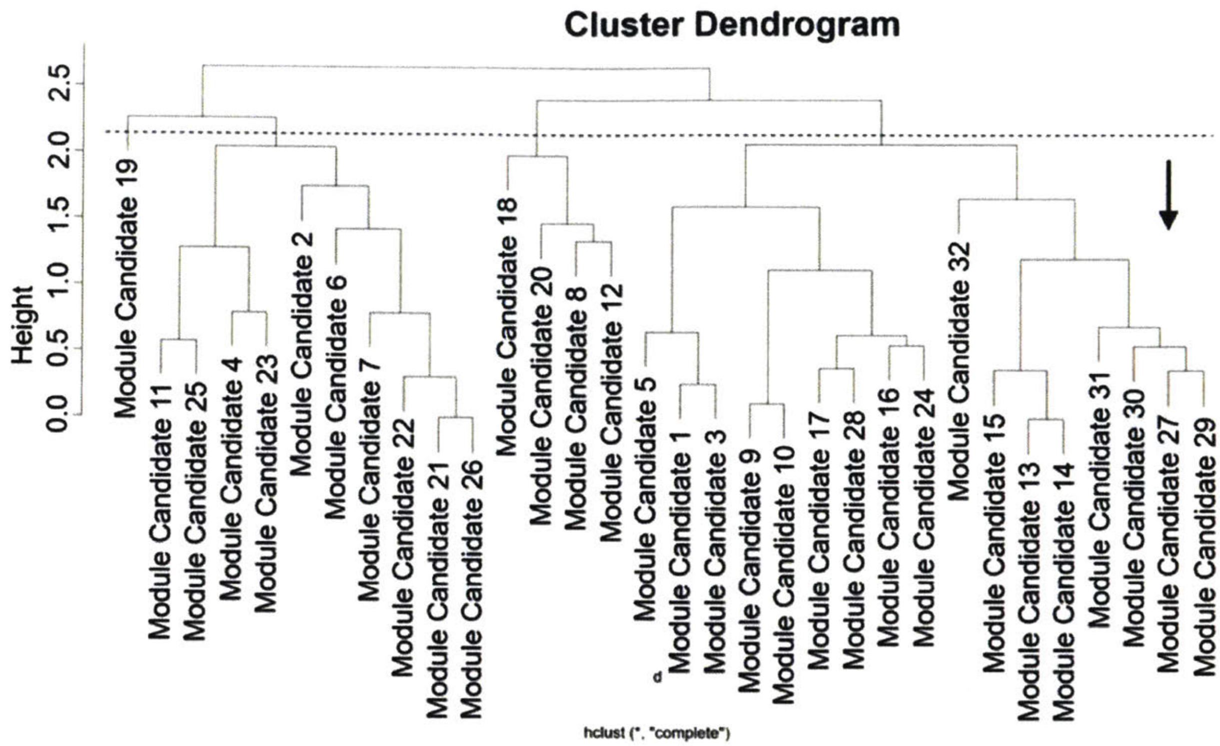

Figure 7-2: Hierarchical clustering of The Product

function explained in section 6.2, whereas the height shows the distance between each pair of *function carriers* or modules, or a *function carrier* and a module. This dendogram is useful if we want to have a quick look at how the modules could be created, and how many would be a good number. We can slide a line as the dashed line shown in Figure 7-2 and observe the potential modules. The number of vertical lines that the horizontal dashed line intersects with, represents the number of modules that we could have at that level and the clustering structure below the dashed line represents the composition of those modules. In addition, if desired, we can select the number of modules that we want to have and R could depict those in the dendrogram for us. The code below groups the *function carriers* in 13 clusters and enclosed them in red rectangles (See Figure 7-3).

```
#Identify k clusters in the dendrogram
groups <- cutree(fit, k=13)
#Enclose clusters in red rectangles
rect.hclust(fit, k=13, border="red")
```

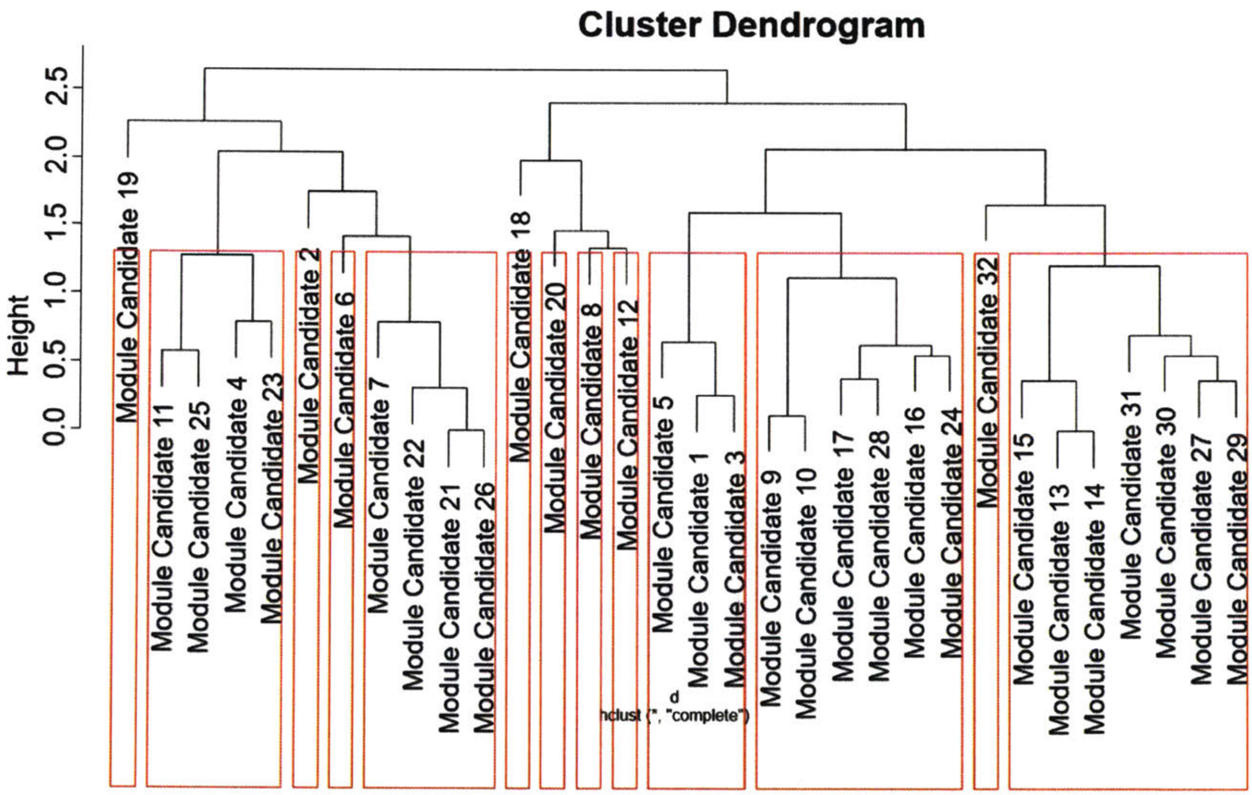

Figure 7-3: Hierarchical clustering - 13 clusters

Another tool that we can use to understand the structure and the impact of the *module drivers* in the different *function carriers* is a heat map. This will allow us to observe at first sight how the modules should be formed and what *module drivers* are the main cause of the module formation (See Figure 7-4).

```
#Scale data to mean =0, sd=1 and convert to matrix
clust_scaled <- as.matrix(scale(clust_n))
#Create heat map without reordering columns
heatmap(clust_scaled, Colv=F, scale='none')
```

On the heat map we can observe, for example, that the *module driver* "upgrading" plays an important role of the *module candidates 12, 4* and *23* as it displays a lighter color. This plays a role on the decision of whether grouping these three *function carriers* to create a module or not.

Now that we have a better understanding of the structure of the data, we can run the *K-means* algorithm to find out how the clusters (modules) could be arranged. The data from the MIM was already prepared for running the algorithm (loaded in R, normalized, etc.), the data frame is stored as "clust", we will assign the new name "kmodular" for running *k-means*.

```
#Assign new name to the data frame: kmodular
kmodular<-clust
#Run kmeans algorithm on the data and assign it to res
res<-kmeans(kmodular,13)
Display the results
res
```

After running the algorithm, Figure 7-5 below, shows the number of elements (*function carriers*) that are assigned per cluster.

Every *function carrier* was assigned to a cluster number as shown in Figure 7-6 below.

The method suggests that the modules should be comprised as follows:

The modular concept has now been generated. This concept has to be evaluated by the team either as proposed by MFD™ or just by making sense of the product architecture and its feasibility. In order to make an evaluation of these modular concept, we will compare it to the modular concept depicted in Table 6.4 as it resembles, in essence, the current

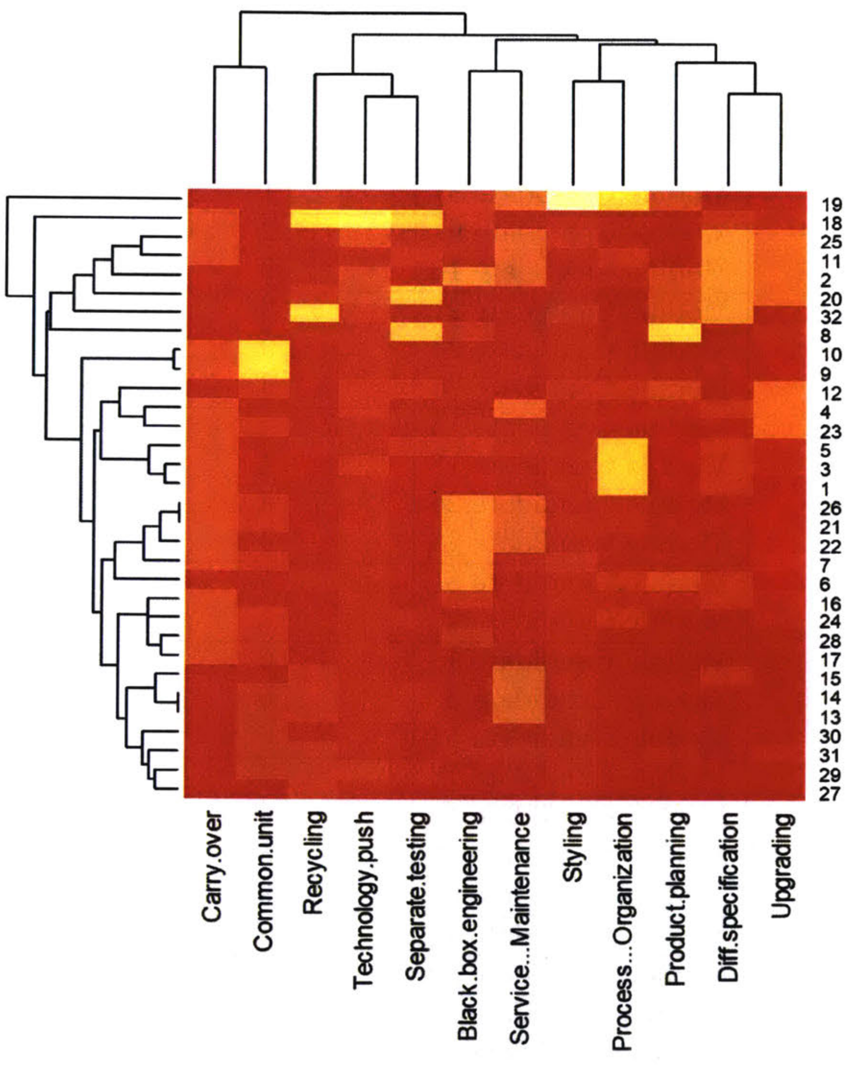

Figure 7-4: Heat map of the hierarchical clustering of MIM

Table 7.3: Clusters and content

Function carriers	Module Number
Module Candidate 13	1
Module Candidate 14	1
Module Candidate 15	1
Module Candidate 27	1
Module Candidate 29	1
Module Candidate 30	1
Module Candidate 31	1
Module Candidate 9	2
Module Candidate 10	2
Module Candidate 21	3
Module Candidate 22	3
Module Candidate 26	3
Module Candidate 16	4
Module Candidate 17	4
Module Candidate 24	4
Module Candidate 28	4
Module Candidate 8	5
Module Candidate 20	5
Module Candidate 1	6
Module Candidate 3	6
Module Candidate 5	6
Module Candidate 18	7
Module Candidate 12	8
Module Candidate 23	8
Module Candidate 32	9
Module Candidate 7	10
Module Candidate 19	11
Module Candidate 2	12
Module Candidate 4	12
Module Candidate 11	12
Module Candidate 25	12
Module Candidate 6	13

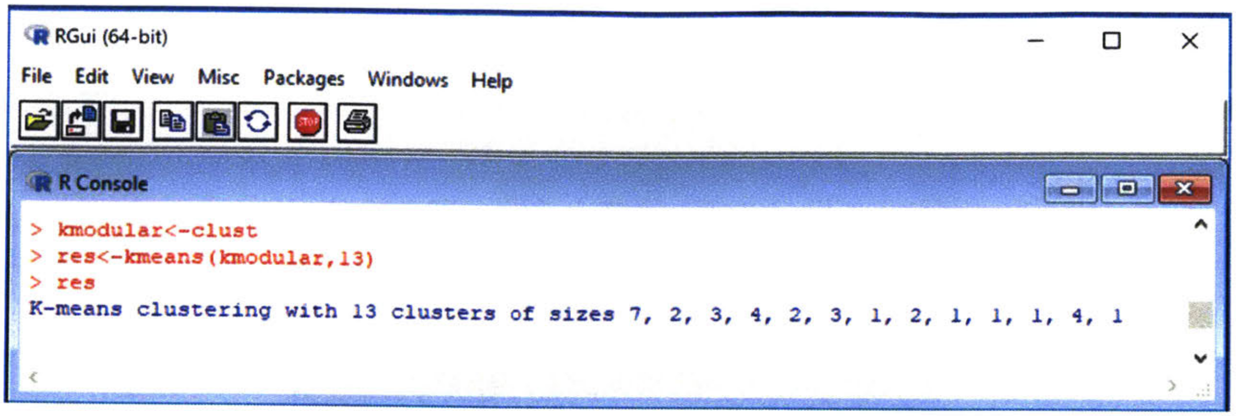

Figure 7-5: Number of elements per Cluster

non-modular platform.

First, we notice that some of the *function carriers* that ended up as a module by themselves are the same: *Module candidate 6* and *Module candidate 32*. Others differ with no fundamental change, for example: *Module candidate 18* in Table 7.3 is by itself and in Table 6.4 it has been grouped with *Module candidate 20*. However, where the fundamental difference comes is in modules like the one formed by *Module candidate 13*, *Module candidate 14* and *Module candidate 15* or the one formed by *Module candidate 21*, *Module candidate 22* and *Module candidate 26* in Table 7.3. Having such modules would imply an important departure from the current non-modular platform design. The implications of having such module would significantly change the FRs and DPs as compared to ones from the current non-modular design. Having *Module candidate 13*, *Module candidate 14* and *Module candidate 15* in one module might be possible but it is important to think about the implications; in other words, at what cost? It might be that the technical challenge that represents to have these *function carriers* together does not outweigh the benefit of having these in the same module.

It is important to notice that besides the information that defines the data points, there can be background knowledge that must be considered prior to the formation of the clusters. This background information can interact with the algorithm as constraints of the nature of must-link or cannot link data points. For example, in the case of The Product, the *function carriers*: *Module candidate 21*, *Module candidate 22* and *Module candidate 26*, it is not desirable to have them at the same module as it is physically complex due to geometric

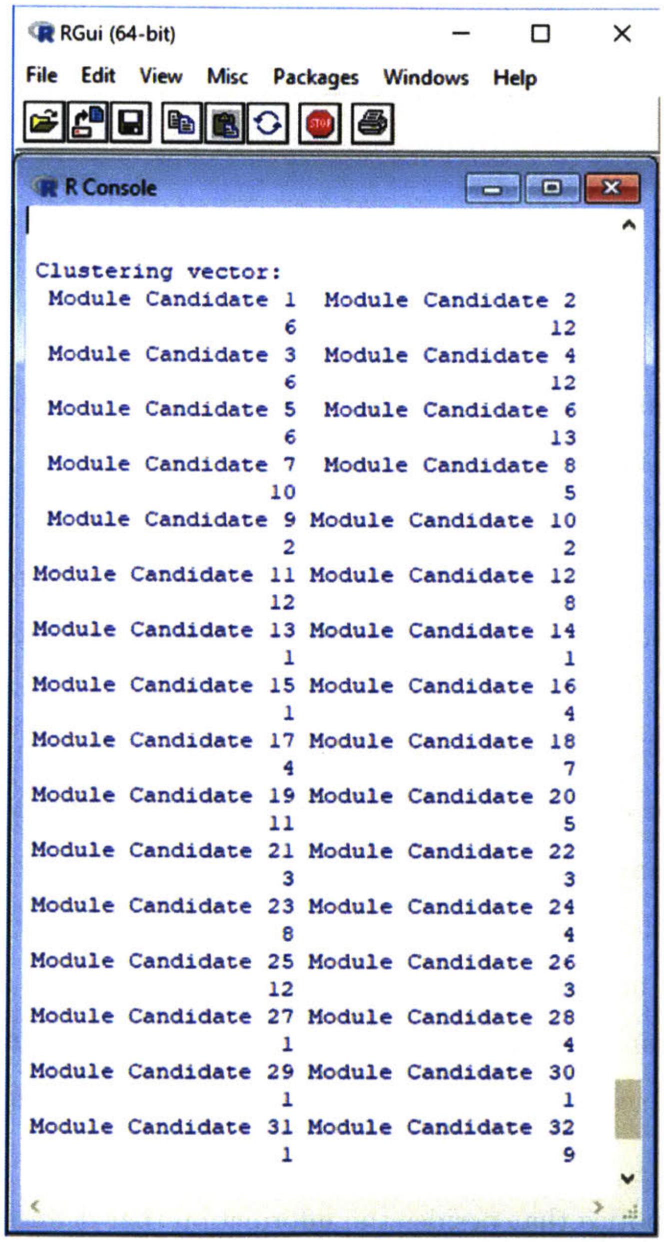

Figure 7-6: Clusters assignment by K-means it R

constraints. However, *K-means* grouped them in the same cluster since they are very similar in their ability to be modular.

7.2 Summary

This chapter proposes a different approach to the task of generating modular concepts. The proposed method, builds on the use of *module drivers* (From MFD™) for determining the ability of the *function carriers* to become modules.

The method prepares the data that the MIM provides by normalizing it in order to work on the same range on all of the *function carriers* and to have consistency on the formation of the clusters. The use of the software R was introduced to run the clustering algorithms.

The two main clustering techniques that exist were introduced for partitioning the data: hierarchical and partitional.

Using hierarchical clustering, we were able create a chart that displays the level of proximity between the different *function carriers*. We defined proximity between two *function carriers* as the closeness obtained from the Euclidean distance between the two point in the Euclidean space. Also, we were able to select the number of clusters that we wanted to create and we enclosed the *function carriers* in the resulting clusters with red rectangles. In addition, we introduced the use of the heat map in order to depict in one picture, how the modules could be created, what *module drivers* are the main influencer for this creation and the intensity of the influence.

We used partitional clustering with the *K-means* algorithm. The data was normalized as with the case of the hierarchical clustering however in this case, it was necessary to select the number of clusters that we wanted to create. This is the main difference with hierarchical clustering, where it is not necessary to know the number of clusters that we are trying to generate.

A modular concept was generated with this method and it was evaluated by comparing it to the modular concept generated only with the MFD™ method. The similarity on the results was noted but also we discussed some fundamental differences that might lead the designers to rethink the product architecture. However, it was questioned whether the benefits from the modular concept obtained with this method supersede the cost of the technical challenge of creating a totally different platform.

Conceptualizing a product as a list of functions, can be helpful to come up with a design that really meets the needs of the customer. Bringing back Axiomatic Design from section 3.1, once the customer needs have been defined, the mapping process has to happen in a "solution-neutral environment". In other words, in order to define the FRs, one should not think about existing designs or what the design solution should be. Otherwise, one would end up defining the FRs of an existing product and the purpose of motivating creative thinking would be defeated. Therefore, one potential limitation of using these clustering methods as presented in this chapter, is precisely that it creates the modules with the *function carriers* that have been previously defined. Thus, if the *function carriers* were not created in a "solution-neutral environment", the creation of modular concepts would be biased towards an existing design and this will defeat the purpose of evaluating the *function carriers* on every *module driver* to come up with the modular concept.

The definition of the modules is key to the success of the modular platform as the decisions taken during this process might influence other decisions down the value chain. For example, it might set the criteria to select a particular supplier or a particular manufacturing location.

Due to the flexibility of modular platforms, an option that is naturally enabled is the outsourcing of the modules. Modular platforms make this possible due to the independence of the design of the modules and the manufacturing of them; given that a number of design rules are followed and a systems integration entity controls the processes. Outsourcing the modules might be desirable for a number of reasons, being costs and proximity to the customers among the most important. The next chapter presents a case for modularity, based on the analysis of the feasibility of outsourcing the platform.

Chapter 8

Making the case for modularity at The Portfolio Company

At the introduction of this thesis, the potential benefits of implementing a modular platform were listed. So far, the previous chapters have laid out the background, the theory, the implementation of modularity in The Portfolio Company and the introduction of new methods for creating modules. However, it has not presented the case for implementation. Are there any direct and indirect cost benefits by migrating to a modular platform? This chapter addresses this question in a qualitative way as derived from a cost analysis that was performed during the internship and also proposes an outsourcing model suitable for the modular platform at the Portfolio Company. Cost ratios, market position and product comparisons have been omitted in order to protect the Portfolio Company's confidential information.

8.1 Cost analysis

A very important yet basic analysis for understanding the benefits of the modular platform is the cost analysis. This analysis started with a few basic questions:

- Where is the current platform manufactured?
- How much does it cost to produce the current (non-modular) platform?
- Where are the customers located?

As explained before, The Portfolio Company offers two main platforms and multiple configurations of The Product. For the purpose of the analysis, it was decided to pick the largest revenue generator model of each platform and use it as the base for the analysis. The two platforms will be referred as *Platform A* and *Platform B*. It is important to note that the costs are based on the BOM (Bill of Materials) of existing platforms instead of the modular ones, as it is the most accurate data available. Therefore, this analysis does not account for the following:

- New pricing from suppliers on the new required parts.
- The lower costs on some items as a result of achieving economies of scales due to the consolidation of the five platforms in one.
- The lower costs on some parts due to the standardization and reduction of unique part numbers. Savings as a result from achieving a faster time to market.
- Any other savings as a result of reduction on operation complexity

In addition, the cost data related to the tier 3 CM was based on the model that the Portfolio Company currently has with this CM. The cost data related to the tier 1 CM was according to a quote obtained from this CM. No change in the market share of these platforms was assumed, the units to be sold are the same as for the current platforms.

Platform A - Current situation

The current situation of the operations for *Platform A* are as follows:

Manufacturing site

The final assembly for *Platform A* is in the US at the facility of The Portfolio Company (in house).

Customers locations

The market is divided into AMER (Americas), EMEA (Europe, the Middle East and Africa) and APAC (Asia-Pacific). An important share of the revenues of *Platform A*, comes from AMER and EMEA. This product is one of the main revenue generators of this segment of the company.

Lead time

The product lead-time depends on the location of the customer. If the customer is located in AMER, the lead time is 4 weeks and if it is located in EMEA or APAC the lead-time is 8 weeks.

Cost drivers

The cost drivers that were considered are as follows:

- Direct material
- Direct labor
- Freight
- Material overhead
- Labor overhead

Where the items are considered as follows:
Direct material: cost of purchase parts directly taken from the costed BOM. Direct labor: direct cost of labor (wages).

Freight: It is divided into freight-in and freight-out. Freight-in is the shipping cost to bring the purchase parts into the manufacturing facility and freight-out is the cost of shipping the final product to the customer. In the case of the products manufactured in the US (this is the case for *Platform A*), freight-in is included in direct material.

Material overhead: in The Portfolio Company the overhead associated with procurement is absorbed with the material utilized and it is called material overhead. Labor Overhead: the manufacturing overhead is absorbed with the material utilized and it is called labor overhead.

Quality

The main quality metric that The Portfolio Company tracks is Annualized Failure Rate (AFR) which is defined as the number of visits that a service technician makes to a customer during the first year after the delivery of the machine, multiplied by 100. This counts visits are per request from the customer due to any failure or abnormality.

R & D (Research & Development)

The R & D department is located in the US, in the same facility where the final assembly is located. The concept development, design, design validation and verification along with sustaining engineering is performed by the R & D department.

Platform B

The current status of the operations for *Platform B* are as follows:

Manufacturing site

The final assembly for *Platform B* is in part manufactured in the US and APAC by a CM (Contract Manufacturer).

Customers locations

The market is divided the similarly as for *Platform A*.

Lead time

In this case, for the customers located in AMER, the lead time is 8 weeks, for EMEA it is 9 weeks and for APAC it is 4 weeks.

Cost drivers

The cost drivers that were considered are as follows:

- Direct material

- Direct labor
- Freight
- Material overhead
- Labor overhead
- Other cost in APAC

Where the items are considered as follows:

Direct material: cost of purchase parts directly taken from the costed BOM (Bill of Materials). Direct labor: direct cost of labor (wages).

Freight: Same as *Platform A*, but in this case, there is freight-in cost at the CM.

Material overhead: in The Portfolio Company the overhead associated with procurement is absorbed with the material utilized and is called material overhead. Similarly, at the CM, there is an absorption of the procurement overhead.

Labor Overhead: for the product manufactured in the US, the manufacturing overhead is absorbed with the material utilized and is called labor overhead. In the case of APAC, a fraction of the manufacturing overhead is absorbed at the non-consigned direct material.

Quality

The B platform also uses AFR as the main metric.

R & D (Research & Development)

Same as *Platform B*, the R & D department is located in the US.

Other costs in APAC

This item is related to the CM in APAC, it includes SG& A (Selling, General and Administrative expenses), profit, and the burden on the cost absorption on the US due to having this operation overseas.

The study was conducted by working closely with the VPs of Operations and Global supply chain and by gathering all of the necessary information from the related departments, including: accounting, operations, supply chain and engineering. As mentioned before, in order to protect the confidential data, no actual cost or ratios will be presented in this thesis.

Manufacturing scenarios

One of the main benefits of modular engineering is flexibility. Modularity in design provides flexibility in terms of where the design of the modules can be performed as it can happen at multiple locations and in parallel. In addition, it provides the flexibility to manufacture the modules wherever is more convenient and to perform the final integration (assembly) of the modules where ever it makes more sense. The following options were selected according to the particular situation of the Portfolio Company, resources available from the current footprint and from similar models taken from other portfolio companies.

Platform A - Manufacturing options

Option 1

The portfolio company has been working on a mixed model with a tier 3 CM in APAC. This model consists of having some portion of the procured material consigned to the CM, which means that the CM takes care of procurement and inventory and the rest is procured by the Portfolio Company and stored at the CM's facility. This option proposes to manufacture all of the modules of *Platform A* in APAC with this tier 3 CM granting a 40% control of the material.

Option 2

This option proposes to manufacture all of the modules in APAC with a tier 1 CM controlling 100% of the material.

Option 3

In this case, the platform would be 100% outsourced (no consigned material), the manufacturing location would be a mix of USA and Europe with the purpose of being closer to the customers and it would be performed by a tier 1 CM in both regions.

Option 4

This option is similar to *option 3* but instead of doing 100% outsourced, it would be 40% controlled by the CM.

Platform B - Manufacturing options

Option 1

Current model makes some of the final products in the US and others in APAC. This option proposes to make them all in the US in house.

Option 2

This option also proposes to manufacture all of the modules in APAC with a tier 3 CM controlling 50% of the material and the rest by the Portfolio Company.

Option 3

Same as *option 2*, but the CM would be tier 1.

Option 4

In this option, all of the modules are manufactured in APAC by a tier 1 CM that controls 100% of the material.

Option 5

This is a dual model with manufacturing locations in APAC and Europe. The material is 100% controlled by the CM in both locations. Highlights and considerations

Platform A

As shown in Table 8.1 below, all of the options offer savings and they are ranked from 1 to 4, 1 being the one the offer the largest savings. However, there are some nuances that need to be discussed. These are the highlights of the analysis:

- Doing all of the production of the modules in APAC with a 40% tier 3 CM controlled (*Option 1*) shows the largest savings. This might seem as the go-to option since there is an existing relationship with the tier 3 CM. However, there are concerns about the quality and capacity of this CM and it is not clear that it would be able to handle this new project.

- The second best option in terms of savings is *ption 4*. This option is more desirable since it is with a tier 1 CM that displays expertise and capacity. Another portfolio company is currently working with this CM and they report having a successful relationship backed by good quality and performance.

- In addition, with *option 4*, the duplication of operations (USA and Europe) would allow to lower the lead-time for the EMEA customers as every location will supply the market of its proximity avoiding long distance shipping. It is expected that the lead-time with this model will go from 8 weeks to 4 for the EMEA customers.

- *Option 3* is a variant of *option 4* that offers less cost savings, since the material would be 100% controlled by the CM. However, this could be a good option in the future in order to reduce complexity. In addition, there is potential to work with this CM in order to achieve cost saving on the direct material as they have leverage with the suppliers.

- *Option 2* makes less sense as it proposes to make all of the product in APAC and the customers for this platform are mainly in AMER and EMEA. That is the main reason why this option present the least cost savings.

	Current model All in House (USA)			OPTION 1 - All out sourced (APAC) 40% controlled (tier 3 CM)			OPTION 2 - All out sourced 100% CM controlled (tier 1 CM)			OPTION 3 - All out sourced 100% controlled (Global Presence with tier 1 CM)			OPTION 4 - All out sourced 40% CM controlled (Global Presence with tier 1 CM)		
Where is it built?	USA			APAC			APAC			USA	Europe		USA	Europe	
For what region?	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC
Ranking of savings	Base			1			4			3			2		

Table 8.1: Platform A cost analysis

Platform B

As for *Platform A*, in Table 8.2, we show the rankings of savings, these are the highlights of the analysis:

- Doing all of the production in the US, will actually increase the costs. In addition, this is not desirable since, there is a risk that the lead-time might increase.
- The highest savings are presented by *option 2*. However this option would require to use the tier 3 CM in APAC and concerns have been raised about the capacity and quality of this CM.
- The next best option in terms of savings, is *option 3* which is practically *option 2* but working with a tier 1 CM. This would be more desirable since the diference in cost is not significant and the benefits of risk mitigation in terms of capacity and quality are remarkable.
- One of the most atractive options is *option 5*. It offers two locations for manufacturing (APAC and Europe) and the savings are not very different from the other options. This option enables the posibility to offer lower lead-time to EMEA (from 9 to 4 weeks).

	Current model (APAC and US)						OPTION 1 (US) All in House			OPTION 2 (APAC) All out sourced 50% consigned (tier 3 CM)			OPTION 3 (APAC) All outsourced 50% Consigned (tier 1 CM)			OPTION 4 (APAC) All outsourced with 100% controlled (tier 1 CM)			OPTION 5 (APAC and Europe) All outsourced with 100% controlled (tier 1 CM)		
Where is it built?	USA			APAC			USA			APAC			APAC			APAC			APAC		Europe
For what region?	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	EMEA	APAC	AMER	APAC	EMEA
Ranking of savings	BASE CASE						5*			1			2			3			4		

*This option does not offer any savings and it is more costly than the base case

Table 8.2: Platform B cost analysis

8.2 Outsourcing model

With the insight and data from the cost analysis and some strategic considerations, now this section proposes a vision of the manufacturing strategy that best supports the modular platform in order to capture its benefits. The model will be based on selecting *options 4* and *5* for *Platform A* and *B*, respectively.

Manufacturing strategy - Platforms A & B

It was discussed in section 8.1 that *options 4* and *5* would create the best scenario to support modularity on *Platform A & B* respectively. Recapitulating, *option 4* for *Platform A* consists of outsourcing all of the modules to a tier 1 CM with presence in USA and Europe. The CM would control 40% of the material. The reason for this mixed model where the CM only controls a portion of the material is to allow the Portfolio Company to still have control over the most critical parts. *Option 5* for *Platform B* consists of outsourcing all of the modules to a tier 1 CM with presence in APAC and Europe. The CM would control 100% of the material. There are some actions required for the plan to work and those are listed below.

Strategy

Benefits

- Proximity to the customers in EMEA allows for a shorter lead-time
- The duplication of operations (USA and Europe/ APAC and Europe) would remove complexity, allowing each manufacturing site to focus on the demand of its covered regions.
- Labor costs are lower in Europe and APAC
- Freight-out costs are lower from Europe to EMEA

Downsides and risks

- It is the first time that the Portfolio Company would work with this tier 1 CM (Even though other portfolio companies have worked with them)
- If everything else stays the same, by manufacturing in other locations other than in house, it would decrease capacity utilization, increasing the cost absorption in house. Therefore, a burden was considered in the analysis (not shown in this thesis).

- By working on this new model there are new gaps that were not existing before. For example, since the current model is all manufactured in the US, all of the sustain engineering activities were performed in house, however with the new manufacturing facility there is a need of handling sustain engineering and there is disadvantages of handling from long distance.

- The design and manufacturing of modular platforms, requires system integrations capabilities, therefore this need has to be covered.

Required actions

Once the vision of the manufacturing strategy is selected, a detail plan has to be designed in order to migrate from the current manufacturing model to the modular one. This thesis does not present the transfer plan; however, these are some highlights of the plan:

- In order to mitigate the risks, the transfer of manufacturing to other locations does not have to be all at the same time. Some modules can be transferred first. This would allow time to prepared documentations and also will give the opportunity to test the capabilities of the CM.

- The design of some of the modules can also be outsourced.

- Put in place a plan to protect IP. Since the modules would be manufactured in multiple locations and by CMs, it is necessary to protect the IP.

In order to support the transfer plan, some actions are required from different departments:

Operations

- Train QA (Quality Assurance) technicians to adapt to the changes in inspections of systems rather than only final product.

- Manage the relationship with the CM.

R & D

- Address organizational gaps: create a systems integration group.

- Implement the necessary changes in NPD (New Product Development) process in order to create the mechanism to allow modules to be designed and manufactured by third parties. This includes the need to create source controlled drawings, requested validation and verification from suppliers, the creation of ATP (Acceptance Test Plan) for every module and other documentation related to the systems integration.

Outsourcing model

Figure 8-1 below, depicts a simple footprint of the current model and the future modular platform.

	In House	CM			
		Tier 3	Tier 1		
	USA	APAC	USA	Europe	APAC
Platform A	☑				
Platform B	☑	☑			

	In House	CM			
		Tier 3	Tier 1		
	USA	APAC	USA*	Europe	APAC
Platform A			☑	☑	
Platform B				☑	☑

*This could be either in-house or by the CM

Figure 8-1: Current and Proposed outsourcing model for modular platforms

Chapter 9

Conclusions and Future Work

This thesis documents the precedent of the implementation of modular engineering in a portfolio company of a private equity firm that holds industrial businesses. It acknowledges the actual trends in the industry and hypothesizes that modular engineering could be a practice to stay ahead of the curve and provide quality product to the customers faster and less costly. Presents the background of the product design and development techniques, the state of the art of modularity in the industry and introduces a faster method to propose modular concepts. Finally, it makes the case for implementing modularity by performing a cost analysis in two different platforms of the product and proposes an outsourcing model based on the cost analysis.

9.1 Conclusions

Modular engineering if properly implemented, brings a lot of good practices to the companies. However, the implementation of modular engineering should be considered at an organization level, not at a project basis level. Implementing modular engineering creates so much disruption with the traditional processes and practices that trying to implement it only on a few projects would require an analysis to understand whether it is worth disruption on customers, suppliers, and practically all of the departments on the company. Modular engineering changes the way the products are developed, produced and used, the way the parts are procured, the way the product is inspected and the way the products are shipped and delivered to the customer. In addition, the aftermarket could be different as the service can replace the modules quickly rather than spending hours at the customer site doing root cause analysis. Since every company and product is different, there are not defined ways as to how all of the value chain should change, but modular engineering enables a set of possibilities that were not available before. The outsourcing model could change by sourcing modules instead of parts, as proposed on section 8.2. Every module could be tested prior to the final assembly obviating the need for testing the modules at the final stage.

On the customer front, some companies that have implemented modular engineering, go beyond and create their modules by working on the customer's cost structure. For example, the customer shares with them the percentages of direct costs (maintenance, power, consumables, etc.) that they have by operating their product. Then, the companies customize the product according to the application, of that particular customer. Considering that the customer has the same product, if for one customer the highest cost is power and for another one is maintenance, it probably means that the customers have different applications. Therefore, one of the customers is paying for the extra capacity of the power that the machine has. One solution that a modular engineering could provide is to make the power system a module and offer the customer that does not require as much power, a low power source. Since the *module* drivers are the input to obtain the optimal modules, we can always re-define these *module drivers* in regard to the input from the customer. Effectively, this will be as virtually inviting the customer to the design table for creating a better product.

Oftentimes, modularization is confounded with standardization. Whereas standardization is about using the same solution to solve similar problems, for example using the same parts with the same part number for the same applications; modular engineering goes beyond and creates standardized assemblies. Therefore, modular engineering assumes standardization as its base.

9.2 Future Research

In section 7.1 we discussed about the limitations of the proposed alternate method. It was mentioned that background knowledge about the *functional carriers* might deem some of the generated modules (clusters) unfeasible. One example was the *functional carriers*: *"Module Candidate 21"*, *"Module Candidate 22"* and *"Module Candidate 26"*. One solution, although it would probably defeat the purpose of automating the generation of module concepts, would be to visually assign these *functional carriers* to different modules by looking at their proximity in the dendrogram. There are a few algorithms that have been developed and consider constraints, however the limitation that these algorithms have is that they only consider one couple of "mustLink" data points and a couple of "cantLink". The development of a new algorithm that considers multiple constrains could benefit the process and incentivize the exploration of concepts. Also, in section 7.2, another potential limitation of the clustering method proposed was explained. This has to do more with the mapping process during the product development than with the method itself. The basic idea is that during the mapping process, while defining the FRs, the designers should not think about existing designs or about what the solution should be, as this would introduce a bias towards an existing design and the FRs that are being specified would end up being the FRs of the existing design. Consequently, since a bias has been introduced on the specification of the FRs, the *functional carriers* are biased toward the existing design and the MIM would end up playing a minor role in the creation of the modular concepts.

9.3 Summary

In this section we listed some conclusions coming out of the theory, method, the implementation, the alternate methods and the outsourcing model as a result of the cost analysis. Recapitulating some highlights of the previous chapters, modular engineering offers multiple benefits but the limits and challenges are oftentimes misunderstood and/or overlooked. Axiomatic Design presents solid basis for a mathematical abstraction of the design process and sets the standard for creating good designs, however the implementation in practice of the Axioms and recommendations is not a simple task. MFD™ is a comprehensive method that presents a good introduction to the modularity mindset in the engineering departments of the companies. Nonetheless, as explained in sections 7.2 and 9.2, if fundamental rules are not followed, the method can be played to develop products that are very close to what the they were prior to the use of the method, defeating the purpose of modular engineering. Also, the type of product (VLSI vs. CEMO) play a fundamental role in the ability of a product to be modular, as often times when there is transfer of power between the modules the interfaces are more difficult to define and the modules are frequently dependent on other modules, since by changing the design of one module other are impacted. This defeats the purpose of modular engineering.

As explained before, one of the purposes of this thesis is to present a Use Case with enough theoretical and practical information about the implementation of modular engineering in a portfolio company, to be shared and discussed across AIP's portfolio companies. It is important to acknowledge that even though the industries and products of the portfolio companies are very diverse, this thesis intents to be as general as to be relevant to a broad array of products, but as practical as to be able to take methods, techniques and best practices and start the implementation of modular engineering at any portfolio company.

Bibliography

[1] Yoji Akao. *Development History of Quality Function Deployment.* 1994. Minato, Tokyo: Asian Productivity Organization. ISBN 92-833-1121-3.

[2] Christoph Roser at AllAboutLean.com. Industry 4.0, 11 2015.

[3] BMBF-Internetredaktion. Zukunftsprojekt industrie 4.0 - bmbf, 01 2016. Retrieved 2016-11-30.

[4] Carliss Y. Baldwin Clark and Kim B. *Design Rules: The Power of Modularity, Volume 1.* The MIT Press., 2000.

[5] Anna Ericsson and Gunnar. Erixon. Controlling design variants, 1999.

[6] G. Erixon. *Modular Function Deployment - A Method for Product Modularisation.* KTH Hogskoletryckeriet, 1998., 1998.

[7] H. Ford and S. Crowther. *My Life and Work.* Doubleday, Page, 1922.

[8] Lawrence R. Guinta. *The QFD book : the team approach to solving problems and satisfying customers through quality function deployment.* Amacom, 1993.

[9] Audun Holme. *Geometry: our cultural heritage.* Springer, c2010., 2010.

[10] S. Pugh. Concept selection - a method that works, 1981. ICED'81.

[11] Donald C. Wunsch Rui Xu. *Clustering.* Institute of Electrical and Electronics Engineers, 2009.

[12] Nam P. Suh. *Axiomatic design: advances and applications.* Oxford University Press, Inc., 2001.

[13] Daniel E Whitney. Physical limits to modularity, 2002. Massachusetts Institute of Technology, Engineering Systems Division.

[14] Daniel E. Whitney. *Mechanical assemblies: their design, manufacure, and role in product development.* Oxford University Press, Inc., 2004.