Product and service modularization for variety management in the context of mass customization

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Modularisation des produits et services pour la gestion de la variété dans le cadre de la personnalisation de masse

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GENERAL INTRODUCTION

English Title:

Product and service modularization for variety management in the context of mass customization

Customers nowadays are not looking for standardized goods and services, they are seeking more customized and personalized products and services to fulfill their specific requirements. Therefore, companies have moved towards changing the behavior and the strategy as they induced to customize services and products to fulfill customer needs. Offering a large variety of goods and services may affect negatively the performance of the company. That is the reason why companies have moved towards more technologically progressive approaches that will assist them to meet customer requirements without badly affecting their performance. One of the business paradigms that has been considered as a solution for several years is Mass Customization (MC) (Tseng and Jiao 1996). MC is defined as an approach to provide customized products and services to satisfy customer requirements with a close efficiency to mass production. MC has been increasingly applied by industrial companies over the last 15 years, particularly in the domain of manufacturing.

In recent years, however, it has started to arise in the service domain as the importance of the service industry has been increasing over the years. Companies have been adding services to their offering to satisfy the needs of the customers. Customized services are considered as an important cause of profit for several companies, especially the companies that are familiar with mass customization environment where customer satisfaction is considered with a dominant importance. Several companies are increasing the offering of additional services to be able to fulfill customers' requirements and also to endure in the competitive marketplace (Moon et al. 2010). Some manufacturing companies customize their maintenance and safety services. Other companies like Nike and Addidas developed new customized services that can be integrated into their new products. However, providing customized products and services is correlated with an increase in the internal complexity of the production system. This complexity is elevated when integrating both services and products to build a service-oriented system (Brax et al. 2017).

To overcome that complexity, various methods have been suggested, such as modularity. This method involves building up modules out of many components. Product modularity is described as the usage of compatible and standardized components that will assist in configuring the variety of end products (Schilling. 2000). Modularity arises from the partition of a product into several independent sets of components. This independence increases the usage of the standardized elements and allows the designers to produce more easily a wide range of product variety using a much fewer set of input elements. This applies to the product domain and also the service domain. Modularity contributes to mitigating variety-induced complexity and supporting a smooth configuration process on the final customer's side**.** Modularity is also considered a promising means for developing a higher variety of products with reduced time and cost (Piran et al. 2020).

The increasing interest in services and their importance to fulfill customers' requirements drove on to the question of whether the technologies and the methods that have been applied for products can be applied to services. This brought another question of whether applying modularity in the service domain will lead to the benefits realized in the product domain **(**C.de Mattos et al. 2019; Bask et al. 2010). Integration between products and services can be an obstacle as in most manufacturing companies there is an organizational frontier that appears between manufacturing activities and service activities. Modularity increases the capability of the company that provides the service to adapt to the service offering and gives the customer the ability to configure the service in accordance with his needs which leads to the service variety offering (Lin and Pekkarinen 2011). Using service modules will also allow the structure of the service portfolio which will reduce complexity and increase transparency.

This thesis focuses on an approach to practically implement modularity on a service-oriented system that can be applied to either product or service or integration of both. The approach can help in decreasing the internal complexity that is resulted from increasing the product and service offering. Also, our approach addresses the ability to have similarity measures among service and product elements. The clustering approach is used in the method to build consistent modules of products and/or services. Evaluation of the different clustering outputs is used to identify assess the quality of the clustering results. Different measurement indicators are used to evaluate each output scenario and to evaluate the formed clusters (modules). The proposed method is different from other methods that focus on either service or product modularity and suggests a similarity interaction that is studied between products and services. It will probably simplify the operation management of products and services in the consequent phase and can also have the prospective to increase economies of scale. Finally, a test-case is carried out to validate the method proposed.

The basic outline of the thesis is presented in figure 1. As shown in the figure, the thesis mainly consists of seven chapters. Chapter 1 is an introduction to the main research concept including mass customization, variety management, and modularity. The chapter discusses the research problematics, the objectives of the research, and the questions that need to be answered throughout the research.

In chapter 2, we present and analyze the scientific background in the field of mass customization and variety management. We examine the concept of modularity and also the past researchers' implementations approach for modularity on products and services. We demonstrate the approach of different methods used to apply modularity on both products and services. We present also the past implementation approaches to evaluate the outputs resulting from the application of the modularity methods and the impact of modularity on industrial performance. We finalize the chapter with some key recommendations resulting from this literature review.

The third chapter gives the general conceptual framework that develops the idea of the method proposed in our research. It describes briefly the whole method with the main inputs and the expected outputs of each step. We provide in this chapter an illustrative example in the manufacturing industry to demonstrate the steps of the method that will be defined in the next chapters of the thesis.

In chapter 4, we specify and explain the first part of the method that is related to modularizing the offers of products and/or services. This part of the method answers our first

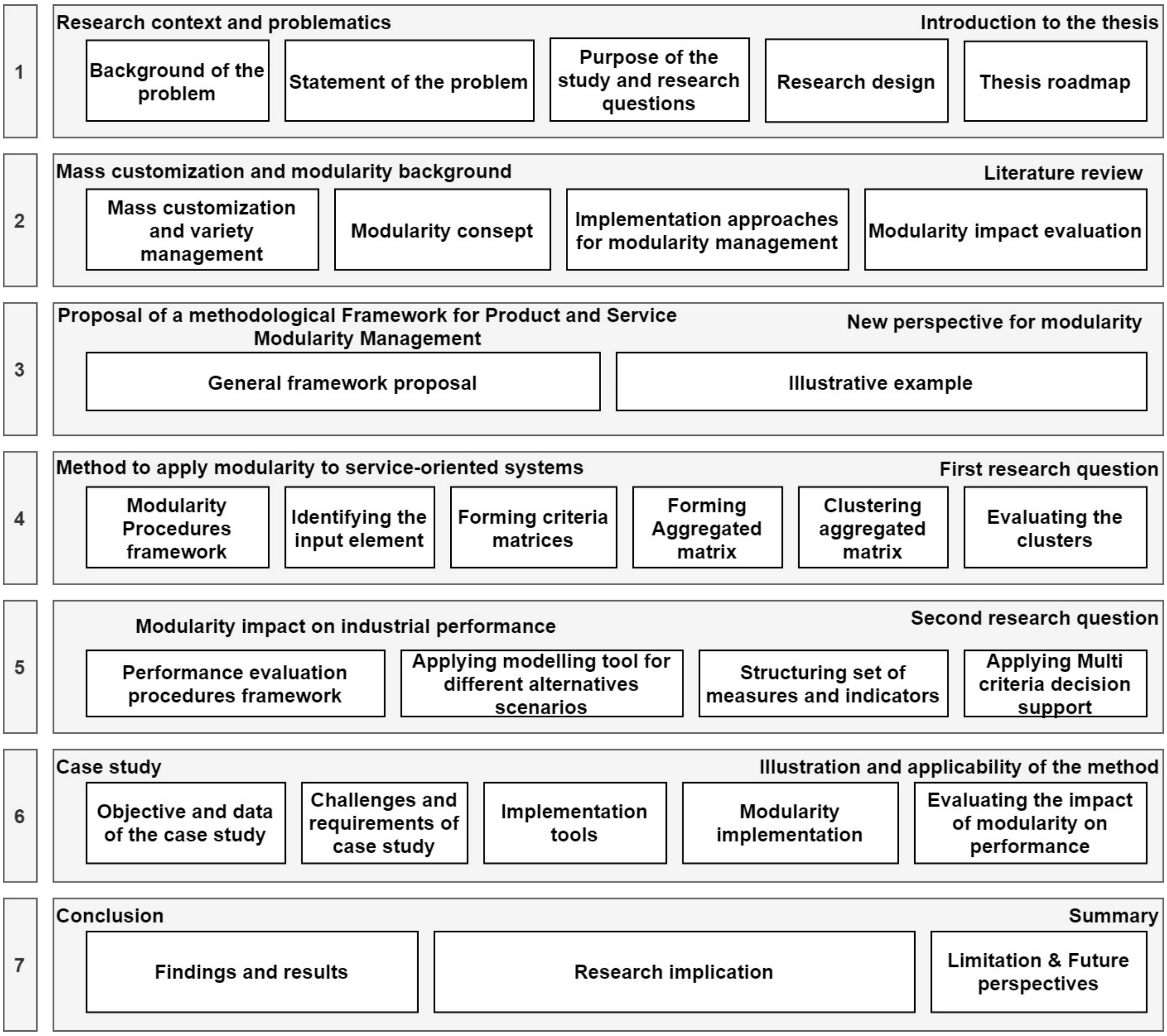


Figure 1. Thesis structure

research question. It describes the detailed steps needed to modularize the input of products and/or services starting from the given input of product and/or services elements to a set of different clusters as an output.

Chapter 5 demonstrated the second part of the method aiming at measuring the industrial performance of the alternative output scenarios resulted from the modularity method in the previous step. This part answers our second research question. We provide a structured set of measures and indicators to discriminate between different output scenarios and assess the industrial impacts of modularity. The chapter concludes with a decision-support method to rank the modularity scenarios and provide insights on the potentially preferred modularity scenario.

In chapter 6, we provide a case study to illustrate the applicability of the method that was demonstrated in the previous chapters. The description of the case study is provided with the tools that are used to demonstrate the case study. The objective of the case study is to present the applicability of the whole method on a service-oriented system that offers varieties of both products and services.

Conclusions are presented in the last chapter (chapter 7). Discussion of the results and the findings, the limitations of the method and the recommended future perspectives are given and discussed in the last chapter.

INTRODUCTION GENERALE

Titre Français :

Modularisation des produits et services pour la gestion de la variété dans le cadre de la personnalisation de masse

De nos jours, les clients ne recherchent pas des produits et services standardisés, ils recherchent des produits et services plus personnalisés pour répondre à leurs besoins spécifiques. Par conséquent, les entreprises se sont dirigées vers un changement de comportement et de stratégie à mesure qu'elles incitaient à personnaliser les services et les produits pour répondre aux besoins des clients. Offrir une grande variété de biens et de services peut avoir une incidence négative sur les performances de l'entreprise. C'est pourquoi les entreprises se sont dirigées vers des méthodes plus avancées sur le plan technologique qui les aideront à répondre aux besoins des clients sans affecter leurs performances. L'un de ces paradigmes commerciaux considérés comme une solution depuis plusieurs années est la personnalisation de masse (MC) (Tseng et Jiao 1996). La MC est définie comme un moyen de fournir des produits et services personnalisés pour répondre aux besoins des clients avec une efficacité similaire à la production de masse. La MC est de plus en plus utilisée par les entreprises industrielles depuis 15 ans, en particulier dans le domaine de la fabrication.

Au cours des dernières années, cependant, la personnalisation de masse a commencé à émerger dans le domaine des services, car l'importance de l'industrie des services a augmenté au fil des ans. Les entreprises ont ajouté des services à leur offre pour satisfaire les besoins des clients. Les services personnalisés sont considérés comme une cause importante de profit pour plusieurs entreprises, en particulier les entreprises qui connaissent l'environnement de personnalisation de masse où la satisfaction du client est considérée avec une importance accrue. Plusieurs entreprises élargissent leur offre avec des services supplémentaires, afin de pouvoir répondre aux besoins des clients et de résister à la concurrence sur le marché (Moon et al. 2010). Certaines entreprises manufacturières personnalisent leurs services de maintenance et de sécurité. D'autres sociétés comme Nike et Addidas ont développé de nouveaux services personnalisés qui peuvent être intégrés dans leurs nouveaux produits. Néanmoins, le fait de pouvoir proposer des produits et services personnalisés est corrélé à une augmentation de la complexité interne du système de production. Cette complexité est accrue lors de l'intégration à la fois de produits et de services pour former un système orienté services (Brax et al.2017).

Pour surmonter cette complexité, plusieurs méthodes ont été proposées, comme la modularité. Cette méthode consiste à former des modules à partir de plusieurs composants. La modularité du produit est définie comme l'utilisation de composants standardisés et compatibles qui aideront à configurer la variété des produits finis (Schilling. 2000). La modularité émerge de la partition d'un produit en plusieurs ensembles indépendants de composants. Cette indépendance stimule l'utilisation des éléments standardisés et permet aux concepteurs de créer plus facilement une large gamme de produits en utilisant un ensemble d'éléments d'entrée beaucoup plus petit. Cela s'applique à la fois aux domaines de produits et de services et contribue à atténuer la complexité induite par la variété ainsi qu'à soutenir un processus de configuration fluide du côté du client final. La modularité est également considérée comme un moyen prometteur pour générer une plus grande variété de produits avec un temps et un coût réduits (Piran et al. 2020).

L'intérêt croissant pour les services et leur importance pour répondre aux besoins des clients ont conduit à la question de savoir si les méthodes et technologies qui ont été appliquées pour les produits peuvent être appliquées aux services. Cela a conduit à une autre question de savoir si l'application de la modularité dans le domaine des services entraînera également les avantages réalisés dans le domaine du produit (C. de Mattos et al. 2019; Bask et al. 2010). L'intégration entre les produits et les services peut être un obstacle car dans la plupart des entreprises manufacturières, une frontière organisationnelle apparaît entre les activités de fabrication et les activités de services. La modularité augmente la capacité de l'entreprise qui fournit le service à s'adapter à l'offre de service et permet au client de configurer le service en fonction de sa propre demande, ce qui conduit à l'offre de services variés (Lin et Pekkarinen 2011). L'utilisation de modules de services permettra également de structurer le portefeuille de services, ce qui augmentera la transparence et réduira la complexité.

Cette thèse se concentre sur une approche permettant de mettre en œuvre pratiquement la modularité sur un système orienté service, qui peut être appliquée soit au produit, soit au service, soit à l'intégration des deux. L'approche peut aider à réduire la complexité interne résultant de l'augmentation de l'offre de produits et de services. De plus, notre approche porte sur la capacité d'avoir des mesures de similitude entre les éléments de service et de produit. L'approche de clustering est utilisée dans la méthode, afin de de générer des regroupements modulaires cohérents (modules d'éléments produits ou services). L'évaluation des différents extrants issus du clustering est utilisée pour estimés la qualité des modules constitués. Différents indicateurs de mesure sont utilisés pour évaluer chaque scénario de sortie et pour évaluer les modules (clusters) formés. La méthode proposée est différente des autres méthodes qui se concentrent sur la modularité des services ou des produits et suggère une interaction de similitude qui est étudiée entre les produits et les services. Cela vise à simplifier la gestion des opérations des produits et services pour les entreprises industrielles et peut également avoir la perspective d'augmenter les économies d'échelle. Enfin, un cas-test est réalisé pour valider cette méthode.

La thèse se compose principalement de sept chapitres. Le chapitre 1 est une introduction aux concepts principaux de la recherche, y compris la personnalisation de masse, la gestion de la variété et la modularité. Le chapitre traite des problématiques de la recherche, des objectifs de la recherche et des questions auxquelles il faut répondre tout au long de la démarche scientifique.

Dans le chapitre 2, nous présentons et analysons le contexte scientifique dans le domaine de la personnalisation de masse et de la gestion de la variété. Nous examinons le concept de modularité ainsi que les contributions de la littérature scientifique concernant la modularité sur les produits et services. Nous démontrons l'approche des différentes méthodes utilisées pour appliquer la modularité sur les produits et les services. Nous présentons également les approches de mise en œuvre passées pour évaluer les résultats de l'application des méthodes de modularité et l'impact de la modularité sur la performance industrielle. Nous finalisons le chapitre avec quelques recommandations clés issues de cette revue de la littérature.

Le troisième chapitre donne le cadre conceptuel général qui développe l'idée de la méthode proposée dans notre recherche. Il décrit brièvement l'ensemble de la méthode avec, pour chaque étape, les principales entrées, la méthode déployée et les résultats attendus. Nous fournissons dans ce chapitre un exemple illustratif dans l'industrie manufacturière pour démontrer les étapes de la méthode qui seront définies dans les prochains chapitres de la thèse.

Dans le chapitre 4, nous précisons et expliquons la première partie de la méthode qui est liée à la modularisation des offres de produits et / ou services. Cette partie de la méthode répond à notre première question de recherche. Elle décrit les étapes détaillées nécessaires pour modulariser l'entrée de produits et / ou de services à partir de l'entrée donnée d'éléments de produit et / ou de services vers un ensemble de différents clusters en tant que sortie.

Le chapitre 5 a présenté la deuxième partie de la méthode visant à comparer la performance industrielle de chacun des scénarios alternatifs résultant de la méthode de modularité de l'étape précédente. Cette partie répond à notre deuxième question de recherche. Nous fournissons un ensemble structuré de mesures et d'indicateurs pour réaliser une analyse comparative entre les différents scénarios de sortie et évaluer ainsi les impacts industriels de la modularité. Le chapitre se termine par une méthode d'aide à la décision pour classer les scénarios de modularité et fournir des informations sur le scénario de modularité potentiellement préféré.

Dans le chapitre 6, nous fournissons une étude de cas pour illustrer l'applicabilité de la méthode qui a été démontrée dans les chapitres précédents. La description de l'étude de cas est fournie avec les outils utilisés pour démontrer l'étude de cas. L'objectif de l'étude de cas est de présenter l'applicabilité de l'ensemble de la méthode sur un système orienté services qui offre une variété de produits et de services.

Les conclusions sont présentées dans le dernier chapitre (chapitre 7). La discussion des résultats et des découvertes, les limites de la méthode et les perspectives futures recommandées sont données et discutées dans le dernier chapitre.

Chapter I.**RESEARCH CONTEXT AND PROBLEMATICS**

I.1. Introduction

The main concept of mass customization (MC) approach is to deliver products and services that meet customer demands of customization while attempting to meet the standards of cost and efficiency of mass production (Mitchell and Jianxin 1996). Mass customization intends to achieve a high diversity of products and services to answer the customized requirements of various types of customers. However, diversifying the offer is correlated with an increase in the internal complexity of the production system and the whole supply chain of the company. This complexity is heightened when considering both products and services jointly in the same offer (Wang et al. 2011).

In this matter, Modularity has arisen as one of the methods to contribute to managing the problem of complexity. The basic idea of modularity is to group components together by using a set of criteria that will result in offering high variety while mitigating the internal complexity (Sun et al. 2017). Modularity has been widely applied in the product domain (Ishii et al. 1995; Tseng et al. 1996; J. K. Gershenson et al. 2003; Blecker et al. 2006; Jiao et al. 2007; Jiao et al. 2007; Lau Antonio et al. 2007; Hu et al. 2008; Wang and Hu 2010; Wang et al. 2011; Hu et al., 2011; ElMaraghy et al. 2013; Danese and Filippini 2013; Zhang et al. 2019). It has been lately addressed in the service domain in the past few years (Voss and Hsuan 2009; Wang et al. 2014; Brax et al. 2017; Pohjosenperä et al. 2018; Mattos et al. 2019).

Most of the methods applied to the service domain are related to the conceptual aspects of modularity frameworks and practical methods to efficiently modularize services have yet to be established (Song et al. 2015; Sakao el. 2017). This is also the case for the integrated product and service system domain. The majority of the research in the integrated product and service domain focuses on implementing just service modularity in an integrated product and service system domain, instead of allowing interactions between products and services being the main object (Sogn et al. 2015; Sakao et. 2017). The research work developed in this thesis will precisely take up the challenge with the objective to implement modularity applied to service-oriented systems conceptually and practically. The service-oriented system is a system that can have offers of either just products or services or real integration of both by Product-Service-System components. The method is considered a flexible one to deal with the modularity of products or services or products and services designed separately or integrated product and service modules. The method allows interaction to happen among products and services that can allow in having modules of both product and service elements. This is shown practically with two different case studies that can help in validating the method.

This chapter is dedicated to building up the context of this research study and presents the research described in this thesis. The following sections will describe the problematic issues that resulted from the diversity of both product and service offers. Based on this, the key challenges to mitigate these issues are discussed before defining the purpose of our study and the research questions. Finally, the research design to resolve this problem is detailed in the last section.

I.2. Background of the problem

The changing behavior of the customer requirements calling increasingly customized and unique goods influence widely the manufacturing companies (Tangchaiburana and Techametheekul 2017). In this perspective, customers expect personalized products and services for their essential needs. In some business segments, customers are not looking for offers of standardized products and services anymore but for offers that can accurately adapt to their individual requirements. This represents a major change in the strategy of manufacturing companies as they are induced to customize their products and services to some degree to satisfy the customer needs and at the same time be able to compete in mass-markets (Piller 2007).

However, the development, production, and distribution of a large variety of products and services can negatively affect efficiency. It can result in a severe increase in costs and lead times, which consequently provokes a reduction in profit. The cost of complexity in the business process administration increases the total costs (Blecker and Abdelkafi 2006). This leads to a transformation in the production processes, towards more customer-centricity, giving rise to new strategies such as mass customization.

The main purpose of mass customization is to deliver products and services that meet the personalized customer needs efficiently while maintaining mass production (Mitchell and Jianxin 1996). Figure 2 illustrates the relation between offering customization and between the cost effect. The more customization the higher will be the cost. Mass customization constitutes an attempt for solving this issue as it is considered as a business strategy that intends to satisfy

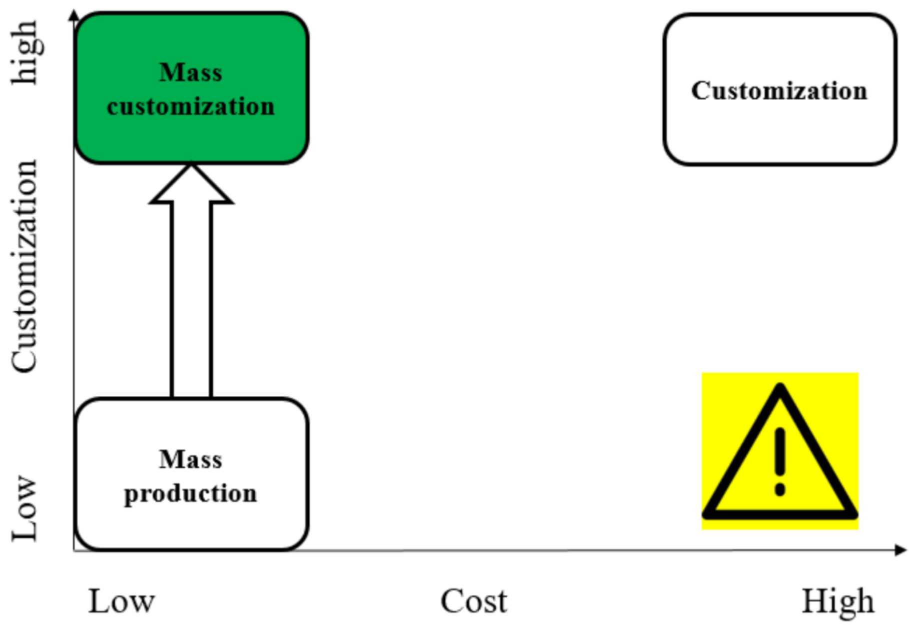


Figure 2. Customization vs Cost

the needs of the customer in terms of personalized and customized goods with costs that don't significantly vary from the cost of the standard products and services (Blecker and Abdelkafi 2006). Although service has been referenced since the very beginning of MC, MC is only applied to mere products in most of the literature review. The full integration of service together with products within the mass-customization process remains a challenge.

Along with those benefits, MC comes also with several challenges such as the increasing of internal and external complexity as a result of offering a higher variety of products and services (Ezzat et al. 2019). External complexity can be referred to as the difficulties confronted by customers when they have to choose sufficient variants out of a large set of products and services possible options. On the other hand, internal complexity is accomplished through operations and tasks related to manufacturing (Blecker and Abdelkafi 2006). A major challenge to MC companies is to mitigate this complexity while still ensuring a variety level that is capable to capture as many customer preferences as possible. Some researchers have focused on implementing methods that decrease this internal complexity while achieving the benefit out of the external variety (Daniilidis et al. 2011). Modularity was recognized as an efficient method to reduce the variety-induced complexity, therefore supporting the success of implementing MC (Wang et al. 2011).

Modularity, in general, is defined as the degree to which the system's component (either product or service) can be combined or separated (Gershenson et al. 2004). Modularity has been widely used in the product domain. As it is used to offer customized products for customers (Lau Antonio et al. 2007; Gershenson et al. 2003; Danese and Filippini 2013). It has been used lately to some extent in the service domain (Mattos et al.2019; Brax et al. 2017). Although several researchers were focusing on product and service modularity separately fewer researches existed that discuss the modularity that covers both product and service together (Brax et al. 2017).

I.3. General Problem statement

Considering the variety offering challenges, the primary concern for companies is to offer customized products and services as much as they can while putting into consideration their performance and their profit. Companies are usually thinking about how to balance between what the customer wants and what the company can offer based on their capacity, costs, and resources?

The shift to offering a solution of both products and services will require the companies to diversify their offering considering the characteristics of such integrated solutions jointing both tangible and intangible elements. It is known that offering variety usually is connected with increasing the internal complexity. And usually, this complexity is heightened when considering both product and service jointly in the same offering.

While the concept of modularity has been widely discussed in the product domain literature at large as a solution method for decreasing the complexity. The applicability of modularity to service or integration of products and services is only poorly addressed (Brax et al. 2017). The increasing interest in the service and the importance of it to fulfill customers' needs drove to the question of whether the methods and technologies that have been applied for the products can be applied to the service. This led to another question of whether applying modularity to the service domain will also lead to the benefits realized in the product domain (Bask et al. 2010).

Modularizing a service-oriented system has been a question in recent years and it is considered challenging. One challenge is to develop a sufficiently flexible method to deal with the modularity of single products or products and services designed separately or even from integrated product and service modules. The question of implementing modularity has been considered as a solution to overcome the complexity that arisen from offering a variety of integrated products and services. Decision-makers would like to have a method that can help in offering varieties of products and services without affecting the industrial performance of their companies. Consequently, the general problem statement is addressed as:

How can modularity management be formalized then implemented for service-oriented systems, to help mitigating industrial complexity while ensuring a high variety level of products and services in order to capture as many customer preferences as possible?

I.4. Purpose of the study and research questions

This research investigates how the concept of modularity can be applied to a service-oriented system. The thesis focuses on elaborating on modeling and implementing the modularization method for a service-oriented system that can help in mitigating the complexity resulting from the variety offering. This concept aims to generate a variety of offerings of both products and services in a way of forming modules that can potentially integrate products and services. The rationale of the study is to reinforce the modularity of a set of products and services through generating, evaluating, and comparing alternative modularity scenarios. So the goal of this thesis is to efficiently show the usage of modularity as a driver to help reducing industrial complexity.

Applying modularity to service-oriented systems enhances the ability of the manufacturer to adapt to requirement changes and as well reduce the costs and the lead-times (Nepal et al. 2008). In the latest few researchers, the modularization of both products and services has been an interesting research area. (Song et al.2015) used a reformed service blueprint and fuzzy graph to form service modules of service activities and resources. (Sakko et al. 2017) created a method to form service modules of product and service systems (PSS). However, the vast majority of the methods stay on a conceptual level, and practical methods to proficiently create modules for integrated products and services have yet to be developed.

To answer the scientific challenge of modularizing service-oriented systems, it is necessary to break the focus of our thesis into 3 sub-questions:

- How to define a method to modularize a system that contains both products and services in a way to increase offering variety and to improve internal company performance?
- How to evaluate different output scenarios for offering a variety of product and service elements that is resulted from the modularity method.
- How to provide a decision-support model to rank the scenarios and provide the most suitable solution based on the industrial context that can help in mitigating the industrial complexity

To pursue the above-mentioned objectives and issues, two main research questions are formulated to provide orientation for the research process:

RQ1: How to modularize offers of products and/or services?

This first question is posed to generate a method that can provide a solution to be able to modularize a service-oriented system. This method is expecting to provide the flexibility to modularize elements of either product or service or integration of both of them, helping in identifying the relationship between products and services according to different criteria that will likely ease the operation management of products and services in the subsequent phase and as well can have the potential to boost the economies of scale. Providing this method should help managing the internal complexity that is arisen from offering a diversity of products and services.

This question can be divided into several sub-questions that need to be investigated:

- How to identify and model the relationship between elements of products and/or services?
- Which rationale method and algorithms should be proposed to generate groupings of elements to form a set of different output clusters?
- How to evaluate the quality of the set of output clusters?

The objective of this study is to provide a holistic method to be able to modularize either product, service, or integration of both. Unlike the traditional methods focusing on product or service separately, the proposed method aims to question how to study the similarity among products and services. So an objective is to provide an approach to help in building up similarity relationships among elements of products and/or services according to a set of predefined criteria. This research aims to apply modularity using different clustering techniques to form several alternatives output clusters. The objective is to evaluate the cluster to be able to provide decision-makers with insights into potentially preferred clustering alternative outputs.

The second research question is:

RQ2: How to evaluate and compare the industrial performance impact of several alternative modularity scenarios, to help managing industrial complexity?

The second question is identified to develop the evaluation criteria method. It is used to measure the industrial performance impacts of the formed modularity scenarios. The evaluation criteria are expecting to support the comparison of the different modularity scenarios and thus to contribute to helping decision-makers to manage offer variety.

This question as well can be distributed into several sub-questions:

- How to model the set of alternatives modularity scenarios while considering the needed activities and the resources?
- How to build up an indicator system to assess the impact of modularity on the industrial organization and performance and to discriminate among the alternative modularity scenarios?
- How to provide a formal procedure to rank the alternatives modularity scenarios and provide a decision support system?

Evaluation criteria are used in the method to discriminate the alternative modularity scenarios in terms of industrial performance. The research objective is to help the decision-makers of the companies to choose the most suitable scenario for their industrial context. This research gives an approach to have a method that provides the best results in a given context. Another objective is to have several evaluation indicators to evaluate the different results that can provide valuable support for comparative analysis of alternative modularity outputs.

I.5. Research design

Based on these research questions and objectives, a research design was developed for our study. This section describes the general main steps of the research process as illustrated in figure 3. The left part of the figure describes the procedures used to identify, process, and analyze information for our research and the right part of the figure demonstrates the analysis of those procedures in our research.

The research methodology is considered to be a case study based research protocol. In order to illustrate the application of our proposed method on the service-oriented system, we conduct a case study that includes offers of product, service, and integration of both of them to demonstrate the effectiveness of the proposed modularity method. The case study was considered from the start of the research to understand the context of the methodology and the expectations of decision making to assess the feasibility, facilitate the development of the method.

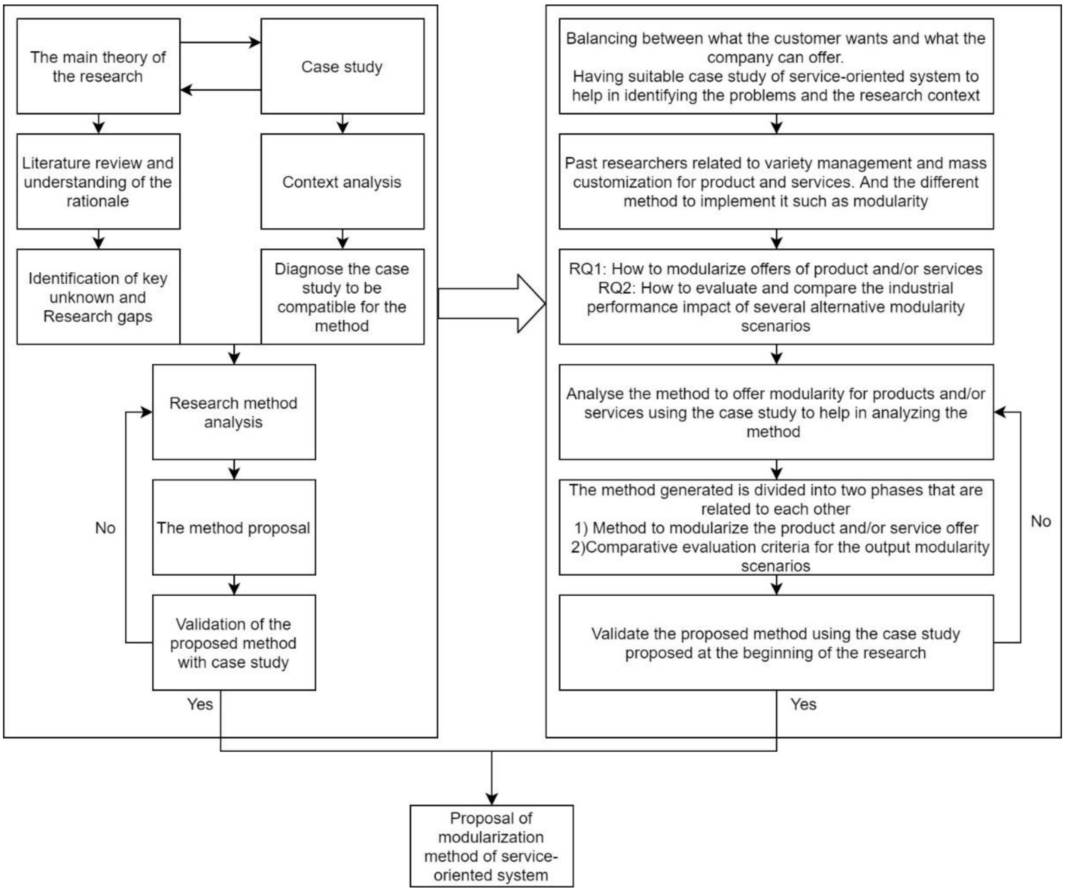


Figure 3. Research design

The main steps are described as follows: 1) The thesis study starts first by analyzing the industrial and scientific context of the study, which is to balance between what the customer expects in terms of variety of products and services and what the company is able to offer.

2) After that, a broad overview and synthesis of the existing literature are developed. This is related to mass customization and modularity methods. In this step, an overall analysis of the existing literature is proposed examining the contribution of this literature to the field of applying modularity method to product, service, and integration of both using the context analysis of the case study.

3) This leads us to identify the research gaps and the issues related to our research. Identifying the gaps guide us to define the two main research questions to be addressed. The gaps and the research questions are compatible with the case study.

4)After recognizing the gaps, the questions, and the objectives of the study, the next phase consists of analyzing the potential methods that could solve the identified research questions. This phase is divided into two sub-steps: first is related to formalizing a method to modularize a service-oriented system, and the second is to establish a method to evaluate the performance of the modularity scenarios. The case study is used to analyze and formalize the method. After finishing the analysis, the method is proposed and will undergo the last phase needed to validate the applicability of the method. If it is valid so the method is proposed and validated and if it is not valid so another analyzing and formalizing phase will be done and another formalized method is proposed.

Figure 4 connects and summarizes the needs and research gaps, the objectives of the research, and the research questions with the expected outputs to answer the posed research questions.

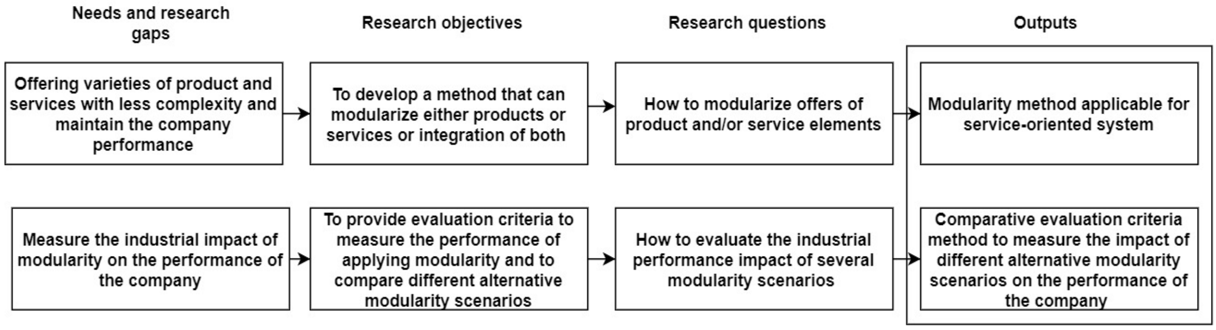


Figure 4. Relationships between needs and research gaps, research objectives, research questions and outputs

I.6. Conclusion

This chapter explored the general challenges of providing a diversity of offers of products and/or services that will, at the same time, satisfy the customer needs and contribute to the positive development of the industrial performance of the company, with the objective to present the research method developed in this thesis.

The trend nowadays in the manufacturing industry is to shift to integrated product and service offerings. Because of this, applying mass customization to these offerings requires rethinking from the manufacturing industry. The outcomes of applying mass customization to integrated product and service offerings are more complicated as they deal with additional detailed elements that link the components of product and service together. One of the major challenges for applying mass customization in manufacturing companies is to mitigate the internal complexity while keeping a variety level that can capture as many customer requirements as possible.

To overcome this complexity, applying modularity is considered as a promising means to generate high variety while maintaining good performance of the company. Our research focuses on applying modularity to a service-oriented system that was introduced before. The general introduction made it possible to highlight that the application of modularity to service-oriented systems poses scientific challenges from which we deduced 2 targeted research questions to be developed in the rest of the thesis.

The primary review of applying mass customization besides the challenges resulting from integrating product and services leads us to conclude that adopting a modularity method for a service-oriented system is a promising method to manage the complexity and the challenges of such offering. It also supports the idea of decision making for modularizing the elements contributing to the company’s offering and ultimately supporting variety management.

In order to highlight the scientific basis of mass customization and variety management, the next chapter explores the key concepts of mass customization and variety management and challenges for their deployment within industrial companies. Moreover, applying modularity on products and services will be explored to shed light on the idea of modularizing service-oriented systems.

Chapter II. MASS CUSTOMIZATION AND MODULARITY BACKGROUND

II.1. Introduction

In order to cope with customer needs for very personalized products and services, companies are changing their strategy to adopt the customer-driven strategy by offering more diversity of both products and services that will consecutively advance the competitive advantage for earning revenue (Alptekinoglu and Corbett 2004). Mass customization (MC) is considered as a possible business strategy for companies that will meet the needs of market diversity (Pourabdollahian and Copani 2015).

Even though implementing mass customization has several benefits it comes also with several challenges such as the internal complexity that is a result of offering a high variety of offers for different customers (Hvam et al. 2017). Nowadays one of the keys to address these challenges is modularity, which is considered as a mean for increasing variety and enhancing flexibility. This concept has been widely discussed in the product domain, however, its applicability to service, the applicability of modularity on service-oriented systems and as well the impacts of modularity on the industrial performance of the company were poorly addressed. The literature analysis will introduce the background and concept of mass customization and variety management. Also, the literature will review the existing researches to implement modularity on products, services, and the integration of both.

To do so, the remainder of this chapter is organized as follows, the first section provides the background in relation to the concepts of mass customization and variety management. In section 2 a focus is put on the concept of modularity as one of the key methods to deal with variety management in a MC context. Section 3 describes implementation approaches of modularity in past researches aiming to modularize systems and offerings. Section 4 presents an overview of the existing indicators to measure the impact of modularity on industrial performance. A discussion of the advantages and the limits of the literature will help us in clarifying the scope of the proposed modularity method for service-oriented systems.

II.2. Mass customization and variety management

In this section, we explain the background and the evolution of mass customization. As well, we discuss the central principle that the approach is based on.

II.2.1. Introduction to Mass customization

Studying the production progress from the past to the present is useful to enlighten the understanding of mass customization. With the industrial revolution, the concept of mass production dominated the manufacturing domain. The Henry Ford model was introduced in 1908 (Kaplan and Haenlein 2006). Ford has a significant effect on the history of mass production in terms of providing the first platform that is based on products that were produced in high quantity with a specific structured design. Ford has the famous motto of "*You can have any color car as long as long as it's black*" as shown in figure 5 (Alizon et al. 2009). Because of that, producers put their focus on standard products for large homogenous market sectors. This allowed the producers to recognize lower prices because of the economies of scale with the condition of control and stability (Pine, 1993).

During the mid-1950s, the desire to obtain customized products was increased and was

Figure 5. Henry Ford T model (Alizon et al. 2009)

introduced for the first time by smith in 1956 (Kaplan and Haenlein 2006). The market sectors were adapting their efforts according to the customer requirements that established the side of demand in the market (Smith 1995). Unfortunately, a balance between cost-effectiveness from the standard mass-produced and the highly customized products that have expensive prices could not be achieved.

Stanely M. Davis invented the term mass customization in 1987 as producing products or services to satisfy the needs of the customer with an efficiency that is near to mass production (Davis 1987). The MC was described as "*The ability to deliver separately designed products and services to each customer through a process of high agility, integration, and flexibility without giving up the scale economies*" (Davis 1987). Subsequently, several researchers have extended the dimensions and the definition of mass customization. The reason for the extension of this concept was twofold. From one point of view, a variety of customers' needs and requirements expanded and were further exposed to changes (Hart 1995). From the other point of view, this process was raised by the enterprises since technology's advances increased strongly the flexibility of the processes in the production and allowed them to strongly build-up opportunities for the diversity of product in marketing while maintaining economies of scale (Pine et al. 1995; Mueller-Heumann 1992).

The definition has been varied and modified throughout the years. (Kotha 1995) labeled MC as a method in which companies apply management methods and techniques to be able to offer variety and customization of products through fast responsiveness and flexibility. (Mitchell and Jianxin 1996) described MC as a goal to provide customer satisfaction with increasing customization and variety without a corresponding increase in lead time and cost.

Likewise, (Reichwald and Piller 2009) clarify MC as the aftermath of the increase in each customer demand. To be able to satisfy each of the customer's needs in a better way, the company must realize these needs. Meanwhile, it is difficult for an enterprise to fulfill the personalized requirements of every customer without interfering with the customers themselves. Customers need to have a dynamic role in the realization process of products and services, drifting the value-creation from a producer-focused approach towards a model of mutual value creation between and customers producer (Reichwald and Piller 2009; Von Hippel and Katz 2002).

MC was considered at the beginning as a concept that would replace the existing concept of mass production (Pine 1993). Though, it was shown that MC is not necessarily considered as a replacement for existing mass production. It is rather considered as an extension of the capabilities that are already existed in the company (Kotha 1995). Some examples from the industry that can support this controversy are Nike and Adidas. They were able to provide the customers with offers of customizable products such as ("NIKEiD" and "mi Adidas") without replacing their principal business. They maintain their approach of mass production and expand it with more customizable offers that can address better the personalized needs of the customers who would like to be actively involved in the product design (Piller et al. 2012).

(Reichwald et al. 2004) explain that MC shifts the development of the traditional product to a two-stage model. The first stage is related to the company that needs to offer the solution space. The second stage changes the role of the customer from a passive role to an active role in the process of design as he acts as a co-designer. Figure 6 shows the shift from mass production to mass customization. In mass production the role of the customer was passive and there was no interaction between the producer and the customer. However, in MC the role of the customer changes to be active and there is an active dialogue exchange between the producer and the customer (Piller and Walcher 2017). (Piller 2004) describes MC as an idea to shift from the producer oriented approach to a customer-driven approach that offers value-

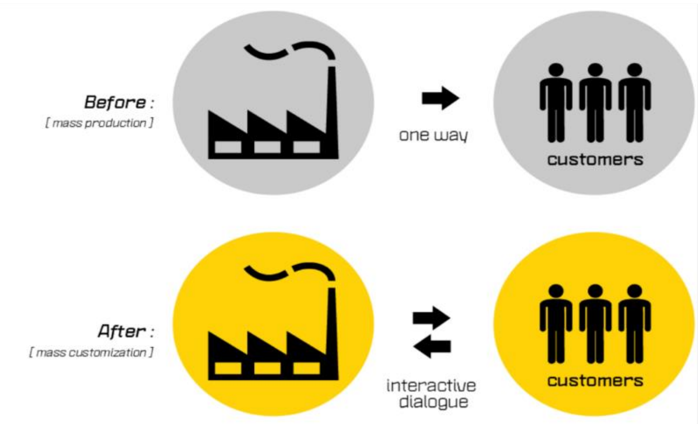


Figure 6. Mass production vs Mass customization (Piller and Walcher 2017)

added products that can satisfy each of the individual customer's needs with a profitable relevant cost.

(Piller 2004) refers to MC as a process of a customer co-design of products and services that meets the requirements of every customer concerning certain product characteristics (Boer et al. 2013). Even though MC definition has been addressed in slightly different ways through the years, MC can be seen as a system that uses flexible processes, information technology, and organizational structures to provide a varied range of products and services that meet the specific requirements of each customer, at a cost near that of mass-produced items. It is also stated that MC is considered a systematic notion that involves all the aspects of production, delivery, development, and product sale starting from the customer choice to receiving the final offer. (Da Silveira et al. 2001)

MC is sometimes mixed up with the term personalization. Personalization is related to filtering and selecting information objects that each customer can choose the information in his consumer profile, which gives data to the supplier about his previous and potential choices in the future. Consequently, the supplier will be able to provide the customer with some recommendations by estimating the specific choices of the customer. In conclusion, the participation of the customer does not exist in the term personalization (Piller 2007). On the other hand, the participation of the customer is different in the case of MC. The customer plays an active role in the method of MC in the co-design phase for designing the product that they would like to purchase (Franke and Piller 2003). MC provides the process and the experience that involves the interaction between the product and the customer. Therefore MC is considered as a process, not a result.

Nowadays with the technology growth and the demand rising, customers would like to have unique products that correspond to their own needs. With this growing demand, the companies are urged to produce solutions that are unique and personalized to not only satisfy the customer needs but also to be cost-effective for the companies.

II.2.2. Mass customization capabilities

(Salvador et al. 2009) believed that defining MC concerning a set of required capabilities would be a crucial phase to the construction of the general theory of MC and it will be a useful accomplishment for practice. Accordingly, three necessary and fundamental capabilities to develop MC would be required: a) Solution space development, b) Robust process design, and c) choice navigation.

Solution Space Development: When a company is seeking to implement MC concept to its processes, it needs to understand the distinctive needs of its customers. This is the opposite of the mass production concept where the company emphasizes “central tendency” among its consumers’ needs and offers them standard products with limited variants. Moreover, in MC, product attributes have to be identified in which customer’s needs diverge the most. When the information and knowledge of customer preferences are built and understood, the company becomes able to satisfy the needs of the consumers. The company becomes able to define its "solution space", which determines what the company is able to offer and not. (Salvador et al.2009).

Robust Process Design: The company that would like to implement mass customization needs to guarantee that the increase in the diversity of the offers will not harm the operation of the company and its supply chain (Pine 1993). Because of that, companies need a robust process design that will be able to reuse the existing supply chain and organizational resources to satisfy the diversity of the customer needs. With such a capability the customized goods are likely to be delivered with efficiency and reliability that is comparable with mass production.

Choice Navigation: Companies that offer mass customization have to support customers to identify their own solutions and problems while reducing complexity as much as possible. When the customer is exposed to numerous choices, the cost of the evaluation can simply exceed the increased benefit from having more choices (Salvador et al. 2009). This is called the "paradox of choice" where numerous amount of options can decrease the value of the customer instead of maximizing it. The customer can think of delaying or even canceling their decision to buy. Consequently, the company should clarify and make the navigation of the company's diversity of products easier from the perspective of the customer.

During the process of mass customization, the company may decide to enhance all three capabilities at the same time or to prioritize just one or two of them. For instance, figure 7 shows that Dell improved and has perfected its own capabilities to set up its processes to be very robust and to define well its own solution space but still, it needs to enhance its capability of choice navigation (Salvador el al.2009).

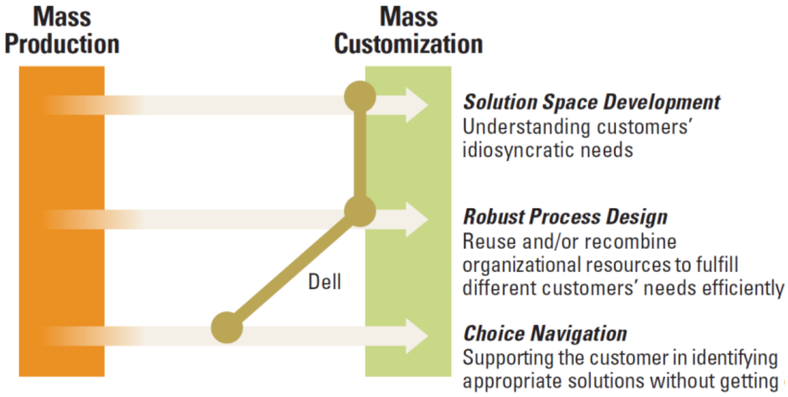


Figure 7. MC capabilities (Salvador et al.2009)

II.2.3. Variety management

In the strategy of MC, variety management is considered to be essential as a large range of variants of products and services should be proposed (Medini et al. 2018). Flexibility is considered as an essential driver to manage the various changes of either services or products during production, transport, storage, and delivery.

Product variety refers to the number of variants of products that aim to meet the numerous customer requirements (Medini et al. 2018). Product variety permits the fulfillment of the customer needs and requirements. It permits customers to have a diversity of options that can satisfy their needs and requirements (Kahn.1998; Blecker and Abdelkafi 2006; Elmaraghy 2009). On the contrary, the reduction of product variety has a negative effect on the quality of purchasing and on the frequency of shopping. However, too much variety can lead to the frustration or confusion of the customer (Huffman and Kahn 1998; Piller 2004; Blecker and Abdelkafi 2006; Matzler et al. 2011). Consequently, the relationship between customer purchasing behavior and product variety is not linear.

Many manufacturing companies are now heading towards product variants and low-volume products instead of high-volume standard products to more different. (Schuh 1995) has explored the effects of product variety and introduced a design that illustrates the shift from high-volume standard products to low-volume individual products. He showed how this shift impacts the cost and the position of competitive (Figure 8). The figure shows that the curve of the frequency of products is changing and is becoming wider. There is a crucial point where the enterprise has many product variants that are non-profitable. So the enterprise will get in the loss zone when the costs (actual) surpass the revenues. Determining the optimum variety level is considered a challenge for many industrial companies. Models and tools are required to make sure that the optimal level of product variants is well defined that can maximize the consumer value (Abdelkafi 2008; ElMaraghy et al. 2013; Medini and Boucher 2016).

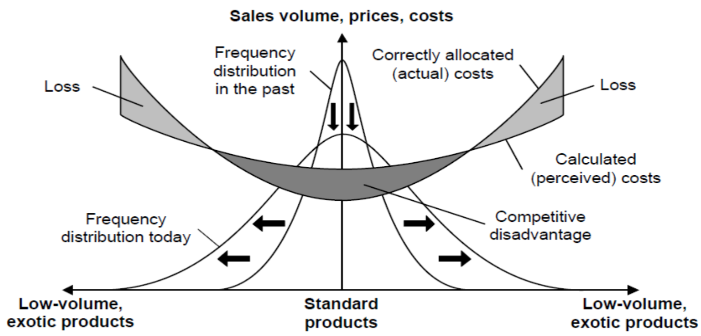


Figure 8.The complexity challenge of manufacturing companies (Schuh 1995)

While variety management was more focused on the product domain it has been addressed also in the service domain. Since the focus of offering a solution of services to the customers is growing through the markets, companies will need to diversify their service offering considering the difference in the characteristics between product and service. Service variety is defined as the number of service options that are contained in the offering. The service variety management is mainly based on the service modeling and engineering method (Medini et al. 2018). Service can be categorized into two categories: a) back-office that can refer to standard services that are done without having an interaction with the customer and b) front office that symbolizes customizable services usually included in the system of delivery (Sievänen 2008). Services of back-office can be reached by the ‘push flow’ of the supply chain of the product, while the services of the front office are related to the '*pull flow*' part. However, the research and studies on service variety are rare compared to the research and studies on a variety of products (Ramdas 2003, Smith et al. 2007, Apte et al. 2008).

To be able to cover the individualized customer demand, a personalized and customized offer that is related to the various offers of products and services is required. This customized offer should normally increase customer satisfaction and will likely increase the internal complexity that impacts the performance of the company. One of the challenges of variety management is how to manage the offering of external variety while mitigating the internal complexity and ensure sufficient performance of the company that is related to cost, responsiveness time and flexibility (Medini et al. 2018). Effective variety management permits reaching economies of scope, by generating high variety based upon an inadequate number of references, and economies of scale by acquiring the standardization of mass customization.

Some researchers have focused on implementing methods to mitigate this complexity and at the same time achieve the benefit out of the external variety, the one offered to the customer.

To obtain the variety's potential benefits, many companies attempt to find economies of scale. Economies of scale are concerned about a given product or service while economies of scope intend to reduce the average costs within a set of products or services. One approach to accomplish these economies is to increase the resources' commonality used within different product variants (Medini 2015).

II.2.4. Mass customization and variety management challenges

Implementing MC has several benefits that allow companies to overtake competitors. Nevertheless, identifying all the benefits does not certainly mean that such a strategy will be successfully implemented. Several customers are hesitant to buy their own customized goods and also several companies are doubtful of the practicability of the strategy of MC. Challenges to implementing MC can be classified into two main categories, internal complexity and external complexity (Blecker and Abdelkafi 2006).

External complexity: It refers to the hesitation faced by customers when they would like to customize their products. Customers feel confused and hesitant about having the ideal decision for choosing their goods. This is because of the large variety of environments and the big product selection. This is called external complexity. It normally arises because of three different reasons: a) the customer lacks the knowledge of the product, b) the ignorance of the customer about his requirements, and c) the limit of information that is needed to process the human's capacity. It is challenging to reduce the complexity of the external variety of MC. In case that the customer doesn't order the correct goods, his trust in the solution that is related to MC will terribly decrease. However, a convenient configuration system will allow companies to decrease the level of external complexity, helping to implement MC more efficiently (Blecker and Abdelkafi. 2006).

Internal complexity: It refers to the difficulties faced by the companies because of the large variety, inducing higher internal complexity underlying the operations of the company. For instance, internal operations can face increasing costs and a decrease in the acceleration of the supply chain (Blecker and Abdelkafi. 2006). (Wildemann 1995) stated that a wide-ranging product variety cannot be fabricated without efficiency loss. It is shown in a study that increasing the number of products to double in the program of production will increase the unit cost by 20-35%. Additionally, the variety in MC increases complexity in both the supply side and on the distribution side. The distribution networks are obliged to deliver individually customized products on a per-item basis and are required to provide efficient and effective after-sale services (Blecker and Abdelkafi. 2006).

High complexity can be considered beneficial if it provides an irresistible value proposal to customers. Additionally, providing customized offers does not certainly add to the complexity as it depends on the design of the product (ElMaraghy et al. 2013).

(Schuh and company 2012) have deduced from a study that has been made for hundred companies that they have analyzed for more than 16 years and it is beneficial to consider both the external and internal perspectives on variety-induced complexity (figure 9) (ElMaraghy et al. 2013). The external complexity related to the market defines the product that is derived from the customer-desired features, functions, and options. The focal questions are identified with the product setup and capacities required by the customers and the market. The core principle is ''*As few variants as possible and as many as necessary*''. The company's view on the internal complexity depends on evaluating the external complexity of the range of the product variants and the ability to produce several product variants in an efficient way. This is demonstrated by the effects of the complexity of the product on production and process planning, logistics, manufacturing, supply chains and Inventory management, to cope with a specific level of variety (ElMaraghy et al. 2013).

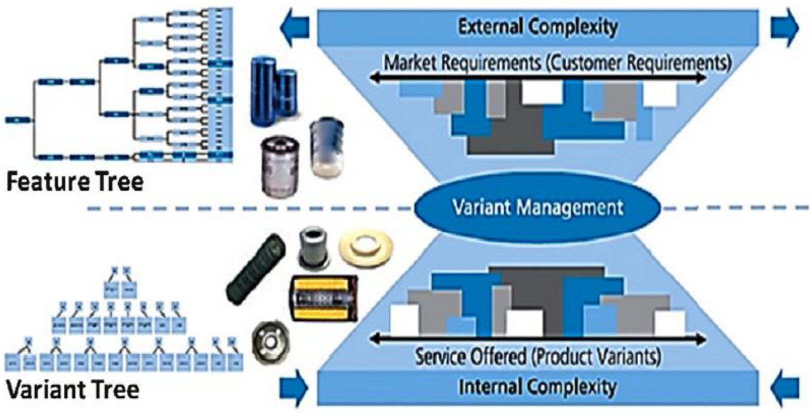


Figure 9. External and internal complexity due to variety (Schuh and company 2012, ElMaraghy et al.2013)

II.3. Concept of modularity

Modularity originated first in system sciences and it is usually applied in the domain of manufacturing, design, and engineering. It is generally used for controlling and decreasing the complexity and offers flexibility to production and product processes (Henriques and Miguel 2017; Wang et al. 2011).

More specifically, the concept was introduced by the formative work of Simon (Simon 1962) to be used as a strong and effective method against complexity in operational production. He explained modularity as "*closely as perishable systems, where the interfaces among the subsystems (modules) are weak but notable*". (Walz 1980) defined modularity as "*assembled of standardized elements of dimensions for flexibility and variety in use*". (Schilling 2000) describes modularity as "*The degree in which the components of the system can be disconnected and reattached at the most abstract level*". The complexity of the production is decreased by arranging a set of predefined elements that can be replaced or improved without changing the functionality of the system (Baldwin and Clark 2000). They describe modularity as "*A specific model of relationships that lies between elements in a set of parameters, tasks, or people. Principally, modularity is considered to be a nested hierarchical structure of interdependence amongst the main elements of the set* ". Modularity is considered to be an adaptable concept as it is applied in several various domains.

A Module is defined as a part of the system which cooperates with some other parts and whose boundary is identifiable. It is considered as a unit whose internal structural elements are strongly connected and are relatively weakly connected to other elements in the other units (Baldwin and Clark 2000). The literature review proposes that the most significant definitions are originated from product design and engineering domains. Two different approaches can be considered when defining a module (structural and functional) (Miraglia 2014). The functional approach identifies the module as a component of a system that is functionally separated from the other components that lie in the same system (Suh 1990). The structural approach refers to a module that is built up of components that are strongly connected within themselves and weakly connected with other components from other modules (Baldwin and Clark 2000).

(Ulrich and Tung 1991) suggest six types of modularity following the customization and the interfaces of components and mixing them (figure 10) (Duray et al. 2000). The first type is the component-sharing modularity. Sharing of components between products, such as the same motor being used in a drill, a sander, and a hand jigsaw. Products are built up around a base unit that has common components. An example of this type is the elevator. The second type is component-swapping modularity. Exchanging one or more components in a product, different features can be chosen, which indicate different components. Modules are chosen from a list of options (components) that can be added to a base product. An example of this type is personal computers. The third type is cut-to-fit modularity. It is applied when products have a unique dimension. It changes the dimension of a module and then integrates it with different modules.

An example is eyeglasses. Mix modularity is the fourth type. It is similar to component-swapping modularity until integrating different modules as the module loses its unique identity. House painting is an example of this type. Bus modularity is the fifth type, It is the capability to include a module to a current series. In another word, it happens when one or more modules are added to a current built base. Track lighting is considered a good example of bus modularity. The last type is sectional modularity. The Product variants are obtained by mixing and arranging standard modules in a unique way that can be kind of similar to swapping modularity. An example of sectional modularity is a Lego game.

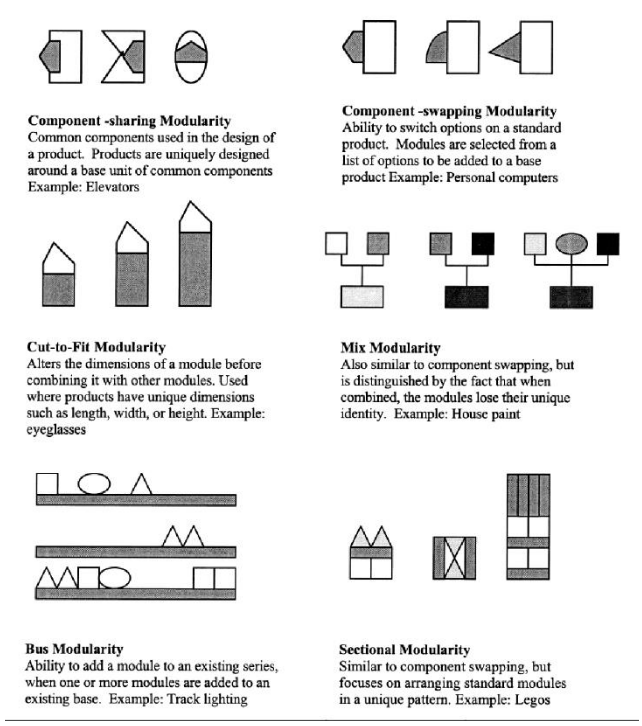


Figure 10. Modularity types (Duray et al. 2000; Ulrich and Tung 1991)

II.3.1. Product modularity

Because of the global competition between the companies, manufacturers have to handle the requirement of the customers to have high product variety, more customized products, shorter product life cycles, and the increasing costs of the development (Kotler 2003; Pine 1993). The modularity notion was widely suggested as a strategic method to be able to cope with those challenges that the manufacturing companies are facing (Pamela Danese and Roberto Filippini 2013; Wang et al. 2011; Lau Antonio et al. 2007; Garud et al. 2003; Du et al. 2001; Ulrich and Eppinger 2000; Baldwin and Clark 2000; Fine 1998; Sanchez and Mahone, 1996; Pine 1993; Starr 1965).

Much of the research into the concept behind modularity arises from (Suh's 1990) independence axiom which declares that "*The functional requirements independency is retained in good product design.*" Consequently, each function that a product executes would be independent of all other functions the product executes. This has led to examining for interaction between functional independence and physical independence.

Ulrich and Tung (1991) describe modularity in the products concerning two characteristics of product design: minimization of interactions between the physical elements of product and similarity between the functional and physical architecture of the design. Also, Ulrich (1995) positions that a modular product has a one-to-one mapping between the product's physical components and functional elements in the function structure.

Modularity has been applied to the product domain as it considered to have a wide array of benefits such as the increase in feasibility change, the economies of scale, product variety increase, easier product maintenance and decreased lead times (Wang 2009; Pahl and Beitz 2007; Gershenson et al. 2003; Meyer and Lehnerd 1997; Pine 1993;). In scientific literature, several definitions are used to characterize product modularity. (Ulrich and Tung 1991) outline product modularity as a 'relative property' that relies upon the degree of minimization of minor interaction between physical elements and similarity of functional and physical product architecture. (Sanchez and Mahoney 1996) argue that product modularity can be seen as the independency or 'loose coupling' of the product. (Schilling 2000) claims that product modularity is a continuation describing precision, decoupling, separateness, and mixing of the product components. (Starr 1965) positions that a product can be highly modularized if the components of the product can be reused or transferred in an abundant range of products, to be able to maximize the variety of a product.

Product modularity is considered as one of the key elements for the strategy of mass customization of products. The idea is to use a limited number of a set of modules to have an output of several product variants (Gershenson et al. 2003). The idea of mixing the modules in different combinations will lead to an output of high product variety. Moreover, the high volume is attained by using a small number of modules across a large number of variants of products

Product modularity is considered to have an important role in determining the strategy to design product architecture (Ulrich and Eppinger 2000; Fine 1998). Product with low modularity eases the optimization of the components of a product to the particular product, whereas the products with high modularity allow a large range of variants of a product by mixing the modules of the product (Mikkola and Gassmann, 2003). (Pine 1993) proposed that companies should use modular components that are applicable to be configured into a large variety of end products to be able to reach mass customization. In mass customization, highly modular products can generate economies of scale by having modular components shared with other products. Modular products support component standardization that causes an increase in product variety without badly affecting the cost (Mikkola and Gassmann 2003).

(Galvin and Morkel 2001) discussed the adoption of modular product architecture for the bicycle, supporting manufacturing companies to meet the requirements needed for cost reduction and product innovation. Modularity has been closely related to defining product architecture given its potential to decrease the complexity and offer more variety. Indeed, it decomposes the complex product into several parts (Piran et al. 2016)

Putting into consideration the potential advantage of using modularity in the product domain, some research studies have explored methods of applying modularity in the product domain. (Kusiak and Huang 1996) proposed conceptual method for determining the modular product of electronic components while putting into consideration the performance and cost. (Jiao and Tseng 1999) analyzed the impact of the modules on the concept of MC using a case study of an Electronics company. (Stone et al. 2000) introduced a new approach by identifying modules for product architectures in various consumer products. (Kimura et al. 2001) established a product modularization strategy over a family of products using similarity in functionality, product life cycle, and commonality of product. (Yigit and Allahverdi 2003) explored the optimization usage of product variety in a reconfigurable manufacturing system by selecting correctly the instance modules of a modular product. (Fredriksson 2006) examined a method to boost the modular system efficiency by planning and using several mechanisms of designing. (Jacobs et al. 2007) investigated the product modularity effects on quality, cost, time, and flexibility. They concluded that modularity influences directly each one of the perspectives measures. (Paralikas et al. 2011) investigated the impact that product design modularity has on assembly systems using an automotive case study. (AlGeddawy and ElMaraghy 2013) proposed a study that focuses on building product hierarchical architecture using design structure matrix (DSM) based on the optimum granularity level and the number of modules. (Zhang et al. 2014) concentrated on the effects of product modularity on the capability development of MC.

Following the past research studies, all authors give valuable aspects to product modularity. They addressed several methods that can implement the product modularity and also investigated the effects of modularity on the performance of the firm that shows the importance of applying modularity in the product domain.

II.3.2. Service Modularity

The Service domain has been increasingly recognized as an important solution and it has participated more in the global economy (Jaaron and Backhouse 2017; Donati 2017). This has driven enterprises to pursue new methods to be able to offer more personalized and efficient services (Brax et al.2017; De Mattos et al. 2019). Service modularity has been proposed as a way to develop services that can be adaptable and flexible to the requirements of the customer at a somewhat low cost (Voss & Hsuan 2009). The notion of service modularity was first presented by (Sundbo 1994) who observed the rising tendency in a pragmatic study of the segment. He defines modularity as a transitional step between customization and standardization. The discussion about the concept of service modularity has been in debate over the years (Bask et al. 2010).

Mass-service companies have lately tried to apply modularization to their service offerings to be able to benefit from economies of scale (Sievänen 2008). However, a little amount of research has addressed service modularization due to the natural difficulties of modeling a service, and most of the research has focused on maintenance and service of products (Geum et al. 2012; Gershenson et al. 2003). Several factors have been mentioned as important to design service modularity. Those factors are the labor operation that is involved in the process, the abstraction level of the service process, and the effect of the aspect of service on the attribute of the products (Park et al. 2012). (Holmqvist and Persson 2004) observed how important is integrating the service in product development. They also addressed the requirement of considering service when talking about modularization. They argued that the modularization of services has to be considered ahead in time if the companies would like to benefit from the production perspectives and R&D.

Service modularity was described as an approach to managing the service system's complexity by distributing it into simpler parts that can be joined to satisfy the customer's needs (Chorpita et al. 2005; Pekkarinen and Ulkuniemi 2008; De Blok et al. 2014; Lin and Pekkarinen 2011; Cabigiosu et al. 2015). (Heckl and Moormann 2009) suggested that modularity is considered as a tool that can be used to eliminate the influence of the customer and for structuring the process of the service. (Rahikka et al. 2011) believe that the provided services in modular form can impact the observation value of the customer in the domain of professional services.

A critical question in modularizing a service is how to classify the individual components of a service offering and how to decide which of these components can be formed as modules (Salvador et al. 2002). This question associates with the logic of granularity which is the clarification of the choices of the design involved in breaking down a service offering into modules. One issue in this involves how the multidimensional nature of services impacts their breaking down into modules. (Voss and Hsuan 2009) selected four breaking down levels: industry, service bundle, service company and service component. (Moon et al. 2011) broke down the services into service families, services, modules, components and attributes.

To define the interaction between the components of services, a set of criteria has to be defined to define the perspective of the interaction between them. (Song et al. 2015) considered the independence between components in the perspective of three dimensions: functional perspective where it refers to the relevance between functions among components of service, process perspective where it refers to the conversion of information and material between two components and last but not least the resource perspective where two components share the same service resources.

Taking into consideration the effect of service modularity on the companies, some researchers started to explore new methods for modularizing the service. (Geum et al. 2012) suggested a framework for service modularity using the House of Quality structure using the interrelationship based approach and driver-based approach. (Böhmann and Krcmar 2006) discussed the architecture of the modular services in a theoretical way and they give the application to the IT industry as an example. (Yu et al. 2008) developed a modularization modeling method for industrial service design to be able to customize the service packages. (Yang and Shan 2009) used a relationship matrix that identifies the functional relationship between the activities of the services that can then help to identify the service modules. (Ho et al. 2009) discussed an approach to modularize the service of the business process by breaking the process into a set of modules. Those modules are defined as a group of services that have low coupling and high cohesion. (Bask et al. 2011) proposed a framework that analyzes in terms of customization and modularity, the service production process, customer service offering, and the service production networks. (Lin and Pekkarinen 2011) suggested a framework for designing the logistics service based on the house of quality and the concept of modularity. (Wang et al. 2011) provided the attributed and the concept of the system of the service process. They provided as well the key factors for applying service modularity. They presented a service modularity model with four parts, service technology, service information, service staff, and service entity. (Tuunanen and Cassab 2011) proposed the service modularity by integrating service process design with insights into software engineering. (Carlborg and Kindstorm 2014) explored the domain of service modularity in positioning and developing efficient services while putting into consideration the diversity of the customer requirements and the potential of services.

Authors such as (Hyötyläinen and Möller 2007; Pekkarinen and Ulkuniemi 2008; Lin and Pekkarinen 2011; Böttcher and Klingner 2011) argued that the usage of service modules will enable the structure of the service portfolio. This will help in increasing transparency and reducing complexity. Service modularity can increase the visibility of the service offering to the customers. It can make the customer understand the prices and the customer will be able to understand his role in the service process (Pekkarinen and Ulkuniemi 2008; Rahikka et al. 2011; Ulkuniemu and Pekkarinen 2011; Liu et al. 2016). Modularity increases the ability of the company that provides the service to adapt to the required service offering and also the customer will be able to configure the service according to his own demand. This leads to the service variety offering (Voss and Hsuan 2009; Lin and Pekkarinen 2011; Brax et al. 2017). Modularity allows reduction of cost and lead time with the idea of process standardization that leads to efficient use for the resources and service processes (Meyer et al. 2007; Voss and Husan 2009; Brax et al. 2017). To achieve the above benefits, service modularity enablers have been identified as necessary conditions for service modularity.

The enablers of service modularity are considered as conditions that are prerequisites to permit the application of service modularity (Silander et al. 2017; Mattos et al. 2019). Modular strategy is considered as a first enabler. It is the alignment of customer requirements, company strategy, and the service type (Bask et al. 2010; Lin and Pekkarinen 2011; Løkkegaard et al. 2016). The definition of modules, their function, and their interaction is necessary for the configuration of components (Liu et al. 2016; Løkkegaard et al. 2016). Service company providers should have the competencies to develop the modular service offering by developing their human resources (Voss and Hsuan 2009; Bask et al. 2011).

In accordance with the past research studies, all authors provide beneficial aspects to service modularity, but most of them addressed from the conceptual and theoretical perspective framework and process. Some of the research studies addressed the granularity level and the criteria of interaction that is quite important to identify service modularity however, some important characteristics related to the key features of service modularity remain unaddressed. The significant question of how to modularize services practically has rarely been dealt with (Song et al. 2015). This fact proposes that these benefits have been mined from the literature of product modularity.

II.3.3. Product and service modularity

With the fierce competition of the markets, the integration between product and service in the offer can increase the attraction of the customer and differentiate companies (Wang et al. 2011). However, adding the service component to product development adds development complexity such as the interaction between people (Morelli 2006). With the evolution of product and service integration, companies are facing some challenges such as longer customer lifecycles, shorter product-service lifecycles, increased outsourcing, rapid fulfillment needs, and mass customization demands. To handle the mass customization of the integration of products and services, physical products and services should have different collocation (Wang et al.2011).

Modularity has been suggested to overcome these challenges by providing companies with the ability to offer fast and customized products and services without demolishing their old design. While much research is concerned by either product modularity and to some extent service modularity, little research has focused on applying modularity to a mix of products and services (Larsen et al. 2018). Modularity can be distinguished as a method to standardize the production of product-service systems and provide customized services that will lead to better profitability and customer value(Bask et al. 2010).

(Sun et al. 2017) proposed a modularization method for product-service systems (PSS) by identifying the functional requirements of both products and services. (Li et al. 2012) addressed the interrelationship among products and services and how they can handle the customer service and physical needs. They concentrated on the principle of partitioning modules of integrated service product. (Song et al. 2015) proposed a modularization method for product extension service (PES) that is a service solution based on a product that can aid the manufacturing companies to achieve profitability and growth of sustainability. (Wang et al. 2011) proposed a framework of modular development that consists of three parts: product, service, and functional modularizations. (Sakao et al. 2017) proposed a method to modularize services by creating service modules from service components to customize efficiently PSS.

II.4. Implementation approaches for modularity

The main context scope of modularity enhances standardization thus positively impacting time and cost. Moreover, applying modularity and developing standardized components improve the quality of the product and ease the maintenance and diagnosis of the product (Kusiak 2002). To achieve the positive modularity effect, several constraints and factors have to be considered. Therefore, the implementation of modularity has to be defined clearly and should include the life cycle of the offer, quality issues, and the technology that is needed to realize the full potential (Daniilidis et al. 2011).

Throughout the years, several implementation approaches and methods to achieve modularity in product and service domains have been introduced. (Pimmler and Eppinger 1994) presented a Design structure matrix (DSM) that shows the dependency between a set of components to analyze and model the architecture of the product. (Stone et al. 2000) proposed a systematic approach to analyze the modules of a product, based on a functional criterion structure. (Cheng et al. 2012) proposed a new systematic method for modularizing the product based on the axiomatic design (AD). They decomposed the product hierarchically in functional, process, and physical domains according to AD. (Ericsson and Erixon 1999) introduced the method of modular function deployment (MFD) to develop modular products.

Thus, several methods have been introduced to help in modularizing the offer. The main purpose of those methods is to be able to visualize the interdependencies among the input components for modularity. In this thesis, DSM will be used as it is used to visualize and apply the relationship indices among the elements.

II.4.1. Design structure matrix (DSM)

DSM was first introduced by (Steward 1981) and was outlined as a design methodology or a tool to display the interaction among elements in a complex product or system. DSM reinforces the formation of modules that are necessary to develop product modularity (Eppinger et al., 1990). DSM is a square matrix that has identical labels of columns and rows. The off-diagonal cells indicate the dependency or interaction of each element to another (Qiao et al. 2017).

DSM was originally designed to manage the organizational issues in the companies and was not intended for modularization. Yet DSM was advanced by additional research studies that allow DSM to process the input data in other different ways rather than just organizational issues such as modularity (Browning 2001). There are mainly two main categories for DSM: time-based and statics DSM. In the time-based DSMs, the arrangement of the columns and rows shows a flow-through time, therefore time-based DSMs are usually examined by sequencing algorithms. Static DSMs signify the relationship between the elements of the system that permanently exist, such as the components of the product architecture. Static DSMs are typically analyzed using clustering algorithms.

According to (Browning 2001), there are four DSM branches that are useful for product developers, project managers, project planners, organizational designers, and system engineers (figure 11):

a) Component-based DSM: Mainly used in the case of modeling the system architectures that are based upon the components and their relationships.

b) People-based DSM: Generally used in the case of modeling the structure of an organization based on people and their interactions.

c) Activity-based DSM: Commonly used in the case of modeling activity networks and processes based on the activities and their dependencies.

d) Parameter-based DSM: Normally used in the case of low-level modeling relationships between parameters and decisions.

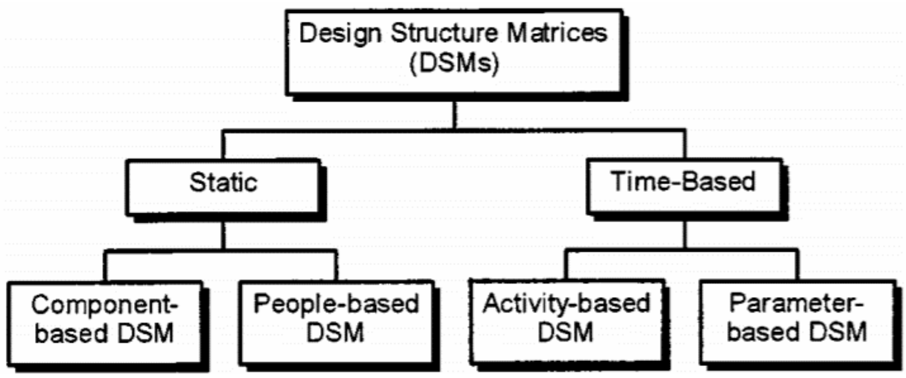


Figure 11. DSM branches (Browning 2001)

The DSM branch that is commonly used for product modularity is the component-based DSM as it documents interactions among elements in system architecture (Browning 2001). (Eppinger and Browning 2012) identified several types of interactions for component-based DSM. Some of the interactions can be well defined and can be visible such as physical proximity of coupling parts or material flow among them, while others may be hidden and not visible such as vibrations or transfer of heat. (Pimmler and Eppinger 1994) suggested four types of interaction between elements of component-based DSM.

a) Spatial: describes the needs for orientation or adjacency between two elements.

b) Energy: describes the need for energy exchange or transfer between the two elements.

c) Information: described as the need for signal or data exchange between the two elements.

d) Material: describes the need for exchanging material between the two elements.

The weight or the strength of the interactions between the elements of the DSM is considered the degree level of the interaction strength amongst the elements. The higher the interaction index, the stronger is the interaction between the elements. There are different ways to build DSM: one approach is the binary DSM that consists of just a notation of 1 and 0 to distinguish whether there is an interaction between two given elements or not. In this approach of binary DSM, there is an absence of degree level of interaction. The other approach is called numerical DSM. It is used to show numerous levels of interaction between the elements. Those numbers can be integers or real numbers. Generally, the larger the number is, the higher the interaction between the elements. The scales of interaction can as well use positive and negative values (Qiao et al. 2017). This can help in the differentiation between desirable interactions and undesirable interactions.

(Eppinger and Browning 2012) presented the DSM of products, where the interaction is marked with either color, linguistic variables, shapes, and numbers. (Shoval et al. 2016) suggested building two numerical DSMs that signify the strength of the assembly and function connections such as weak, strong, or moderate. DSM allows for regulating the necessary level of detail about accessible data and has been previously useful in many industrial companies (Sakao et al. 2017).

(AlGeddawy 2014) presented an efficient methodology to design product family architecture using a DSM model. (Bradshaw et al.2012) used DSM to investigate various system configurations to determine which component of the system of a naval ship design should be modularized. (Kashkoush and ElMaraghy 2017) used DSM to represent various interactions between product components in building modular product architecture. (Sakao et al. 2017) provided a method to support the designers to be able to create modules of services by using DSM.

DSM shows the potential to be applied in modularization of service-oriented system offers that cope with complexity and variety. In our thesis, we use the component-based DSM that is a part of the static DSM. It will help us in identifying the interaction between the elements of the service-oriented systems and also will give us the advantage to rank our interaction by using the idea of numerical DSM.

II.4.2. Clustering analysis

Clustering is considered to be a valuable technique for observing the systems' structure. Clustering analysis is considered the principal approach to offer modularity (Li et al. 2014). Clustering can be identified as the task of grouping a set of objects in a way that the objects that lie in the same group (cluster) are more similar (in some sense or another) to each other than to those that lie in other groups (clusters) (Chen and Huang 2007). It is the main task of preliminary data mining and a common method for statistical data analysis (Ezzat et al. 2020). Clustering uses a theoretical graph of cluster algorithms to rearrange the columns and rows of the matrix by grouping greatly connected nodes, called clusters (Kaur and Kaur 2013). Managers and engineers can easily recognize and identify interfaces between those clusters by grouping the nodes that have high interaction with each other into clusters (Yang et al. 2014). Clustering analysis is used in many fields, including pattern recognition and machine learning. Cluster analysis depends on various algorithms that differ considerably in their notion of what establishes a cluster and how to efficiently find them. Clustering techniques are mostly used to generate modular architecture through trade-off commonality between the elements of product or services (Ezzat et al.2020). The elements that are in a grouped cluster have a classification of a high degree of similarity between each other (Chen and Huang 2007).

The result of the clustering analysis is to maximize the internal interaction between elements in each cluster and minimize or eliminate interactions between clusters (external interaction) (Baldwin and Clark 2001; Yu et al. 2003; Sharman and Yassine 2004). However, external interactions between the clusters can be beneficial when the system context is considered. Engineers and managers may need interaction between two teams to share common resources. This disagreement may have been based on a component-based DSM, particularly in binary DSM analysis. In an organizational DSM, the overlap can signify a person that contributes to each group, guaranteeing the sharing of important information.

(Altus et al.1996) suggested as well to minimize the size of the clusters. Another consideration, it may be beneficial to have some overlapping between the clusters. Even though it is not possible to optimize those considerations, clustering analysis is considered to be supportive of integration analysis. The clustering algorithms rearrange the columns and the rows, while seeking a solution for the objective function. The objective can be to minimize the coupling between the clusters and minimize the size of the largest cluster. So the rearranged matrix will have the clusters along the diagonal of the matrix (Browning 2001).

Several techniques of clustering are available in the scientific literature. Each one of those techniques can be implanted through several alternative clustering algorithms. The cause of having more than one technique approach is because there are several ways to implement it. (Fraley and Raftery 1998) propose the idea of dividing the clustering approaches into two different categories of technique (hierarchical and partitioning). Figure 12 shows The classification of the clustering techniques.

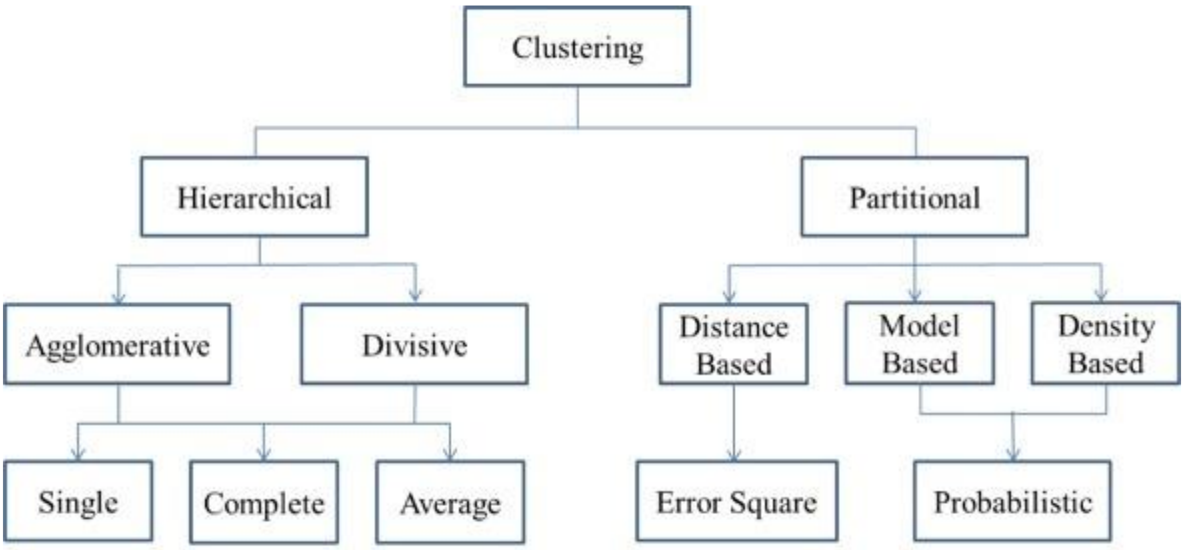


Figure 12. clustering techniques (Farley and Raftery 1998, Saxena et al.2017)

II.4.2.1. Hierarchical clustering technique

Algorithms that fall under the category of hierarchical clustering technique group the elements following a hierarchical procedure. Hierarchical clustering is based on the idea that the data points nearer in the data space show more similarity to each other than the data points situated further away. The procedure starts with classifying all data points into separate clusters and then aggregating them as the distance decreases (Kaur and Kaur. 2013). There are mainly two forms of the hierarchical clustering technique: *agglomerative hierarchical* clustering and *divisive hierarchical* clustering (Murtagh 1984). The agglomerative clustering uses a bottom-up approach. It generates the clusters by starting with a single object and then merging smaller clusters into larger ones till all the elements are laying in a single cluster. On the other hand, divisive clustering uses a top-down approach. It divides the cluster that contains all the elements into smaller clusters until each element form a cluster with itself (Saxena et al. 2017; Ezzat et al.2020). Both ways of clustering produce a hierarchy of clusters that leads to the formation of what is called a dendrogram, as shown in figure 13.

The similarity measures of the hierarchical clustering methods can be categorized into three main categories:

a) Single-linkage clustering: it is also called the minimum method. In this type of linkage, the link between two clusters is defined by two single element pairs of each cluster that are near to each other. The distance between two clusters is identified by the closest distance from one element of one cluster to one other element in another cluster. This definition can also explain similarity. The similarity between two clusters is equal to the largest similarity of one element from one cluster to another element from the other cluster (Saxena et al. 2017).

b) Complete-linkage clustering: it is also called the maximum method. In this type of linkage, the distance between two clusters is defined as the longest distance from one element of one cluster to any element of the other cluster (Saxena et al. 2017).

c) Average linkage clustering: it is also called the minimum variance method. In this type of linkage, the distance between two clusters is defined as the average distance from one element of one cluster to any other element from another cluster (Saxena et al. 2017).

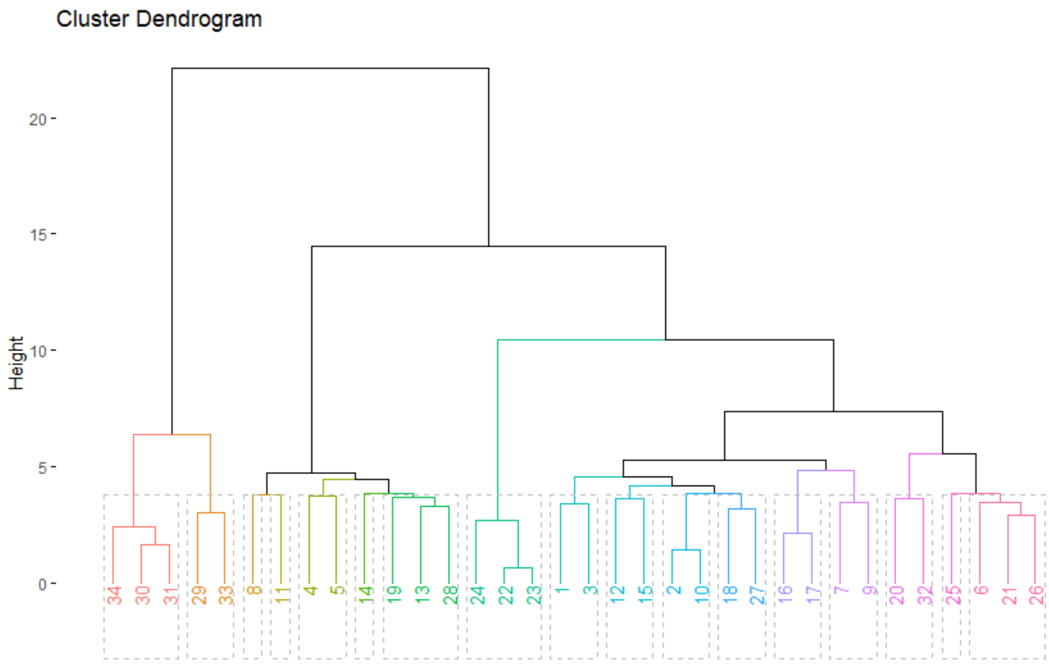


Figure 13. Dendrogram example

II.4.2.2. Partitioning clustering technique

It is different from the hierarchical clustering technique as data are assigned into k- clusters that do not have any hierarchical structure through enhancing criterion functions (Lam and Wunsch 2014). They are also referred to as non-hierarchical as each instance is placed in exactly one of k mutually exclusive clusters. The notion of similarity is derived by the closeness of a data point to the centroid of the clusters in the iterative partitioning algorithms (Swarndeep and Pandya. 2016). Partitioning clustering algorithms produce several partitions and evaluate them using specific criteria. Euclidean distance is considered the most commonly used criterion. It refers to the distance that is considered to be the minimum between points with each of the clusters that are available and assign the point to the cluster. The algorithms that fall under this technique requires in advance to identify the number of clusters (k) that are needed to be generated. Several algorithms are known and identified for this technique such as k-means and k-medoids (Ezzat et al. 2020).

k-means is one of the simplest and best-known clustering algorithms (Lam and Wunsch 2014). It was first represented in 1967 by James Macqueen (Swarndeep and Pandya 2016). In this type of clustering, the cluster is identified by its centroid which is generally the mean of the points (elements) in the cluster. The objective function for this algorithm is the sum of inconsistencies between a point and its centroid that is signified by an appropriate distance(Pradeep and Shubha 2010). k-means is a partition of objects (elements) into clusters such that each object is in exactly one cluster, not several. The algorithm mainly consists of three main steps: a) initialization by setting initial medoids with a given k. b) dividing all data points into k clusters c) updating k centroids based on newly formed clusters k-medoids is considered an adaption of k-means. It is considered to be more robust to outliners and noise. k-means is more sensitive to outliers since a mean is manipulated easily by extreme values. The difference between k-means and k-medoids is the center of the cluster. k-means use the mean of the points as the center of the cluster while k-medoids use an actual point to represent the center of the cluster. Medoids represents a set of clusters that the average dissimilarity for all the objects in the cluster is minimized. It is similar to the concept of mean or centroids. Figure 14 shows the difference between the concept of mean and medoids. The red point is the center of the cluster. In the case of the k-means since the rightmost point is an outlier, so it cannot represent the correct cluster center since it is greatly influenced by the outlier. On the other hand, k-medoids is robust to the outlier so the cluster center is correctly represented and is not influenced by the outlier (Jin and Han 2011).

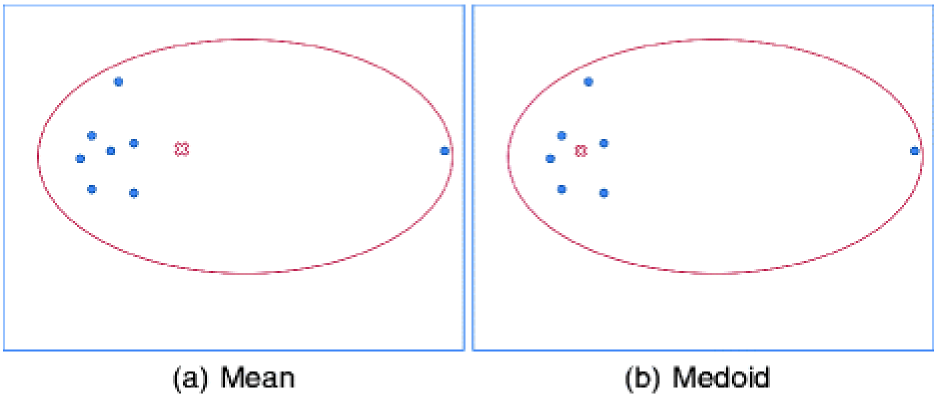


Figure 14. Mean vs Medoid (Jin and Han 2011)

Partitioning around medoids (PAM) is the algorithm used to represent the k-medoids clustering method (Kaufman and Rousseeuw 2005). The main steps of the algorithm are as follows: (i) the *k*-medoids are randomly chosen in the dataset to be the initial medoid ; (ii) all the elements are then assigned to the nearest medoid among the ones forming the required amount of clusters; (iii) then the medoid is recalculated through calculating the mean of the datasets in each of them; (iv) this is repeated until there is no more change in the medoid (Velmurugan and Santhanam. 2010).

II.4.3. Clustering evaluation

Comparing the quality of the results of the clusters is considered an approach that is done after clustering analysis. It is used in helping to evaluate the modularity in the product architecture and form strategies for the product architecture interfaces (Hölttä-Otto et al. 2012). The output from the clustering method may have more than one scenario. Hence, clustering evaluation should be done to verify which scenario is better in terms of the quality of the cluster. Another performance evaluation will be needed to choose the most suitable scenario based on the industrial context. Several research studies have focused on measuring the output of the clustering between elements of product and system architectures. In the research studies, there are two kinds of indices to evaluate the output clustering: modularity metrics and clustering indices. Modularity metrics are based on the DSM that have been used to measure the modularity of a product's architecture into modules. Clustering indices are used to measure the quality of a given cluster. it is not related to DSM and it is mainly related to the output results of the clustering techniques algorithm.

II.4.3.1. Modularity metrics.

Measuring the modularity metric of the product architectures have been considered widely after the 1990s (Jung and Simpson 2016). (Thebeau 2001) proposed a clustering method using an index that is called TotalCost. It is defined as the summation of the costs related to the connectivity of inter-and intra-cluster. To determine whether a component can be moved into a selected cluster, ClusterBid is used to measure the degree of fitting between the module and the component. It is also used to determine if the component can be moved to a selected cluster or not.

(Whitfield et al. 2002) proposed a modularity index that is called 'Module Strength Indicator' (MSI). This index is used to measure the internal connectivity in the module and the external connectivity of the module.

(Guo and Gershenson 2004) presented a metric to measure modularity without putting into consideration the size of DSMs. If the internal interactions between each element in each module are maximized while the external interactions between modules are minimized, so the value of the modularity metric is maximized.

(Hölttä-Otto and de Weck 2007) presented the singular value modularity index (SMI) and non zero fraction (NZF). The SMI can calculate the degree of modularity of components in product architecture, and the NZF is to evaluate the coupling density of connections between components. The values of the SMI and NZF for a DSM are constant without taking into consideration the sequence of components in the DSM and the module boundaries. Therefore, applying the SMI or NZF as an objective function is not appropriate for clustering the DSM (Jung and Simpson 2016).

(Yu et al. 2007) developed the metric Minimum Description Length (MDL). MDL can measure the needed amount of information to describe the size of the module, the connectivity within each module and between the modules and each other, and the DSM size. MDL is based on coding the modular structure in a binary string format. (Kulkarni et al. 2018) provided a method to evaluate and compare different clustering methods using the minimum description length metric.

Modularity metrics vary in the literature, but using the current methods rises questions about evaluating the modularity of different types of DSMs or clustering the DSM. Modularity metrics have been used to measure the degree of modularity for precise architectures. Hence, the efficiency of many present metrics relies on the type of DSM as some metrics could only be used if the type of the DSM used in the method is Binary DSM where the similarity indices are either 1 or 0. Also, some of the values of the metrics are directly proportional to the size of the DSM so it will be difficult to compare modularity between architectures of different sizes.

II.4.3.2. Clustering indices

Another type of evaluation is the clustering indices that are different from the modularity metric in terms of usage as they don't rely on DSM. It is used to measure the validation of the total number of clusters since both hierarchical and partitioning clustering do not give the optimal number of the output clusters. There are two kinds of clustering indices evaluation: internal clustering when the result of the clustering is evaluated based on that data set that was used in the clustering method. This type of evaluation is the most popular and is the one used for our study to measure the quality of the formed clusters and to discriminate between the different clustering techniques. The other type is an external evaluation where the results of the clustering are evaluated based on the data that was not included in the clustering such as class labels and external benchmarks (Feldman et al. 2007).

Several cluster validity indices have been introduced in the researches (Amorim and Hennig 2015). The application of different clustering algorithms usually results in different outputs of cluster formation. Therefore, it is useful to evaluate the performance of each of the outputs of the algorithm methods in terms of the accuracy and validity of the output clusters. Cluster validation and evaluation is considered as an important tool. One of the major challenges for the cluster analysis is estimating the optimal number of clusters for a given data set. That is why several evaluation indices were proposed to identify the optimal number of clusters (Tibshirani et al. 2001).

Silhouette width was first defined by (Rousseeuw 1987). It is considered a ratio type index that is based on silhouette values. It measures how well every element fits into the cluster it has been assigned to, by measuring how similar is the element to its proper cluster compared to the other clusters. The value of the index is normally from -1, 1 with 1 being the best formation of clustering, and -1 is the worst one. The average overall silhouette width for the whole data set of elements is the average for all elements in the entire dataset. The maximum overall average silhouette indicates that this scenario with the number of clusters is the best clustering. Hence, the number of clusters with the largest overall average silhouette index is considered as the optimal number of clusters (Ansari et al.2011). Silhouette index performed well compared to other cluster validity indices based on several comparative experiments (Arbelaitz et al.2012). Another advantage of the silhouette index is that it can work with any distance measure (Amorim and Henning 2015).

Dunn's index (Dunn 1974) is a metric to evaluate the clustering algorithms. It is identified as the ratio of the minimum distance between clusters and the maximum cluster diameter. The minimum distance evaluates the separation of the clusters and the maximum cluster diameter evaluate the cohesion. Dunn's index can be applied to general distance measures (Amorim and

Henning 2015). It is considered to be sensitive to the information in the feature of noise but it is still considered as a general structure index to compare different types of clusters.

Another clustering evaluation method is the elbow method. Elbow method observes the percentage of explained variance as the number of clusters function (Bholowalia and Kumar 2014). It is considered the oldest method to determine the needed number of clusters in a data set (Kodinariya and Makwana 2013). The main functionality of this method is to choose the number of clusters so that adding another cluster does not give much better modeling of data.

Another important and useful clustering evaluation method is the gap statistic method. It was first identified and proposed by (Tibshirani et al. 2001). It can be applied to any clustering method (hierarchical and partitioning). The gap statistic computes the total in the variation of intra-cluster for different values of k (clusters) while putting into consideration the expected values beneath the invalid reference distribution of the information. The optimal clusters estimate will be a value that magnifies the gap statistic (i.e, that allows the largest gap statistic). This means that the structure of the clustering is at a great distance from the random uniform distribution of the points.

As can be seen here several methods in the past research are used to evaluate the output clusters whether it is modularity metrics or clustering indices. For our method in the thesis, we focus mainly on how good the elements lie in their own clusters. In other words how consistent each of the elements is in its proper cluster. This will give us insights about how good are the formed modules and also whether some elements cannot form a module with other elements or not. Therefore we will focus on the clustering indices and evaluate the consistency of the output clusters to choose the optimal scenario.

II.4.4. Impact of modularity on the performance.

After measuring the quality of the formed clusters, other evaluation criteria are needed to measure the impact of modularity on the performance. Those other evaluation criteria will discriminate between different alternative scenarios in terms of the industrial performance impact that each of the alternative scenarios has. This can help the decision-makers in choosing the most suitable scenario of the alternative scenarios based on the industrial performance of each one.

Because of the nature of competition between companies, the outcome of the performance indicates that the companies should be able to create products that have a competitive advantage compared to other products. Due to the global competition, companies have to deal with offering a high variety of the product and the customization of the product, the fast increase in the development costs and the short life cycles of the product (Kotler 2003). In the product domain, using modularity in the product architecture has been broadly recommended as a strategic decision to resolve the above issues (Du et al. 2001). Companies that offer products with high modularity will have a large range of product variants by arranging the product modules (Mikkola and Gassmann 2003).

It is strongly suggested that for companies to be able to achieve mass customization they have to use modular components that give the company the ability to configure a large range of variety of products and services. In the strategy of mass customization, products that have high modularity will gain economies of scale through the modular components that are shared with other products. Also, Modular products establish the idea of component standardization that enhances product variety without badly affecting cost (Mikkola and Gassmann 2003).

Product modularity is considered to be useful while dealing with complex products as it limits the interaction scope between the elements or tasks. Therefore it has the potential to reduce the amount of cycling time that occurs in a production or design process. It also reduces the development cycle to approach the shorter product’s life cycle with lower development costs (Baldwin and Clark 2000).

Because of the potential benefits of product modularity and how good the effect it has on the enterprise and also the gain of economies of scale of the companies by the idea of the modular components. Several research studies were done to examine the impact of product modularity on the outcome performance of the companies.

There are several dimensions of the performance evaluation in the literature and that we structured the coming sub-sections according to four dimensions.

II.4.4.1. Product Cost

(Karmarkar et al.1987) indicated that the costs of the spare parts increase from the higher failure rates of modules with regard to components. Product modularity can have a meaningful variety of final products and at the same time enables a standardized production process (Salvador et al. 2002; Jacobs et al.2011). The significant decrease in the number of components results in a reduction of the risk pooling in the inventory, increased economies of scale, and reduced set-ups (Tu et al.2004). (Hargadon and Eisenhardt 2000; Ernst and Kamrad 2000) suggested that costs are lowered while using product modularity concept because of the faster assembly of the implemented modules that will allow faster delivery that has a shorter lead time. (Fisher et al. 1999) suggested that companies can benefit from modularity since it can help them to reduce investment costs.

(Kortmann et al. 2014) indicated that by enabling modularity, manufacturing companies might have enough flexibility to adapt to the product variety without having critical effects on costs. This is mainly obvious in the environments of manufacturing which intend to produce with low unit costs to sustain the higher level of the structures of the cost as well as in delivery times and the manufacturing systems (Sabry 2016).

On the other hand, one study suggested an opposite finding that indicates that product modularity does not certainly lead to the reduction of cost (Kutner et al. 2005). The study summarizes that the process of product modularity causes an increase in the costs of the spare parts. That is because of the high failures of modules regarding the components. However, there is a limitation of this study that no comparison between the spare parts cost that is required by modular products and that of the integrated products.

Most of the literature review indicated that product modularity has a positive impact on the cost performance of the companies. This was shown in some researches by studying the impact of applying modularity in different stages of manufacturing such as procurement cost, inventory cost, maintenance cost and production cost. Other researches identified a coefficient between product modularity and cost using a survey that is done among several companies.

II.4.4.2. Product flexibility

Another performance capability of the company that the modularity has an impact on it is flexibility. Flexibility in manufacturing or products states the ease and the quickness with which factories will be able to respond to changes in conditions of the market (Ndubisi et al. 2005). It shows the capability of the factories to react on time to the needs and requirements of the customers (Jacobs et al., 2011). Flexibility in manufacturing is defined also as the ability of a company's manufacturing system to focus on the changes in customer demand and to configure quickly or reconfigure the manufacturing system's operations to cope with the trends of the customers. During the process of production, flexibility can lead to a competitive advantage (Yusuf et at.2004). There are several advantages of flexibility for the companies, that is why companies are trying to set up more flexible manufacturing systems. (Lorenzi and Lello 2001) suggested that the flexibility of the production mix is increased with the usage of product modularity.

Product modularity offers flexibility that allows the companies to satisfy a variety of customer requirements. It offers several advantages to the manufacturing industry by reducing waste, the number of labor, and inventory level. Also increasing the quality improved productivity and quality performance and enhancing cost. (Lee and Tang 1997) discovered that product modularity increases the flexibility of the inventory's work in process (WIP). (Lin and Bush 2010) proposed that a modular system can sustain its flexibility by combining part of its components with other components through the interface that was already defined to achieve different functions. This will produce more variants of the products, to accommodate the environmental changes by organizing the existing components to build a new system of manufacturing without the need for redesigning all the components in the system. Furthermore, flexibility addressed quick responsiveness to cope with the changing customer demand, competence, and the dynamic environment that need the capability to reconfigure for short-lived manufacturing processes and also for designing modularity of products (Sabry 2016).

(Gangnes and Van Assche 2011) stated that flexibility in the electronic industry can be increased by applying product modularity. Product modularity allows the companies to reuse components, to easily substitute specific components of the technological system, and to enable the companies to decrease the costs of communicating and trading. (Ro et al. 2007) stated that a modular product design allows a higher risk of changing the design that permits late product changes. This leads to better design solutions and prevents the requirement for whole product changes. This develops the manufacturing flexibility and the design that is required for market change.

The relationship impact of modularity on flexibility was defined by building up a research hypothesis regarding the relationship between product modularity and flexibility dimension and then a comprehensive survey is done through several companies testing the hypothesis made of whether flexibility is impacted positively or negatively by the implementation of product modularity

II.4.4.3. Product cycle time

(Ulrich, 1994; Sanchez et al. 1996) claim that product modularity is considered to be beneficial to decrease the time that is related to product testings and also related to detailed designing. (Lorenzi and Lello 2001) stated in their research that product modularity leads to a reduction in the cycle time of the production process. Product modularity allows the manufacturing of modules to occur at the same time and arranges and combines them based on order requirements thus cycle time is decreased. (Pil et al. 2006) stated that modular product design needs that the design of the product should include fewer dependencies between the subsystems and the components which require meaningfully less complexity and instantly decrease the design alternatives numbers. When the functions that are represented to each component or subsystem are decreased, the cycle time performance will be decreased (Sabry 2016).

(Danese and Filippini 2010) approve that product modularity has a positive effect on the speed of the introduction of the product that depends on the cycle time of the new product development cycle time. This reflects the total time that starts from the concept generation of the product to the introduction of the product and also achieves the assigned performance of the schedule on-time. (Sohail et al. 2010) suggested that product modularity has a positive effect on reducing the cycle time of offering the final product. They stated that product modularity leads to reducing cycle time by manufacturing and assembling the modules in parallel.

The relationship impact of modularity on the cycle lead time was defined by building up a research hypothesis of whether the implementation of product modularity impacts positively or negatively the cycle lead and then a comprehensive survey is done through several companies testing the hypothesis made using regression analyses.

II.4.4.4. Product quality

(Rocha et al. 2015) proposed that product modularity is considered to be a concept that can influence the improvement of production efficiency and product quality. (Feitzinger and Lee 1997) proposed that product modularity improves the quality of the product because problems can be reduced to specific modules instead of the whole product. This will facilitate doing corrective action for the specific module. A study at General Motors stated that the use of the concept of modular design and standardization was going to enhance product quality (Suzik 1999). (Kusiak 2002) suggested that applying standardization will lead to revenue gains and quality for a product or service. (Onkvisit and Shaw 1989) stated another effect of product modularity on quality can be seen from a customer's perspective. The total effect of quality is improved when having a clear image of a company that offers a standardized product as the perception of the customers of quality is improved (Jacobs et al. 2007).

Surveys and hypotheses were also used to discover the impact of implementing product modularity on the quality of the product.

II.4.4.5. Modularity impact on service

Recent researches have addressed the impact of modularity on the service domain. (Böttcher and Klingner 2011) described theoretically in detail the goals of modularity while focusing on the aspects of reduction of efforts improved transparency, the structured configuration of individual services, the reduction of complexity, reuse, and improvement and enhancement. (Ho et al. 2009) theoretically suggest that modularity offers the ability for companies to provide quick, customized products and/or services without destroying old product and/or service designs by recombining and reusing components.

(Kazemi et al. 2011) claim that modular services may be simply reused in different contexts and can be composed to fulfill new requirements. Service modularity avoids the spread of changes to other services and therefore facilitates the maintenance of service-oriented systems. They explained that the easier someone can understand a service, the better understanding someone will have about the functionality of the service (Dorbecker and Bohmann 2013).

(Lin et al. 2010) presented an increase in the responsiveness to offer a variety of services and a decrease in the complexity of service. They applied the logic of modularity to the design process is considered to be a cost-effective and also a flexible way to build up new services of logistics and to integrate the existing modules to be able to fulfill the needs of the customer (Dorbecker and Bohmann 2013).

A modular service platform is considered to increase the flexibility and responsiveness of the company and also it will assist in gaining market share from other competitors. (Pekkarinen and Ulkuniemi 2008) highlight modularity as a method to standardize the production of service. Hence, companies will achieve better profitability and customer value. Another benefit of applying modularity to the service is the ability of the company to customize services to different customers and market segments with less cost. They discussed also the idea of reusing the standardized services that may also be integrated to fulfill and satisfy more demanding needs and requirements (Dorbecker and Bohmann 2013).

II.5. Conclusion and PhD contribution positioning

This chapter examined the main concept and literature review of mass customization and modularity. The literature investigation supported the idea of using modularity as a driver to implement successfully MC in the service-oriented system. DSM method and clustering analysis are shown in the literature review as a potential to be applied for modularizing the service-oriented system. We learned from the literature that manufacturing companies began to integrate services in their customized offering to be able to generate high value for customer requirements.

Most of the researchers focus on service modularity while talking about PSS customization, which resulted in adapting the research of service modularity from a service business context to a PSS context instead of allowing the relationship interaction between products and services to be the main subject (Larsen et al. 2018). Moreover, in the meantime service modularity is the newer field of research on the contrary to product modularity that has been in the field of research since a while ago (Wang et al. 2011). Additionally, a shortfall of research has been identified on the integration between product and service modularity in an integrated product and service system context as researchers have aimed their attention on service modularity and not on modularization of products and services together. Also, the necessity to manipulate similarity measures among service and product elements where the method can be flexible so it could address only products, only services or both of them. That identified the first research question to ask how to modularize offers of products and/or services. The first objective of the thesis is to offer a method that can modularize service-oriented systems and that can be adaptable to modularize either just products or services or integration of both. The method would give a chance to have more than one output modularity scenario to support the decision-makers in choosing the most suitable scenario based on the industrial context.

While several effects of service modularity are discussed in the literature of the past researches, a considerable part of these studies considered the effects only on a conceptual level. While service modularity has been considered as a promising approach to achieve the benefits, most of them are argued at a theoretical level. This fact implies that these benefits have been derived from the literature of product modularity since the research studies only mention the benefit without confirming it in the service context (Mattos et al. 2019). The idea of having several modularity scenarios and having the chance to compare between them to choose the most suitable scenario for the industrial context is missing in the literature. That addresses the second research question: "How to evaluate and compare the industrial performance impact of several alternative modularity scenarios, to help to manage industrial complexity?". The second objective of the thesis is to evaluate the industrial performance impacts for the modularity scenarios in order to help decision-makers to manage and choose the most suitable scenario that can suit their industrial context and decrease the internal complexity.

Clustering analysis is a key step within the modularization process of a system. While several techniques are available to perform the clustering algorithm, there is no exclusively best technique. Each technique will result in different outputs that can help in decision-making for the best result based on the industrial context for the enterprise (Ezzat et al. 2020). Therefore, the rigorous approach of the thesis is to have a method that provides the best results of modularization for a service-oriented system in a given context. Moreover, having indicators to evaluate the different results are important as they provide valuable support for comparative analysis of alternative clustering outputs. While some of the literature addressed the evaluation indicators either clustering or performance, no research addressed both the quality of the formed cluster and its impact on the industrial performance that can help the decision-makers to understand the consistency of the cluster and identify the impact of modularity on the industrial performance.

The next chapter will introduce the general method framework of this thesis to modularize a 'service-oriented system'. The method will be divided into two main parts. The first part will discuss the method to modularize the service-oriented system. It will have several alternative cluster scenarios as an output that is ready to be evaluated. The second part of the method will illustrate the evaluation criteria needed to measure the impact of each of the scenarios on the performance capabilities of the company.

Chapter III. **PROPOSAL OF A METHODOLOGICAL FRAMEWORK FOR PRODUCT AND SERVICE MODULARITY**

III.1. Introduction

Based on the literature review, the approach of the thesis focuses on implementing a modularity method that can be applied to a service-oriented system. This approach aims to decrease the internal complexity resulting from generating a variety of offers of products and services. The approach demonstrates the usage of modularity as a driver to help to mitigate the industrial complexity. Our method intends to support the decision-makers to choose the suitable output modularity scenario based on the industrial context of the company and the modularity impact on the performance of the company by evaluating and comparing several alternatives output scenarios. It will likely ease the operation management of products and services in the subsequent phase and can also have the potential to boost economies of scale. This chapter shows the general methodological framework of the proposed method to modularize the service-oriented system.

The chapter is divided into two main parts. The first part describes the general methodological framework. The method proposed is divided into two main phases based on our two research questions. The first phase addresses the first research question by demonstrating the approach to implement modularity on a service-oriented system. It addresses the procedures needed to implement successfully modularity with inputs that can be elements of products and/or services. Chapter 4 will discuss in detail this first phase of the method. The output will be several alternative modularity scenarios. To choose the most suitable scenario for the company, an approach of evaluating those scenarios in terms of their impact on the industrial performance of the company is also proposed. This will lead us to the second phase of the method, where we can measure the modularity impact on the performance of the industry which corresponds to our second research question. Chapter 5 will discuss in details this second phase of the method

The second part of this chapter describes the illustrative example that will be used to illustrate and describe more precisely the proposed method. This illustrative example is different from the case study that will be discussed in Chapter 6. This illustrative example aims to demonstrate the detailed steps of the method.

III.2. General Framework

This section presents the general framework of the method to modularize a service-oriented system. The main direction of the method is to use modularity as a driver for decreasing the internal complexity resulting from market offer variety. The method requires some adaption for each application case study. It is a generic proposal that will require a decision process by some experts for configuring the method for each case study. The objective is to enable the decision-maker to implement modularity on a service-oriented system and to choose the most suitable scenario based on the evaluation of several alternative clustering outputs. Results from this method will be ultimately useful for the variety management of products and services.

In this chapter, we will explain the general main steps of the method. The general method can be generalized into five main phases as shown in Figure 15. Those five main phases are divided into two main steps. The first step is related to implementing the concept of modularity on a service-oriented system. This step demonstrates the processes of identifying the elements of products and services that are needed to undergo the modularity method to have several alternative clustering scenarios. The second step is to measure the impact of modularity on the performance of the company by evaluating and comparing those alternative scenarios so that it can support the decision-makers to choose the most suitable scenario.

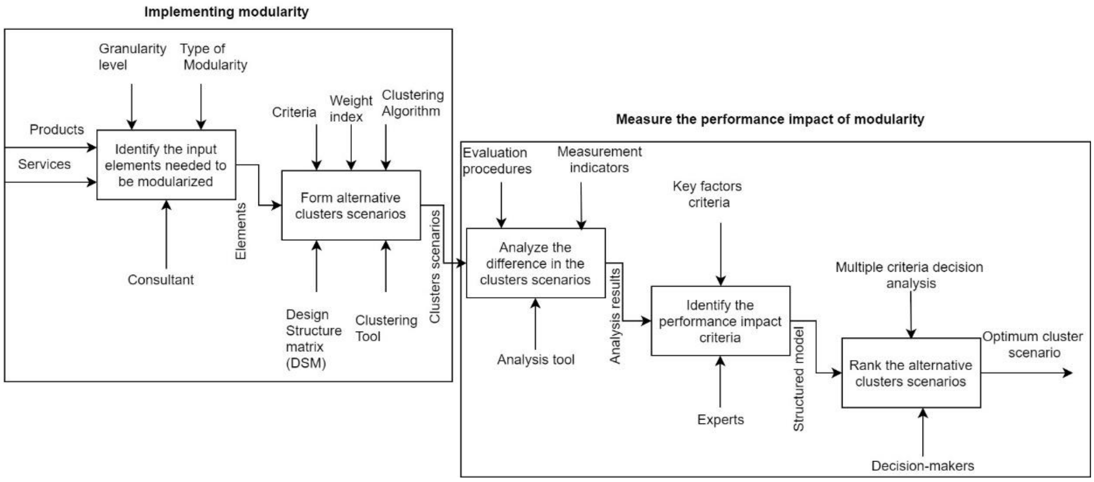


Figure 15. General Framework

III.2.1. Identifying the input elements needed to be modularized

The first main phase of the framework is to identify the elements needs that can be either services and/or products that the company will be able to offer. Elements are the input components of either product and services that will be modularized to form modules of those elements. They can be elementary components of products or elementary tasks for a service. Identifying products and services provides a raw input for the subsequent steps. This input should be refined according to the industrial context. In this sense, several strategies have been identified to be useful for refining products and services identification resulting in various structuring (Ezzat et al. 2019).

Although these strategies depend upon the existing offering of a given company, using some of them contribute towards generating various modularity scenarios, thus opening up further drivers for managing variety offers.

Determining the granularity level has to be set first, either product or service or the integration of both and the detailed level of their components has to be decided. An appropriate level of detail should be determined to aggregate the product and service elements into corresponding modules. This is to ensure the benefit of the different modules, which may be a threat if the included elements can be seen as modular themselves, therefore blowing the main purpose of the modularity concept. The suitable level may not be the same for service elements as product elements (Sakao et al. 2017).

III.2.2. Forming alternatives cluster scenarios

The next phase of the method is to generate several alternative cluster scenarios that will help in identifying the most suitable scenario of modules based on the industrial context. Each cluster consists of a set of elements that have close similarities between each other. Aggregating or grouping the elements into clusters helps in mitigating the internal complexity that is resulted from offering a high variety of products and services. To generate the output clusters from the elements of product and services, similarity indices have to be identified first between those elements and each other. Those similarity indices are defined among the elements of products and/or services based on a set of criteria that needs to be defined. Due to the complexity of similarity evaluation, it is necessary first to identify appropriate criteria for assessing such similarity. In some industrial cases, there can be just one criterion that identifies the similarity indices between the elements and each other while in other cases, there can be more than one criterion that can identify the relationship indices between the elements

Design structure matrix (DSM) is used as a visual representation of the similarity indices between the elements. The DSM will be rearranged to be able to find a clustering where modules minimally similar to each other while components within a module maximally similar to each other. Several clustering algorithms can be used to find the best products and services clustering. The selection of the algorithm is not imposed by the method. Trying different clustering algorithms will lead to generating different modularity scenarios of the service-oriented system and comparing them to end up with the best ones. To proceed with the clustering algorithms, a clustering tool is needed that can implement the clustering algorithms and visualize the output of the performed clustering.

Several alternative modularization scenarios could be considered out of the clustering process. It is either because of the defining criteria or the clustering algorithm. Building the DSM using different criteria will result in different similarity indices between elements, thus different matrixes and clustering scenarios. The selection of the criteria could be refined upon clustering and evaluation which enlighten the decision-maker on the performance of the modularity scenarios. Therefore an evaluation of these alternative scenarios is required to decide which one is the most appropriate.

The formation of different alternative output clustering is the main output of the first phase of implementing the modularity concept. Measuring the impact of each of the scenarios on the performance of the company will help to choose the most suitable scenario based on the industrial context.

III.2.3. Analyzing the difference between clustering scenarios

This is considered the third phase of the method and as well the first phase in the second part of the method. This second part focuses on measuring the performance impact of modularity on industrial performance. It starts by analyzing the differences between the several alternative output scenarios. To be able to analyze the differences between the different scenarios, a set of measurement indicators has to be identified first. Those indicators will be able to identify the differences between the alternative scenarios based on the set of activities and resources.

To identify the measurement indicators that are needed to differentiate the alternative clustering scenarios, a graphical presentation to visualize the process of each of the scenarios has to be done first to reflect the set of activities and the resources used for each of the cluster scenarios. Figure 16 illustrates how one scenario of the output cluster is analyzed. The formed clusters are undergone assembly processes to form the final solutions of product and service offers. C is the abbreviation for clusters and the numbers assigned to it is the index of the cluster. n is the total number of formed clusters after the clustering process. Each of the clusters will be translated into a process that illustrates the formation of the cluster. Each cluster will have its own process so there will be a total number of n processes The list of processes consists of both activities and resources needed to be done to provide the final solution of both product and service offers. Those processes will identify the activities and the resources that are needed to have the set of final solution offers that the customer needed. m is the total number of solution offers that the company can offer. Each of the clustering output scenarios will undergo the same process of scenario analysis.

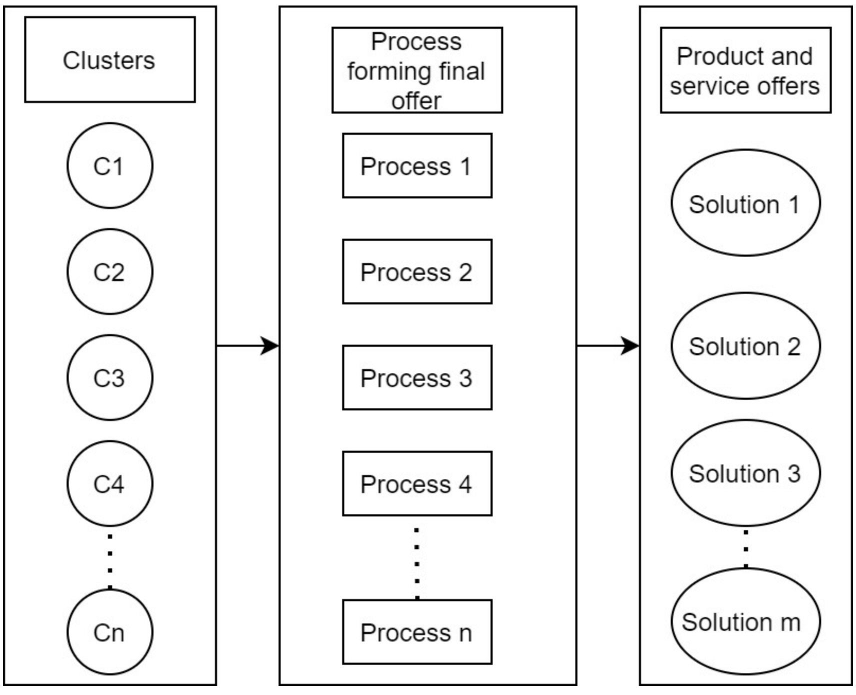


Figure 16. Scenario analysis

Evaluation procedures have to be defined to collect the needed information for the different processes of each of the alternative scenarios. Those procedures are the steps to be followed to be able to analyze the differences in the processes of the alternative clustering scenarios. The procedures will analyze the set of activities and the resources used of each of the processes of each output clustering scenario.

III.2.4. Identify the evaluation criteria model

The next phase is to identify the performance impact criteria. In our method evaluation criteria are generally identified by the experts. Evaluation criteria are needed to measure the impact of modularity on the industrial performance of the company. Those sets of criteria will be the main factor to evaluate the alternative clustering scenarios. Several criteria can be considered e.g. complexity, time, cost,…etc.

Criteria are important to the company that would like to make the decision. Criteria generally help the decision-makers to determine what is going to be a successful decision. One criterion implies a ranking but several criteria usually mean that different rankings are possible according to the standpoint of the decision-makers

Identifying the criteria can be determined via brainstorming or other appropriate methods. The model of the criteria should be clearly stated. The criteria selected by the decision-makers are dependent on the purpose of the industrial context. In the selection, the criteria that arise from the expertise of the organization are mainly used in the process of ranking of alternatives (Russo and Camanho 2015).

III.2.5. Ranking the alternative clustering scenarios

The last phase of the method is to rank the alternative clustering scenarios. After identifying the key factor criteria and the measurement indicators that are needed, ranking the alternative scenarios is the last step. To be able to rank the alternative scenarios, the decision-makers must know and define well the criteria, the purpose, the need, and the alternatives actions to take.

Having more than one key factor criteria will make it more complex for decision-makers to choose the most suitable scenario. Multi-criteria decision making (MCDM) is considered to be a valuable tool when having more than one criteria to evaluate alternative scenarios. It is considered a valuable tool that can apply to such a complex decision.

Nowadays plenty of MCDM methods exist. They are used in many fields and various disciplines from governmental decisions to industrial strategies. One of the current challenges is thus choosing the right process to make a decision. Indeed an inappropriate method for a given decision problem could lead to a lack of quality in the recommendations.

Based on the weight of each criterion, the judgments are weighted and the preferred alternative can be identified based on the ranking result.

III.3. Illustrative example

The illustrative example will be used in the next two chapters to illustrate and demonstrate the method in detail and make it easy to understand. The illustrative example is a simple case study that had been developed during the thesis in collaboration with an industrial company. The company is a supplier to the wind turbine industry that offers a high variety of services to the customers. Modularization of the services is offered to the company to enhance the flexibility and be able to offer new customized offerings without designing a service from scratch.

In this illustrative example, we will apply our method to a set of service activities that are needed to be modularized to form a set of modules of activities instead of a set of service activities. We will try to find similarities among the service activities that can help us in building a similarity relationship among those activities which will result in the formation of modules of activities. This illustrative example is different from the case study that will be represented in chapter 6 in our thesis, notably because the case study (chapter 6) addresses elements of both product and service. The idea of showing two different applications is to demonstrate that our method is applicable to either product modularity, service modularity or the integration of both.

In this illustrative example, the service 'transport booking' is used to easily illustrate our method in the upcoming chapters. 'Transport booking' is a service that is used in the company that consists of a set of different activities that are responsible for shipping the goods from the company to the needed client. It is also responsible for booking the carrier responsible for transporting the goods. This service has four different variants that the company is able to offer for several different customers. Each of the variants has a set of activities that establish each of the services. Each of the service activity consists of its own human resources and its own technological information that help in building the set of activities.

The input data for the modularization are four service blueprints that define the service process for each of the offered service variants. Each service blueprint includes information about activities, resources, technological information, and materials. The service blueprints have been analyzed to extract the required information for building each of the steps of the method.

Table 1 shows the list of activities that are used for the service of 'transport booking'. There are a total of 72 activities that have been used in the different offer variants of 'transport booking' service. There are a total of four variants of the service that were extracted from the service blueprint. Some variants may have some common activities between them and each other. Some activities are always performed in the process of the service without considering which variant. The elements of our method used here will be the set of activities that are going to be modularized into a set of modules in our illustrative example. Those will be the main inputs of the methods.

Table 1. List of activities

Activities	Symbol
Open shipment list	A1
Find shipment ready for booking	A2
Find the first shipment ready for booking	A3
Find order number	A4
Look up order number in the transport management system	A5
Add measurement and weight for deliveries	A6
Choose shipping agent for delivery	A7
Save and close	A8
Insert SHP number in shipment list	A9
Carrier arrives at Nissens	A10
Carrier gives SHP number to warehouse operative	A11
Carrier loads truck	A12
Carrier takes off from Nissens	A13
Open shipment list	A14
Find delivery	A15
Find order number	A16
Open ERP system	A17
Look up order number in ERP system	A18
Find PO number	A19
Sign in to customer’s ITM system	A20
Look up PO number	A21
Check information is correct	A22
Send an email to the help desk with the freight order number and information that needs to be corrected	A23
Receive an email from the help desk when an error has been corrected	A24
Recheck the information are correct	A25
Send an email to the help desk that the information is correct	A26
Book transport in customer’s ITM system	A27
Enter load meter	A28
Enter the pickup reference	A29
Insert pallet with unique reference number	A30
Upload delivery note to booking	A31
Press finish booking	A32
Print CMR papers	A33
Handover CMR papers and labels	A34
Put labels in their respective plastic pocket	A35
Labels are glued on pallets	A36
Warehouse operative handover CMR papers to carrier	A37
Wait for the carrier to receive SHP number	A38
Write an email to the carrier	A39
Inquire time of delivery at customer	A40

Send email to the carrier	A41
Receive time of delivery at the customer from carrier	A42
Sign in to the customer's delivery portal	A43
Check customer's online calendar for available timeslot which matches the carrier time of delivery	A44
Chose timeslot	A45
Enter the number of pallets	A46
Enter customer's item number	A47
Enter PO number	A48
Enter serial number	A49
Press create reservation	A50
Receive an email with the booking confirmation	A51
Forward booking confirmation to customer's email	A52
Open shipment list	A53
Find shipments	A54
Find order number	A55
Open ERP system	A56
Look up order number in ERP system	A57
Find PO number	A58
Enter PO number	A59
Get a delivery note from the ERP system	A60
Find customer's item number in the delivery note	A61
Enter customer's item number	A62
Attach delivery note	A63
Open shipment list	A64
Find the number of pallets	A65
Enter the number of pallets	A66
Send email to customer	A67
Wait for the customer to send back an email with a possible delivery slot	A68
Receive an email with a possible delivery slot	A69
Send an email to the shipping agent to ask if the delivery slot fits	A70
Send new email to customer and request a new timeslot	A71
Send confirmation of timeslot	A72

Table 2 shows the resources needed for the service activity with the type of resource. it can be a human resource that is related to the people who work for the company and in charge of some activities. Technological/tools and material: refers to the material and tools that are needed to implement an activity. And lastly, information that is related to the needed information that is shared between the activities and each other. Some activities can't be executed without having such information. It will help to build up the method when defining the similarity interaction between the elements and themselves.

Those resources were extracted as well from the business blueprint of the service. Each activity is assigned to one or more resources that are either human, technological, material, or information.

Table 2. List of resources

Resources	Type of the resource
Logistics representative	Human
Warehouse operative	Human
Computer	Technology/tools and material
Excel	Technology/tools and material
Transport management system	Technology/tools and material
ERP system	Technology/tools and material
Email	Technology/tools and material
Customer’s delivery portal	Technology/tools and material
Customer’s transport management system	Technology/tools and material
Printer	Technology/tools and material
Plastic pocket	Technology/tools and material
Labels	Technology/tools and material
CMR papers	Technology/tools and material
Pallets with products	Technology/tools and material
Shipment list	Information
Delivery note	Information

The data from table 1 and table 2 are considered as the main inputs that are needed to illustrate our method in the next two upcoming chapters. It will help in easily understand the concept of the method and well illustrate the detailed steps of each phase that was demonstrated in this chapter.

III.4. Conclusion

This chapter summarizes the general framework of our method of the thesis. It gives a general big picture about the method and its key phases. We discuss, in brief, the five main phases that are implemented in our study starting from identifying the elements to ranking the several alternative clustering scenarios in the industrial context.

To be able to easily explain the method, an illustrative example based on a case study in a company is provided. The illustrative example is related to a service provider company that has various varieties of services. Service modularity was presented by the company in order to improve flexibility and to have the ability to offer more customized service offerings without increasing the complexity.

The method is based on the usage of modularity as a driver to help to decrease the internal complexity of the industrial company that is caused due to producing a variety of offers of products and services. It aims at supporting the decision-makers to select the optimal output modularity scenarios based on the industrial context and the impact of modularity scenario on the performance of the company by evaluating and comparing several alternatives output scenarios.

The next chapter will focus on the first part of our general Framework. It will demonstrate in detail the implementation of modularity on a service-oriented system. Detailed steps will be shown and will be illustrated by the example of the service company provider that was introduced in this chapter.

Chapter IV. METHOD TO APPLY MODULARITY ON SERVICE-ORIENTED SYSTEMS

IV.1. Introduction

Implementing modularity has been proposed as a solution method to answer the objectives of the research. The method consists of generating sets of modules, gathered from an initial set of either product or service components. Modularity emerges from the partition of a system into several independent sets of components. This independence boosts the usage of the standardized components while maintaining the opportunity for designers to easily create a wide range of product variety using a much smaller set of input components. This applies to both product and service domains and contributes to mitigating variety-induced complexity as well as supporting a smooth configuration process on the side of the final customer.

Our method focuses on implementing modularity on a service-oriented system as specified in chapter III. The proposed method is different from other methods that focus on either service or product modularity, by studying a similarity relationship among products and services. It will likely ease the operation management of products and services in subsequent phases and could also have the potential to boost economies of scale.

This chapter focuses on an approach for modularization of a service-oriented system. It describes in detail the needed steps to implement modularity on a service-oriented system. It is divided into five main steps that include: identifying the elements, form numerical Design Structure Matrix (DSM), form and aggregated matrix, cluster the matrix, and finally, evaluate the different outputs for both techniques that are used to identify the number and the quality of the clustering output. Different measurement indicators are used to evaluate each output scenario and to evaluate the formed clusters.

We will illustrate each step of the method by using the case study that was proposed in the previous chapter. It will ease the understanding and will give more insight into the usage of our method.

IV.2. Modularity procedures

This section presents the proposed modularity procedures to modularize a service-oriented production system. It demonstrates in detail the first two phases that were defined in the last chapter. The method consists of five main steps shown in figure 17. These are the detailed steps of the first phase of figure 15 in chapter III. identifying the elements, building a similarity DSM, building an aggregated matrix, clustering the matrix, and lastly evaluating the clusters. The first step is the same but more detailed to the first step in figure 15. And the other 4 steps are detailed steps to the second step of the first phase of figure 15. This overall procedure in five steps is generic, but the method involves some adaption to the specification of every application case study. It is a general proposal that will need a decision process by some experts or decision-makers for configuring the method for each industrial context. Some of the parameters that can be adapted are: criteria to evaluate the similarity indices between product and /or service elements, the clustering algorithm that is chosen to form the required clusters and the indicators to choose the most suitable output clustering scenario. The objective of this modularity procedure is to support the decision-maker in choosing the optimal clustering scenario based on the clustering output evaluation. Results from this method will be ultimately useful for the variety management of products and services. In our thesis, we analyze the performance of several output scenarios that are resulted from changing the parameters defined. We also analyze the sensitivity of the results according to changing different parameters. This is different from using the method in an industrial use where we should fix the parameters to be

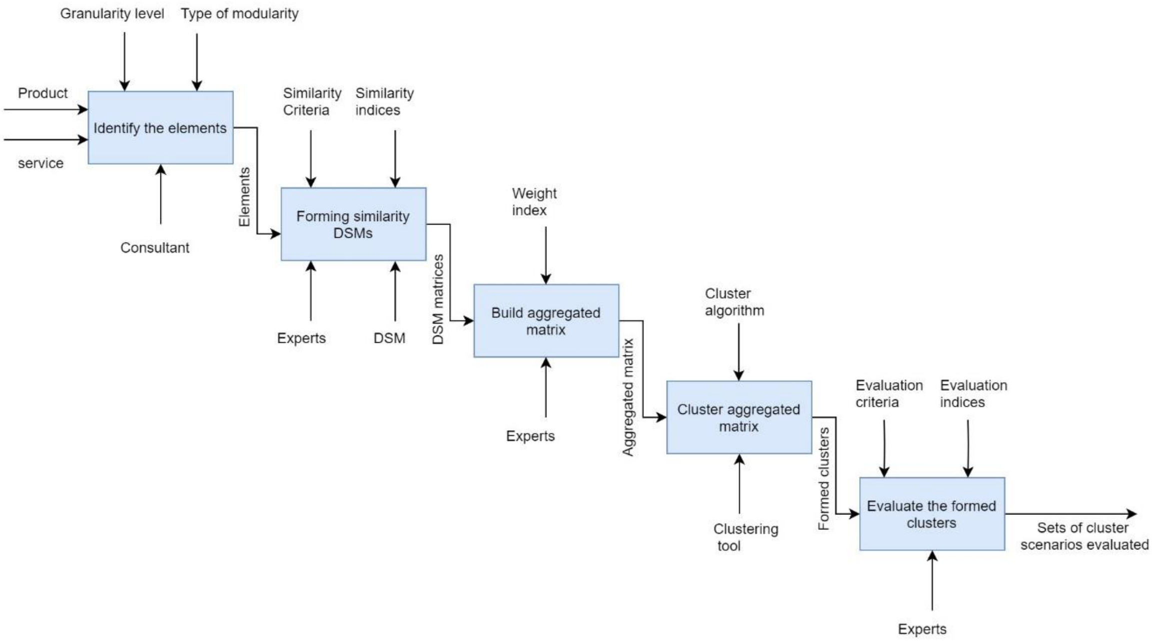


Figure 17. IDEF0 main steps for the method

able to provide a suitable scenario solution for the company The steps of the procedure are detailed in the next sections.

IV.3. Identifying the elements

The initial step of the method is to identify the elements that are needed to be modularized. Identifying the elements provides the raw input for the following steps of the procedure. Therefore, the input should be clarified in accordance with the industrial context. Deciding the granularity level has to be fixed first, either product or service, or the integration of both, and then the detailed level of the elements has to be determined (Figure 18). Based on (Ezzat et al. 2019), two main strategies are proposed to help in clarifying the identification of products and services.

- In the first strategy, there is no modularization a priori of products neither services separately. The elements consist of product elements or service elements at a convenient granularity level, to be decided by the industrial decision-makers. In the case of the product, the elements can be derived from the Bill of Material (BOM). In the case of services, there are mainly two levels for decomposition, either breaking the service package into a list of services or decomposing the service itself into a list of activities.

- Another strategy can be used where both products and services are considered a priori pre-modularized elements. This means that services are modularized distinctly to create service modules and products are modularized distinctly to create product modules. Then, in a second step, both product modules and service modules will be considered as the elements to be integrated to create product-service system modules.

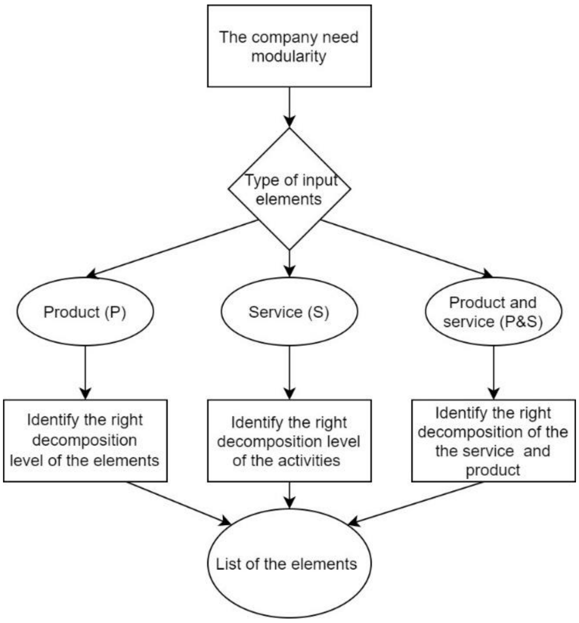


Figure 18. Type of elements

This results in the following hierarchy that is detailed in Figure 19 and it includes the following:

- Service element (SE) is the basic element of service in the service-oriented system. It can be either a list of activities that comprises a service or it can be considered as a list of basic services that offer a specific service package. Different service elements create service modules with different functions.

- Service module (SM) integrates the service elements that have strong similarities with each other. The service elements that are part of different service modules will have a weak similarity that will give the service modules small interdependency amongst each other.

- Product element (PE) is the basic element of the product in a service-oriented system. It can be derived from the Bill of material (BOM) of the product. A specific granularity level of the BOM can be chosen to define the decomposition level of the product elements.

- Product module (PM) integrates the product elements that have strong similarities with each other. The product elements that have strong similarities will form a product module that is independent of other product modules created by other product elements.
- Product and service modules (PS) are formed by product modules, service modules, or an integration of both.

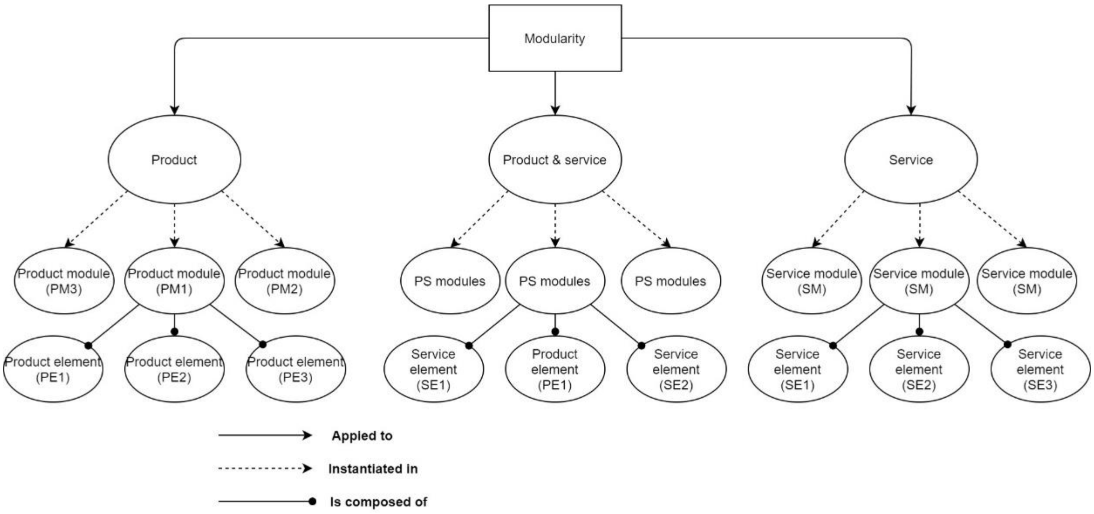


Figure 19. Detailed level of elements (illustrative example)

Based on the above hierarchy, different elements could be considered as an input for the modularity procedure, leading to several scenarios, depending on the granularity detailed level. The selection of these scenarios depends on the existing offering and the company's preference. For example, choosing product modules and service modules as input elements will lead to one scenario. Another one can be done by choosing product modules and service components as input elements that will lead to a different output scenario than the first one (Ezzat et al. 2020).

Although these strategies depend on the existing offering of a certain company, utilizing some of those strategies contribute to generating several modularity scenarios which will result in opening further drivers to manage the offering variety.

We will consider the service activities as we will work on modularizing the service in the illustrative example. The first strategy for identifying the elements is used in the illustrative example in which we will break down the service into a set of elements (in our case will be activities). We have chosen the first strategy since we have different variants of services that consist of each one of a set of activities and the idea is to modularize those set of activities to create a cluster of activities that can form the set of service variants more simply. Thus identifying the activities is needed as they are the main elements of the method. Table 1 in the previous chapter illustrates the set of activities needed. The activities were derived from the service business blueprint of the company. So we gathered all the activities that occurred for different varieties of 'service transport booking' and, in the next steps, we will show how this information is used.

IV.4. Forming the similarity DSM

The identification of the elements is the input for defining the DSMs with two sub-steps that result in an output of several DSMs.

IV.4.1. Define the similarity criteria.

Due to the complexity of similarity evaluation, it is important first to identify appropriate assessment criteria. A set of generic re-usable criteria has been identified as candidates for this step:

- Functional requirements (SC1): measures how much the given elements help in fulfilling the same functional requirement. Design engineers and customers and participate in the assessment of the resulting similarity. For example, if a given functionality or customer need is common between two elements it will result in a similarity relationship.
- Commonality (SC2): measures the concurrent occurrence of given elements in different products and/or services. For example, when two elements are together several final solutions (changing in the variety of the solution) so it will result in a similarity relationship.
- Human resources (SC3): refers to whether two elements are produced by mobilizing the same resource. For example, if a multi-skilled engineer is a common resource in two elements it will result in a similarity relationship.
- Technological information (SC4): identifies whether two elements depend on the same (hardware or software) tools or have in common certain information. For example, if a piece of needed information or a tool is common between two elements it will result in a similarity relationship.

Additional criteria could be used depending on the context of the industrial case. For example in a service, an example of another criterion can be the lifecycle criterion based on the stage that the service will be done. For the case of a product, the life span criterion can be used to discriminate the similarity (the elements that have the same life span will have a strong similarity between each other). Therefore, it depends on the point of view of decision-makers and also depends on the input elements (Ezzat et al.2020).

Illustration. For our illustrative example and our case study, we will use the four criteria that are identified as generic criteria.

Based on the service blueprint, the resources can be extracted and then they will be divided by either human, technological, or information. Table 3 shows part of the resources that are assigned for each activity of the illustrative example. The remaining of the table will be provided in appendix I.

Table 3. Activities with assigned resources

Activities	Human resource	Technological tools /material	Information
A1	Logistics representative	Computer, Excel	Shipment list
A2	Logistics representative	Computer, Excel	Shipment list
A3	Logistics representative	Computer, Excel	Shipment list
A4	Logistics representative	Computer, Excel	Shipment list
A5	Logistics representative	Computer, transport management system	
A6	Logistics representative	Computer, transport management system	
A7	Logistics representative	Computer, transport management system	
A8	Logistics representative	Computer, transport management system	
A9	Logistics representative	Computer, Excel	Shipment list
A10	N/A	N/A	
A11	Warehouse operative		
A12	N/A	N/A	
A13	N/A	N/A	
A14	Logistics representative	Computer, Excel	Shipment list
A15	Logistics representative	Computer	Shipment list
A16	Logistics representative	Computer	Shipment list
A17	Logistics representative	Computer, ERP system	
A18	Logistics representative	Computer, ERP system	
A19	Logistics representative	Computer, ERP system	
A20	Logistics representative	Computer, transport management system	

IV.4.2. Building up the similarity indices.

The value of each similarity index ranges from 0 to 3. If there is no similarity relationship the index will be 0. A complete similarity receives an index of 3. Index value 1 is assigned for weak similarity. And index value 2 is assigned for intermediate similarity. Table 4 shows the data required for each generic criterion to be able to allocate the indices among the elements as well as the evaluation scale. Based on the defined similarity criteria, the elements' inter-relationships are evaluated through experts' judgment resulting in the assignment of similarity indices to these relationships. This table guides experts and decision-makers to assign the similarity indices among the elements, during the application of the method for each case study.

A reduced scale (that is from 0 to 3) of similarity indices was chosen to ease the convergences of experts. Moreover, in case there is a difference in assessment among the experts, a consultation can resolve the differences. Besides the opinion of experts, the process's information that is used will help in assigning the similarity indices among the elements.

Table 4. Similarity criteria indices

Similarity criteria	Data Required	Index 0 (No similarity)	Index 1 (Weak Similarity)	Index 2 (Moderate similarity)	Index 3 (Strong similarity)
SC1	List of customer needs or functionality	The elements don't meet any common customer need or functionality	The elements meet 1-30% of total customer needs or functionality	The elements meet 31-70% of total customer needs or functionality	The elements meet 71-100% of total customer needs or functionality
SC2	Content of the solutions offered to the customer	If the elements are not included in any solution together	If the elements are included in 1-30% of the solution	If the elements are included in 31-70% of the solution	If the elements are included in 71-100% of the solution
SC3	Process model including the resources	If the elements don't share any human resource role	If the elements share between 1-30% of total human resources	If the elements share between 31-70% of total human resources	If the elements share between 71-100% of total human resources
SC4	Process model including the resources	If the elements don't share any technological information	If the elements share between 1-30% of the total technological information	If the elements share between 31-70% of the total technological information	If the elements share between 71-100% of the total technological information

Illustration. In our illustrative case, we will use the four generic criteria of our method. Each criterion c will result in a DSM Matrix representing a given type of similarity among all the elements considered: we will note this matrix DSMc. Analyzing the input data of the company (consisting of a list of process models, the content of the offers and the functionality of the service activities) of the blueprint for each service provided helps in identifying the similarity indices based on the four criteria identified.

Figure 20 shows part of the four numerical DSM that was done. The chosen part shows the differences between the different activities and also shows several similarity indices. Figures 20a and 20b are respectively related to the functionality and commonality criteria.

Activities	A	A30	A31	A32	A33	A34	A35	A36	A37	A38	A39	A40
Insert pallet with unique reference	A30	3	2	3	0	0	0	0	0	0	0	0
Upload delivery note to booking	A31	2	3	2	2	0	0	0	0	0	0	0
Press finish booking	A32	3	2	3	0	0	0	0	0	0	0	0
Print CMR papers	A33	0	2	0	3	1	0	0	1	0	0	0
Handover CMR papers and labels	A34	0	0	0	1	3	2	2	0	0	0	0
Put labels in their respective plastic pocket	A35	0	0	0	0	2	3	3	0	0	0	0
Labels are glued on pallets	A36	0	0	0	0	2	3	3	0	0	0	0
Warehouse operative handover CMR	A37	0	0	0	1	0	0	0	3	0	0	0
Wait for carrier to receive SHP number	A38	0	0	0	0	0	0	0	0	3	3	3
Write an email to carrier	A39	0	0	0	0	0	0	0	0	3	3	3
Inquire time of delivery at customer	A40	0	0	0	0	0	0	0	0	3	3	3

Activities	A	A30	A31	A32	A33	A34	A35	A36	A37	A38	A39	A40
Insert pallet with unique reference	A30	3	1	1	1	1	1	1	1	0	0	0
Upload delivery note to booking	A31	1	3	1	3	1	1	1	1	0	0	0
Press finish booking	A32	1	1	3	1	1	1	1	1	0	0	0
Print CMR papers	A33	1	3	1	3	1	1	1	1	0	0	0
Handover CMR papers and labels	A34	1	1	1	1	3	1	1	1	0	0	0
Put labels in their respective plastic pocket	A35	1	1	1	1	1	3	1	1	0	0	0
Labels are glued on pallets	A36	1	1	1	1	1	1	3	1	0	0	0
Warehouse operative handover CMR	A37	1	1	1	1	1	1	1	3	1	1	1
Wait for carrier to receive SHP number	A38	0	0	0	0	0	0	0	1	3	1	1
Write an email to carrier	A39	0	0	0	0	0	0	0	1	1	3	1
Inquire time of delivery at customer	A40	0	0	0	0	0	0	0	1	1	1	3

Figure 20. a) Functionality criterion DSM b) Commonality criterion DSM

The marked blue diagonal is the marked indices between the same element that has to be equals 3.We can distinguish from the figure that there are different values for similarity indices between the activities and each other. So based on the functional requirement criterion, A30 and A31 have an intermediate similarity relationship with each other with an index value equals to 2. That means that they have some common functionality but do not share the same full functionality. While for commonality criterion, they will have a weak similarity relationship with an index value equals to 1. That means that it is not come for both activities to be together in the same final offer of service but sometimes it happens. For the human resources criterion, they have a strong similarity relationship index with a value equals to 3. That means that they share the same human resources. The same goes for technological information criterion as they have strong similarities between each other thus, they share between them the same tools, material, and information. Activities A30 and A33 have 0 index value in the functionality DSM. This means that they don't share any functionality between them. After identifying the DSM matrix for each criterion, aggregating them in one big matrix is needed. So the next step will be to build the aggregated DSM.

IV.5. Building up the aggregated DSM

The aggregated DSM is used to calculate a synthesis of the various similarity indices presented in the previous step. Two steps are done to build up the aggregated DSM: assigning weights to the various similarity indices, then aggregating the numerical DSMc. The weighting step offers flexibility for the resulting similarity matrix resulting from the aggregation process. Each (product or service) element is represented by one DSM coefficient.

Two options can be envisioned to process the DSMs: to apply the clustering to an aggregated DSM resulting from the various matrices or to apply the clustering to each DSM based on each criterion. It was chosen to follow the first option to use the aggregated DSM as an input for clustering as it gathers the indices needed for all the criteria that are important to build the similarity relationship. Using more than one criterion to build a similarity relationship helps in identifying strong similarity indices. Two steps are done to build up the aggregated DSM: Assigning weights and aggregate the numerical DSMs (Ezzat et al.2020).

IV.5.1. Assigning weights

First, each DSMc will be assigned a weight that corresponds to its importance for the decision-makers. In practice, this weight is assigned by one or several experts. The assigned weights are dependent on each case since the relative importance of the criteria depends on the industrial context. The weight reflects the criterion's importance; the closer it is to 1 the more important the criterion is. The sum of the weights of the indices has to be equal to 1 (see Eq.1) There can be some cases that just need to use one criterion in that case, the aggregated matrix will directly be the DSMc for this criterion.

$$\sum_{K=1}^{n} W_k = 1 \tag{1}$$

Illustration. In our illustrative example, the four distinct numerical DSMs will be aggregated to one aggregated matrix with the aggregated indices. We assign specific weights to each of the criteria SC1 to SC4. We will consider the *functionality* criterion as the most important one with a weight equals to 0.5. The *commonality* criterion will be the second in importance and will be assigned a weight of 0.3. The *human resources* criterion and *technological and information* criterion will both have an equivalent weight of 0.1.

IV.5.2. Aggregating the numerical DSMs

An aggregated matrix A will be generated based on the DSMc. The coefficients of the aggregated matrix A are reflected by (C_{ij}^{A}). These coefficients result from the weighted sum of the coefficients within the criteria matrices as seen in Eq.2

$$C_{ij}^{A} = \begin{cases} \sum_{k=1}^{n} C_{ij}^{K} \times W_k, & i \neq j \\ 3 & i = j \end{cases} \tag{2}$$

Where $W_k$is the weight assigned to the kth similarity criteria, n is the total number of similarity criteria and C_{ij}^{K} is the coefficient for each kth similarity matrix. When i=j that means that the coefficient of the matrix will be the similarity index between the same elements therefore, the index will always be 3 when this happens.

This aggregation is adapted to the way of building clusters for the specific objectives of each case study. Moreover, it makes it possible to analyze and compare several distinct aggregated matrices. This will help in understanding the sensibility of the way the similarity is measured.

Illustration. A part of the aggregated matrix A is shown in table 5. To illustrate equation 2 with the weights 0.5, 0.3 and 0.1 already mentioned for the indices SC1 to SC4, the coefficient between the two activities 'Insert pallet with reference number' (A30) and 'upload delivery note to booking' (A31) for the aggregated matrix will be:

$$c^{A}_{30\ 31} = 2 \times 0.5 + 1 \times 0.3 + 3 \times 0.1 + 3 \times 0.1 = 1.9 \qquad (3)$$

Table 5. Aggregated matrix A

A	A30	A31	A32	A33	A34	A35	A36	A37	A38	A39
A30	3.0	1.9	2.4	0.7	0.5	0.3	0.3	0.3	0.3	0.4
A31	1.9	3.0	1.9	0.7	0.5	0.3	0.3	0.3	0.3	0.4
A32	2.4	1.9	3.0	0.7	0.5	0.3	0.3	0.3	0.3	0.4
A33	0.7	0.7	0.7	3.0	1.0	0.3	0.3	0.8	0.3	0.4
A34	0.5	0.5	0.5	1.0	3.0	1.6	1.6	0.6	0.2	0.2
A35	0.3	0.3	0.3	0.3	1.6	3.0	2.2	0.6	0.0	0.0
A36	0.3	0.3	0.3	0.3	1.6	2.2	3.0	0.6	0.0	0.0
A37	0.3	0.3	0.3	0.8	0.6	0.6	0.6	3.0	0.3	0.3
A38	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.3	3.0	2.1
A39	0.4	0.4	0.4	0.4	0.2	0.0	0.0	0.3	2.1	3.0

We will make another scenario of the aggregated matrix that will be assigned different weights of criteria to be able to compare the output results of the two aggregated scenarios and illustrate how changing the weight of the criteria affect the output clustered scenarios.

An aggregated matrix (A2) is implemented where all the criteria have equal weights. Therefore, all of them will have a weight of 0.25. Table 6 shows part of the aggregated matrix A2. The coefficient between activities A30 and A31 when there is an equal weight of 0.25 to each criterion will be:

$$c^{A}_{30\ 31} = 2 \times 0.25 + 1 \times 0.25 + 3 \times 0.25 + 3 \times 0.25 = 2.25 \qquad (4)$$

Table 6. Aggregated matrix A2

A	A30	A31	A32	A33	A34	A35	A36	A37	A38	A39
A30	3.00	2.25	2.50	1.25	0.75	0.25	0.25	0.25	0.75	1.00
A31	2.25	3.00	2.25	1.25	0.75	0.25	0.25	0.25	0.75	1.00
A32	2.50	2.25	3.00	1.25	0.75	0.25	0.25	0.25	0.75	1.00
A33	1.25	1.25	1.25	3.00	1.00	0.25	0.25	0.50	0.75	1.00
A34	0.75	0.75	0.75	1.00	3.00	1.50	1.50	1.00	0.50	0.50
A35	0.25	0.25	0.25	0.25	1.50	3.00	2.00	1.00	0.00	0.00
A36	0.25	0.25	0.25	0.25	1.50	2.00	3.00	1.00	0.00	0.00
A37	0.25	0.25	0.25	0.50	1.00	1.00	1.00	3.00	0.25	0.25
A38	0.75	0.75	0.75	0.75	0.50	0.00	0.00	0.25	3.00	1.75

A39	1.00	1.00	1.00	1.00	0.50	0.00	0.00	0.25	1.75	3.00

The output of the aggregated matrix A2 differs from the aggregated matrix A that has been done before. This will result in having different clustering scenarios using the same clustering techniques and the same number of clusters.

IV.6. Clustering the aggregated matrix

The next step is to cluster the list of elements based on the aggregated DSM (figure 21). The input for this phase is the aggregated matrix A that was formed in the previous step. Several alternative clustering techniques could be used, with no full possibility to discriminate them a priori. As a consequence, the method proposes to implement and compare two different families of clustering techniques, to let industrial decision-makers the opportunity to select the more appropriate clustering results depending on each case study. Thus, the method will build several scenarios of clustering, to support decision-makers in choosing the scenario that suits their industrial context.

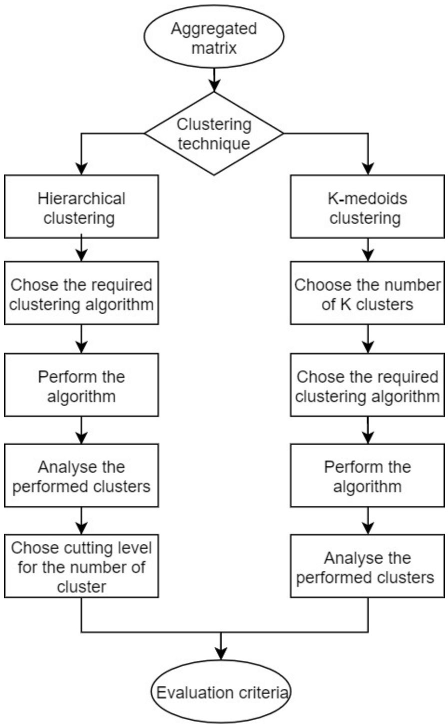


Figure 21. Clustering steps

There are two principles for forming the clusters:

- Overlapping clusters in which clusters can share some elements
- Non-overlapping where each element is assigned to a single cluster

The non-overlapping cluster is the chosen type for our method as we do not need two clusters to have a common element together. Each element has to be assigned to just one cluster.

To run the following clustering techniques on our matrix, it needs to be changed to a distance matrix. The distance matrix is a matrix that contains the distances between the elements of a set. So the similarity index that is done between elements will be considered as distance between those two elements that can be readable for the clustering techniques.

In partitioning clustering, the concept of similarity is derived by the closeness of data points (elements) to the centroid of the clusters. Several algorithms are under the category of partitioning clustering technique including Partition around medoids (PAM) algorithm that is proposed to find an arrangement of objects that are called medoids and they are located centrally in clusters. PAM is considered as a representative of k-medoids clustering technique.

Partitioning Around Medoids (PAM) is the most common algorithm of *k*-medoids. Medoids represents a set of clusters where the average dissimilarity for all the objects in the cluster is reduced. It is close to the notion of mean or centroids. It consists of 3 main steps: First, the number of clusters (K) expected as the output of the method is chosen. Then *k*-medoids are chosen randomly in the dataset to be the initial medoid. Then, all the elements are assigned to the closest medoid among the ones forming the required number of clusters. Then the medoid is recalculated by computing the mean of the datasets in each of them. This is repeated until there is no more change in the medoid (Velmurugan and Santhanam. 2010).

In the case of hierarchical clustering, the concept of similarity is based on how near the data points (elements) are to each other in the data space. The closer data points have more similarities than the data points lying further away. Agglomerative clustering was chosen for the hierarchical clustering technique. It is the method where the clusters are read from bottom to top. This approach will allow the program to read the sub-component first then moves to the parent. It builds the clusters in a hierarchical structure. It starts by making each element has its own cluster. The distance between the elements is calculated and the two elements with the smallest distance will form a new cluster. This is calculated using the ward’s method where the value of this new cluster is calculated using the Euclidian distance between those two elements. The process is repeated until all the elements are clustered together to form one big cluster. A dendrogram is used to visualize the plot diagram of the output of the hierarchical clustering. There can be different scenarios for the output clusters based on the cutting level of the dendrogram. The higher the cutting level the lower is the cluster number.

Applying different algorithms (or techniques) along with different aggregated matrices will lead to several clustering alternative scenarios and outputs. As mentioned in figure 21, this leads to a step of output comparison, in order to choose the scenario suited for each specific industrial case. The indicators used for this comparison step are presented in the next section IV.7

Illustration. Figure 22 shows the dendrogram output that is resulted from the hierarchical clustering of the 72 activities of our illustrative example. While observing the dendrogram output, there can be several different scenarios for the quality level of the clustering based on the cutting level of the dendrogram. For the k-medoids technique, PAM algorithm is used to implement the k-medoids clustering technique. The number of clusters has to be defined before implementing the algorithm. Several methods are used to indicate the optimum number of clusters are presented for k-medoids clustering techniques. And they are used to help in deciding the number of clusters. One of them will be discussed and used in the later section.

For the illustrative case, 10 clusters and 14 clusters can be studied for both clustering

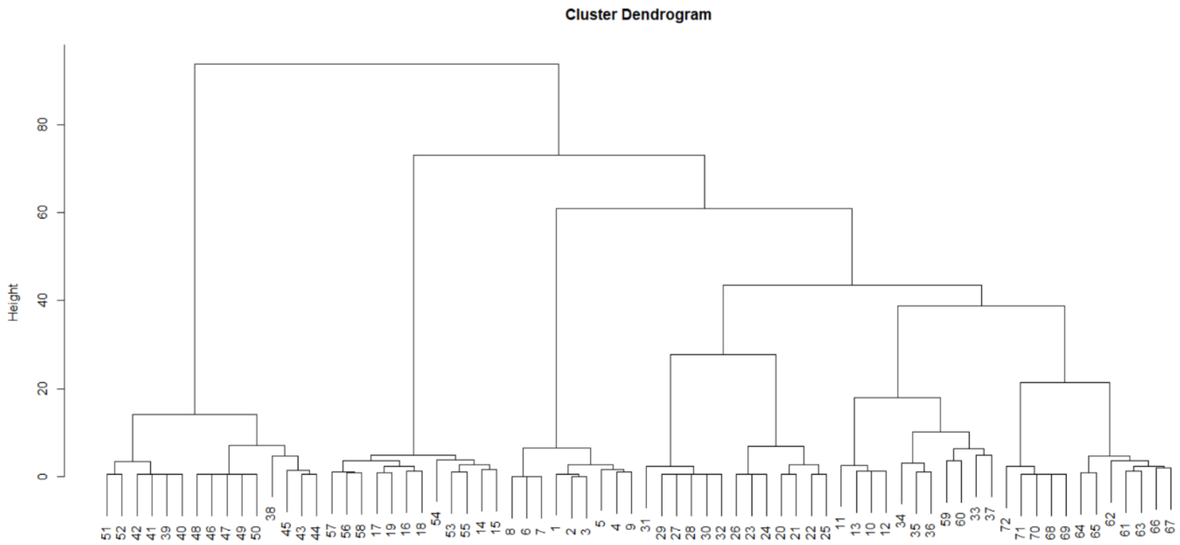


Figure 22. Dendrogram output

techniques and can also be used for the comparison. Those numbers of clusters will be the inputs for both hierarchical and k-medoids techniques for deciding the quality level of clusterings. Normally we would compare just two scenarios, the optimal number of clusters for hierarchical (10) and the optimal number of clusters for k-medoids (14). We decided to add more scenarios to illustrate our approach and also illustrate the usage of the indicators to discriminate between different cluster scenarios.

Figure 23 shows the dendrogram of the hierarchical clustering with 14 clusters as an example. Figure 24 shows the output of k-medoids with 14 clusters.

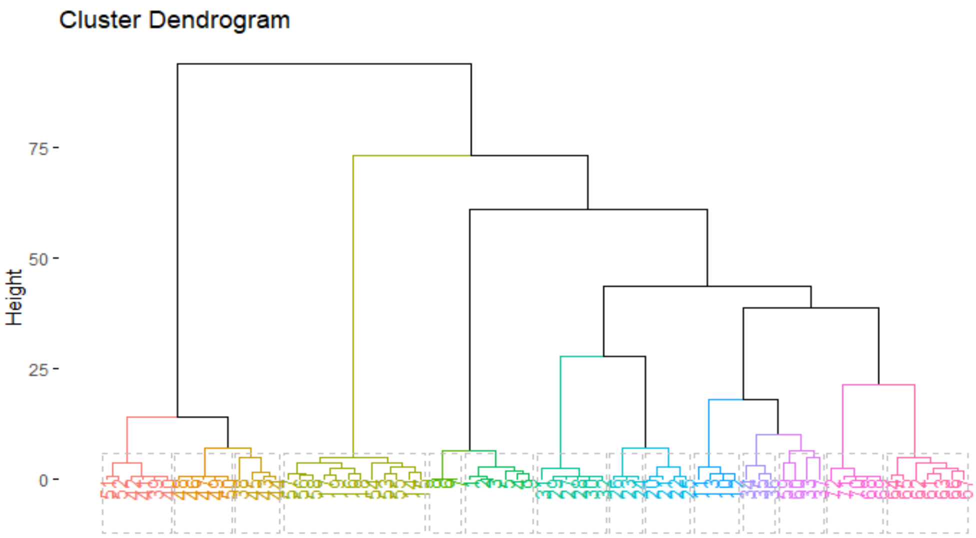


Figure 23. Dendrogram with 14 clusters

In figure 24, Dim1 and Dim2 are the two dimensions to show the variation of the data. Since our clustering has more than two dimensions, so to get a nice plot it is needed to be decreased to two dimensions. A Principle Component Analysis (PCA) is done and it projected the data onto the first two principal components. Those should be the two dimensions that show the most variation in the data. The 26.7% means that the first principle component accounts for 26.7% of the variation. The second principle component accounts for 17.2% of the variation.

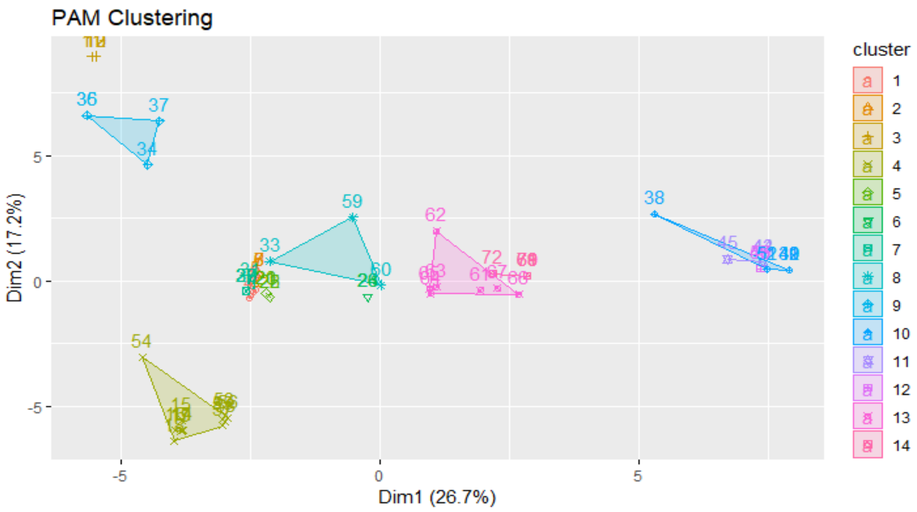


Figure 24. k-medoids with 14 clusters

Several parameters can be the reasons to have the possibilities of alternative clustering scenarios: Because of the different parameters of clustering (number of clusters and the clustering algorithm) and because there could be alternative expert options in the similarity weights as we saw in having two different aggregated matrix by assigning two different weights for each of the criteria. To illustrate the clustering evaluation of the next step, we will have two main scenarios that will be implemented using both clustering techniques. Therefore, to illustrate the example two scenarios from each of the clustering techniques were chosen so we have chosen the optimal number of clusters for each one and also the same number of clusters for the other techniques. So there will be a total of 4 clusterings scenarios in our illustrative example as follows:

- Scenario 1 (S1): 10 clusters with hierarchical clustering.
- Scenario 2 (S2): 10 clusters with *k*-medoids clustering.
- Scenario 3 (S3): 14 clusters with hierarchical clustering.
- Scenario 4 (S4): 14 clusters with *k*-medoids clustering.

Two clustering techniques with two different outputs were the output of clustering the aggregated matrix. Activities were assigned to a set of clusters based on two algorithms either the ward's method algorithm (based on the agglomerative hierarchical technique) where the distance between the elements is calculated and the two elements with the smallest distance will form a new cluster. The value of this new cluster is calculated using the Euclidian distance between those two elements. The other one is the PAM algorithm (based on the partitioning technique). Table 7 shows the 4 clustering scenarios and the elements (in our case, the activities) in each of the clusters.

Table 7. Clustering scenarios (A1)

Clusters	**S1**	**S2**	**S3**	**S4**
C1	A1,A2,A3,A4, A5,A6,A7,A8, A9	A1,A2,A3,A4,A5,A6,A7,A8,A9	A1,A2,A3,A4,A5, A9	A1,A2,A3,A4,A9
C2	A10,A11,A12, A13	A10,A11,A12,A13	A6,A7,A8	A5,A6,A7,A8
C3	A14,15,A16,A17,A18,A19, A53,A54,A55, A56, A57,A58	A14,15,A16,A17,A18,A19,A53, A54,A55,A56, A57,A58	A10,A11,A12,A13	A10,A11,A12,A13
C4	A20,A21,A22, A23,A24,A25, A26	A20,A21,A22,A23,A24,A25,A26	A14,A15,A16,A17,A18,A19,A53,A54,A55,A56,A57, A58	A14,A15,A16,A17,A18,A19,A53,A54,A55,A56,A57, A58
C5	A27,A28,A29, A30,A31,A32	A27,A28,A29,A30,A31,A32	A20,A21,A22,A25	A20,A21,A22,A25
C6	A33,A34,A35, A36,A37,A59, A60	A34,A35,A36,A37	A23,A24,A26	A23,A24,A26
C7	A38,A43,A44, A45,A46,A47, A48,A49,A50	A43,A44,A45,A46,A47,A48,A49,A50	A27,A28,A29,A30,A31,A32	A27,A28,A29,A30,A31,A32
C8	A39,A40,A41, A42,A51,A52	A38,A39,A40,A41,A42,A51,A52	A33,A37,A59,A60	A33,A59,A60
C9	A61,A62,A63, A64,A65,A66, A67	A59,A60,A61,A62,A63,A64,A65,A66,A67	A34,A35,A36	A34,A35,A36,A37
C10	A68,A69,A70, A71,A72	A68,A69,A70,A71,A72	A38,A43,A44,A45	A38,A39,A40,A41,A42,A51,A52
C11			A39,A40,A41,A42,A51,A52	A43,A44,A45
C12			A46,A47,A48,A49,A50	A46,A47,A48,A49,A50
C13			A61,A62,A63,A64,A65,A66,A67	A61,A62,A63,A64,A65,A66,A67

C14			A68,A69,A70,A71,A72	A68,A69,A70,A71,A72

It can be observed that some clusters have strong interdependency between each other as they are repeated together through several scenarios (e.g. A10, A11, A12, and A13), therefore they can be considered as good candidates to form modules. This could direct the decision-makers into some preliminary decisions on what elements, products, and/or services to put together. The comparison between these 4 scenarios is further developed below.

For the second scenario of aggregated matrix A2, table 8 shows the list of scenarios that were done.

Table 8. Clustering scenarios for aggregated matrix A2

Clusters	S1	S2	S3	S4
C1	A1,A2,A3,A4, A5,A6,A7,A8, A9	A1,A2,A3,A4,15,A6,A7,A8,A9	A1,A2,A3,A4,A9	A1,A2,A3,A4,A9
C2	A10,A11,A12, A13	A10,A11,A12,A13,A35,A36,A37	A5,A6,A7,A8	A5,A6,A7,A8
C3	A14,15,A16,A17,A18,A19, A53,A55,A56, A57,A58	A14,15,A16,A17,A18,A19,A53, A55,A56, A57,A58	A10,A11,A12,A13	A10,A11,A12,A13
C4	A20,A21,A22, A23,A24,A25, A26	A20,A21,A22,A23,A24,A25,A26,A33	A14,A15,A16,A17,A18,A19,A53,A55,A56,A57,A58	A14,A15,A16,A17,A18,A19,A53,A55,A56,A57,A58
C5	A27,A28,A29, A30,A31,A32	A27,A28,A29,A30,A31,A32	A20,A21,A22,A25	A20,A21,A22,A25,A33
C6	A33,A38,A61, A63,A64,A65, A66,A67,A68, A69,A70,A71	A34,A54,A59,A62	A23,A24,A26	A23,A24,A26
C7	A34,A35,A36, A37	A38,A43,A44,A45,A46,A47,A48,A49,A50	A27,A28,A29,A30,A31,A32	A27,A28,A29,A30,A31,A32
C8	A39,A40,A41, A42,A51,A52	A39,A40,A41,A42,A51,A52	A33,A38,A60	A33,A59,A60
C9	A43,A44,A45, A46,A47,A48, A49,A50	A60,A61,A62,A63,A64,A65,A66,A67	A34,A35,A36,A37	A34,A35,A36,A37
C10	A54,A59,A62	A68,A69,A70,A71,A72	A39,A40,A41,A42,A51,A52	A39,A40,A41,A42,A51,A52

C11			A43,A44,A45,A46,A47,A48,A49,A50	A38,A43,A44,A45,A46,A47,A48,A49,A50
C12			A54,A59,A62	A54,A59,A62
C13			A61,A63,A64,A65,A66,A67	A61,A63,A64,A65,A66,A67
C14			A68,A69,A70,A71,A72	A68,A69,A70,A71,A72

Some clusters like clusters (1, 2, 4, 5, and 8) don't change and remain the same even with changing the weight of the criteria. We can distinguish that the elements (in our case activities) of those clusters have strong similarity indices between each other for all the criteria. Other clusters such as 3, 6, 7, 9 have a different formation of clusters when we change the weight of the criteria. Therefore the weight of the criteria influences the output of the clustering.

IV.7. Clustering evaluation.

After performing the clustering procedure, comparing the quality of the formed clusters is the next step. More than one index can be used to measure the quality of the clustering and thus the modularity. Our thesis is focusing on indices that can measure how well each element is placed in its own cluster. And to what degree is it different from other clusters? Upon having this information, several indicators can be used to evaluate the scenarios and to help the experts chose the best case scenarios from this point of view (Ezzat et al. 2020).

The proposed method relies on the following index, namely clustering consistency. After identifying the consistency of clustering for each scenario, four indicators are followed to discriminate between the scenarios.

Consistency of clustering: it measures how consistent each element is to its own cluster. It relies on the concept of the silhouette method, i.e. how similar is an element to its own cluster compared to other clusters. The values of consistency range from -1 to 1 where higher values indicate that the element is well matched to its own cluster and poorly matched to the other clusters. If the value of the silhouette index of an element is 0 so the cluster consists of just one element. If most of the elements in one cluster have a high value of consistency then the configuration of that cluster is appropriate. The Eqs (5-7) explain the silhouette index s(i) for a given element.

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}, if\ |C_i| > 1 \quad (5)$$

$$a(i) = \frac{1}{|C_i| - 1} \sum_{j \in C_i, i \neq j} d(i,j) \quad (6)$$

$$b(i) = \min_{k \neq i} \frac{1}{|C_k|} \sum_{j \in C_k} d(i,j) \tag{7}$$

Where a(i) is the average distance between i and all the other points in the same cluster. It can be defined as how well i is assigned to its cluster. d(i, j) is the distance between data points i and j in cluster Ci. $|C_i|$ - 1 it is because d(i,i) is not included. b(i) is the smallest average distance of i to all points in other clusters which the point i is not included.

Additionally, when many elements have a low or negative value of silhouette index, then the formed cluster is not appropriate.

To address this concern, the decision-makers can decide to remove the negative elements from the cluster or create a new cluster with different elements.

After measuring the consistency index of the clustering output, several indicators are needed to be able to compare and discriminate this output with other output scenarios. The consistency index visualizes the consistency of each of the clustering. To be able to differentiate and to compare the scenarios, some indicators are needed to show with numbers the differences between each of the scenarios. There are 4 main indicators to be used here:

(A) The optimum number of clusters: It shows the best number of clusters. It calculates the average silhouette index of all the elements for different values of K clusters. The higher the average index, the more consistent are the elements in the clusters. As shown in figures 25 and 26, the optimal number is 10 for figure 25 that is the hierarchical clustering and 14 for figure 26 that is for K-medoids. In figure 25 we can observe that 8, 9, 11, and 12 can be checked and tested in the scenario as well as their silhouette index which doesn’t differ so much compared to the value of the optimum number of clusters (which is 10). In figure 26, scenarios with 10, 12, and 13 clusters can be checked and tested as well since their silhouette index does not differ so much compared to the value of the optimum number of clusters (which is 14). So we can have several clustering scenarios that have good potential to be good clusters and can be tested later.

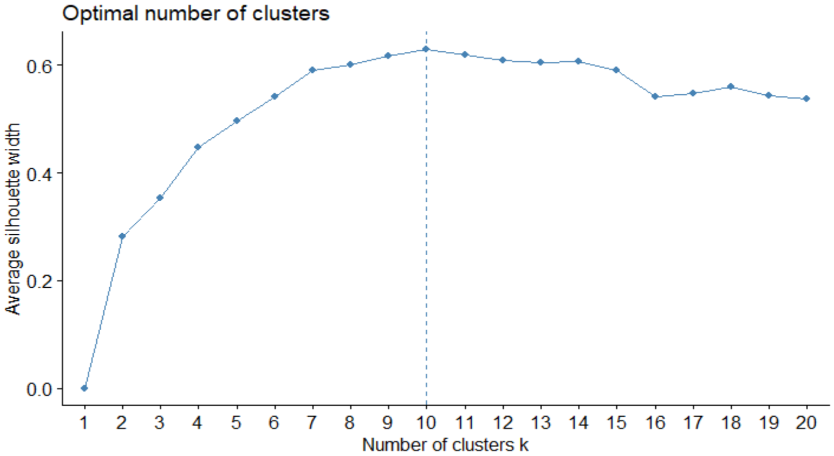


Figure 25. Optimal number of clusters for Hierarchical

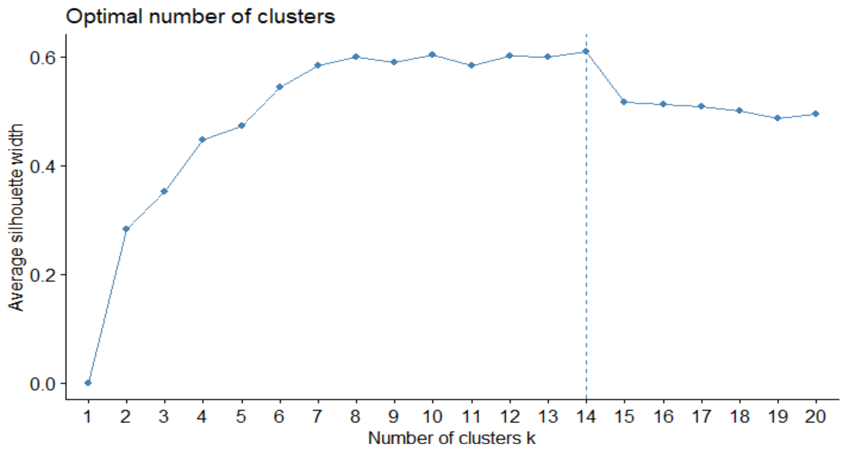


Figure 26. Optimal number of clusters for PAM (k-medoids)

(B) The number of elements under the average index: It measures the number of elements that are below the average index of consistency. Shown in figure 27, is an example of the number of elements under the average index. It can be observed here that there is a total of 4 elements that are under the average index in 4 cluster output scenarios. That means that experts can take into consideration that those 4 elements do not lie within a good cluster. And then it is up to the experts to put them in a different cluster or make each one form its own cluster. A zero silhouette index means that the element is part of a single element cluster.

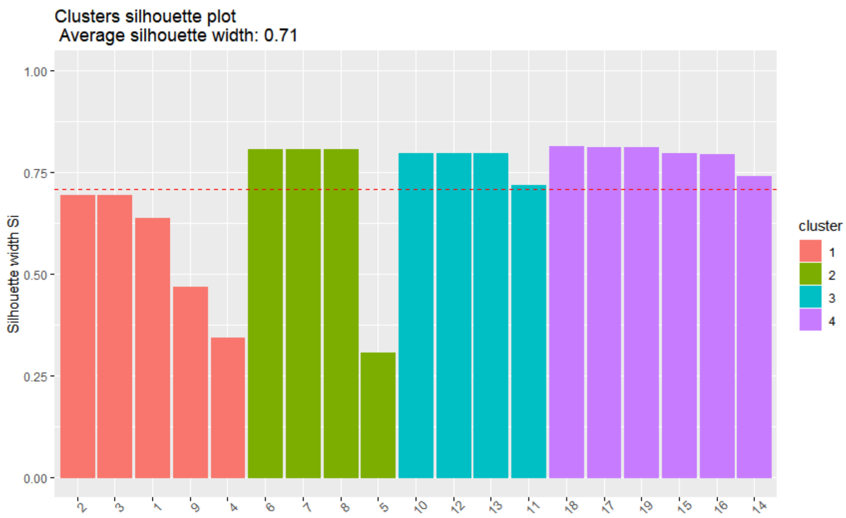


Figure 27. Consistency of clustering

(C) The percentage of clusters not applicable: It measures the percentage of clusters that are not applicable for each output scenario by observing the clusters where most of its elements are under the average index of consistency. The scenario with a lower number will be preferred. Shown in figure 27, an example of the number of elements under the average index. It can be observed here that there is 1 cluster that is totally under the average index, hence it is not applicable for forming an output cluster.

(D) The number of clusters formed: It measures the number of applicable clusters that are created and will be used to build up the modules. It refers to the degree of complexity of the system and also the variety level of the offering. This is measured by deducting the inapplicable number of clusters that each element can form its own cluster or some elements from one cluster and some not. It can be decided based on the decision of the experts. Some elements form clusters with themselves that have an average index equal to 0. Those elements are not counted as formed clusters. In figure 27 it can be distinguished that the applicable number of clusters is 3 since there is one non-applicable cluster.

Figures 28-31 report on the consistency measure of the four scenarios that were chosen in the above step: (S1) hierarchical clustering with 10 clusters (28), (S3) hierarchical clustering with 14 clusters (29), (S2) PAM algorithm with 10 clusters (30) and (S4) PAM algorithm with 14 clusters (31) using the silhouette measure with the different number of clusters. The dotted line shows the average silhouette index for all the elements. The bars refer to the silhouette index for each of the elements within the clusters. The bars that are under 0 silhouette index generally indicates that a sample has been assigned to the wrong cluster.

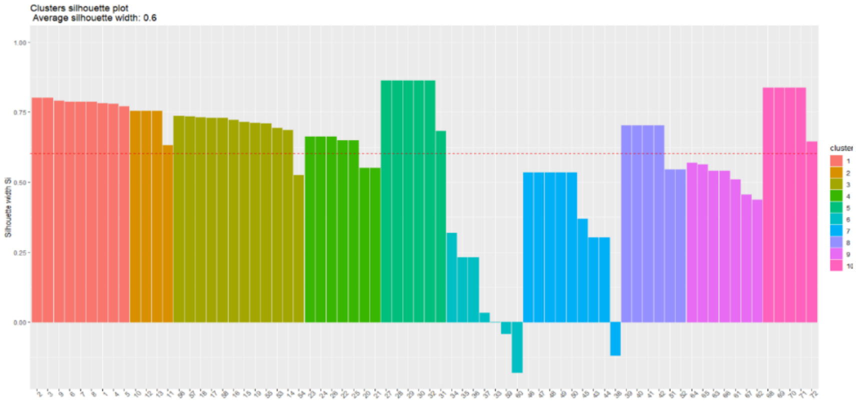


Figure 28. Consistency of hierarchical clustering (10 clusters)

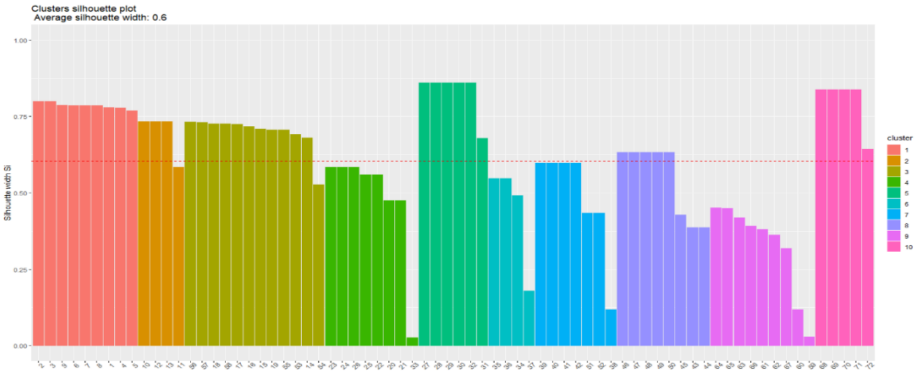


Figure 29. Consistency of PAM clustering (10 clusters)

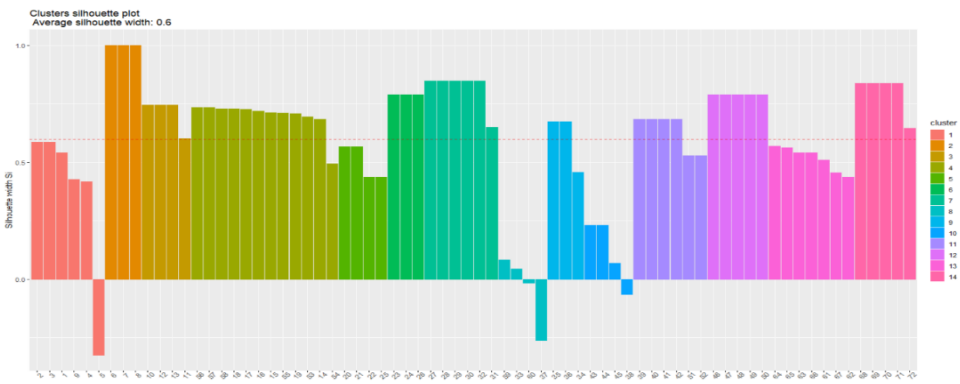


Figure 30. Consistency of hierarchical clustering (14 clusters)

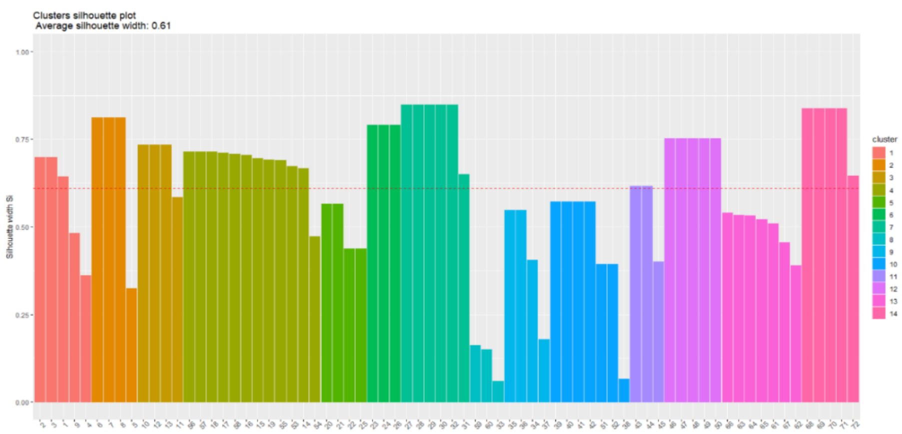


Figure 32. Consistency of PAM clustering (14 clusters)

Figure 32 reports on the indicators evaluating the four clustering scenarios. Figure 32a shows the number of elements under the average index (Indicator B). Indicator C is related to the percentage of non-applicable clusters (figure 32b). Indicator D is related to the number of applicable clusters formed (figure 32c). Each cluster generally includes one or more elements (in our case here activities).

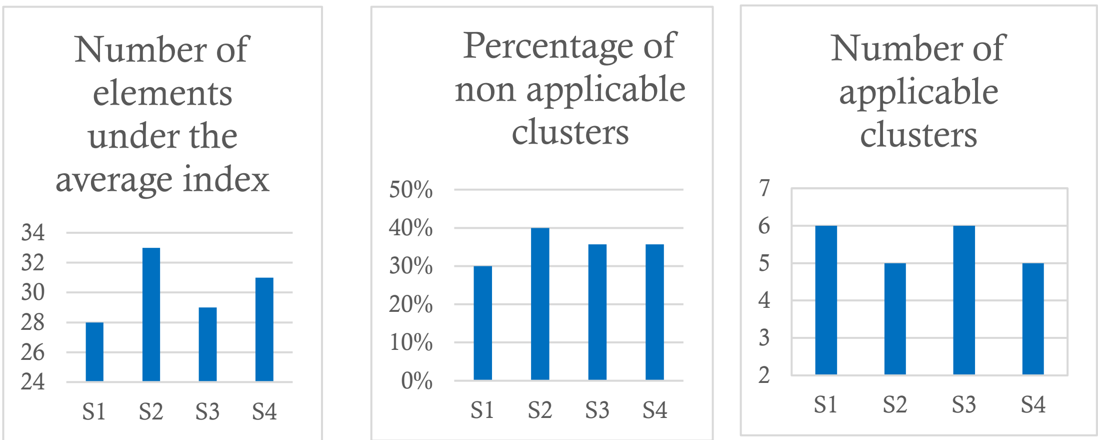


Figure 31. (a) indicator B ; (b) Indicator C ; (c) Indicator D

It can be observed that S1 followed by S3 have the least number of elements under the average index of the silhouette measurement with 28 and 29 respectively. S2 has the highest number (33) of elements under the average index and S4 is considered the second highest with a number of 31 elements under the average index. Regarding the non-applicable clusters indicator, S1 is the best case scenario with only 3 non-applicable clusters out of 10 clusters giving it a percentage of applicable clusters equal to 30%. S3 and S4 are followed by S1 both having 5 out of 14 clusters as non-applicable clusters giving it a percentage equal to 36%. S2 represents the worst case scenarios with 4 non-applicable clusters out of 10 clusters giving it a percentage equals to 30%. The last indicator shows that S2 has the least percentage of applicable clusters with 60% and S1 has the highest percentage of applicable clusters with 70%.

Based on the above S1 can be assumed to be the best scenario based on the cluster quality. This provides decision-makers with a first insight into how to organize the products and services considering the recommendation resulting from the method. The first cluster of S1 is related to activities that are done to prepare the shipment for delivery and create a shipment number. They are done in every variant of the service transport booking. It makes sense to address it as one module instead of addressing it with several activities as it can help in faster design and in more agility against requirement changes.

IV.8. Conclusion

This chapter proposes a method for modularizing service-oriented systems, consisting of products and or services. The method aids in identifying and visualizing similarity indices among the elements that are needed to be modularized according to several predefined criteria. Two different clustering techniques (hierarchical and partitioning) were implemented in the method to highlight the difference in the clustering outputs which prove to be useful. For the industrial application, it is recommended to apply both algorithms with the necessity to compare the results any time they would like to use the method. This can help in deciding which scenario will be suitable for them as sometimes hierarchical clustering will have better output than the k-medoids and sometimes k-medoids will have better output.

Evaluation indicators are proposed to support the comparison of different clustering scenarios to form the output modules.

The method was illustrated with an illustrative example to highlight, step by step, the application procedure. This underlines its applicability. With the example, all the potential of the method has been exploited: it will be further developed with an extended case study in chapter 6.

The method helps in identifying the similarity relationship between products and services according to different predefined criteria and different clustering techniques, resulting in different cluster alternatives. The method also helps in identifying a comparison between different clustering scenarios in terms of the consistency and the quality of the clustering. This is not sufficient since it does not put into consideration the performance of the company and what is the effect of each modularity scenario on the performance of the enterprise. That is why a complementary comparative approach based on the performance evaluation is needed. That is what we talk about in the next chapter of our thesis.

Chapter V. MODULARITY IMPACT ON INDUSTRIAL PERFORMANCE

V.1. Introduction

According to the literature review that was addressed in chapter 2, product modularity is potentially beneficial when dealing with complex products. It limits the interaction between the system components or system functions. It answers the objective to decrease the cycling time that occurs in a production or design process. It also decreases the development cycle to reach the shorter product's life cycle with lower development costs (Baldwin and Clark 2000).

(Lin et al. 2010) discussed a reduction in the complexity of service and an upsurge in the responsiveness to offer a variety of services. Implementing the modularity logic to the design process is considered to be a cost-effective and also a flexible way to build up new services of process. The literature review gave us a conclusion that modularity has a potentially positive impact on the performances of the company but this still needs to be measured to be able to differentiate/prioritize improvement scenarios.

The implementation of modularity on service-oriented systems in our method resulted in several alternative clustering scenarios that still need to be evaluated to find the most appropriate scenario in terms of impacts on the performances of the company.

This chapter evaluates the performance impacts of modularity scenarios referring to several performance dimensions and a set of complementary indicators. This will help in finding the most appropriate scenario based on the industrial context of each industrial case. This part of the method will constitute a pertinent set of indicators and configure a performance assessment method supporting a rigorous analysis of modularity impacts. The method in this chapter will be illustrated by the case study used to explain the method which was introduced in section 3 chapter III.

V.2. Procedure to measure modularity impacts on industrial performance

This section presents the proposed procedure to measure the impact of modularity on a service-oriented production system. It demonstrates in detail the last three phases of the method that were defined in the third chapter. The method consists of four main steps shown in figure 33. The method starts with translating the output clustering scenarios into a set of processes, defining the needed evaluation model with the needed elements, defining the operational measurement needed to measure the processes and lastly ranking the alternative clustering scenarios. The method is general enough to allow for adaptation to industrial contexts based on inputs from decision-makers. The objective is to support the decision-makers in choosing the most pertinent clustering scenario based on its impact on industrial performances.

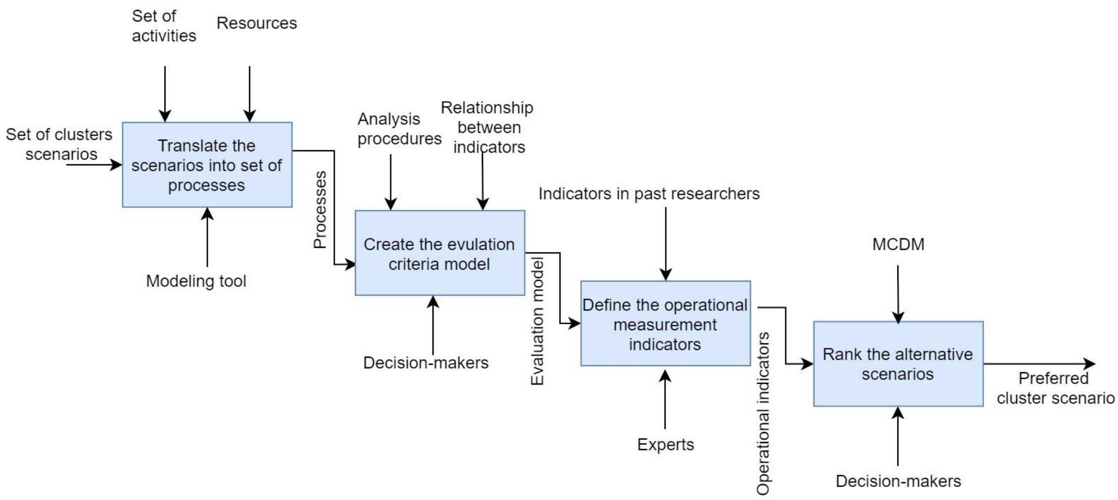


Figure 33. Measuring modularity impact procedure

V.3. Translating the clustering scenarios into processes

The first step is to translate the alternative clustering scenarios resulting from modularity implementation on the product and service elements. This first step requires the experts to have direct access to the knowledge of the industrial processes for the product and service offers that are important for the clustering scenarios. Those clustering scenarios are translated into a set of processes, supporting products and services production and delivery for the final solution. It is thus necessary to define the set of resources and activities required to implement these production and delivery processes. Figure 34 illustrates the transition from clusters to processes and then from processes to the final solution offer. The figure illustrates how clusters of one scenario are translated into a process with a set of activities. i identifies the total number of clusters, j identifies the total number of activities and n identifies the total number of solutions. Each cluster will have its own process that consists of a set of activities with the resources that are required to deliver and process this cluster. The assembled set of clusters identify the final solution offers that are delivered to the customers.

In order to visualize and analyze the set of processes with the needed activities and resources, a modeling tool is needed. There are several modeling techniques and tools that can be used to translate the clustering scenarios into sets of processes. One of those tools and techniques is the Business Process Model and Notation (BPMN).

BPMN is considered as a standard business process modeling that provides a graphical notation to specify business processes based on a flowcharting technique that follows the same logic to activity diagrams from Unified Modeling Language (UML). The original aim of BPMN is to offer a notation that is quickly understandable to all business users starting from the business analysts who generate the initial plan of the business processes to the business

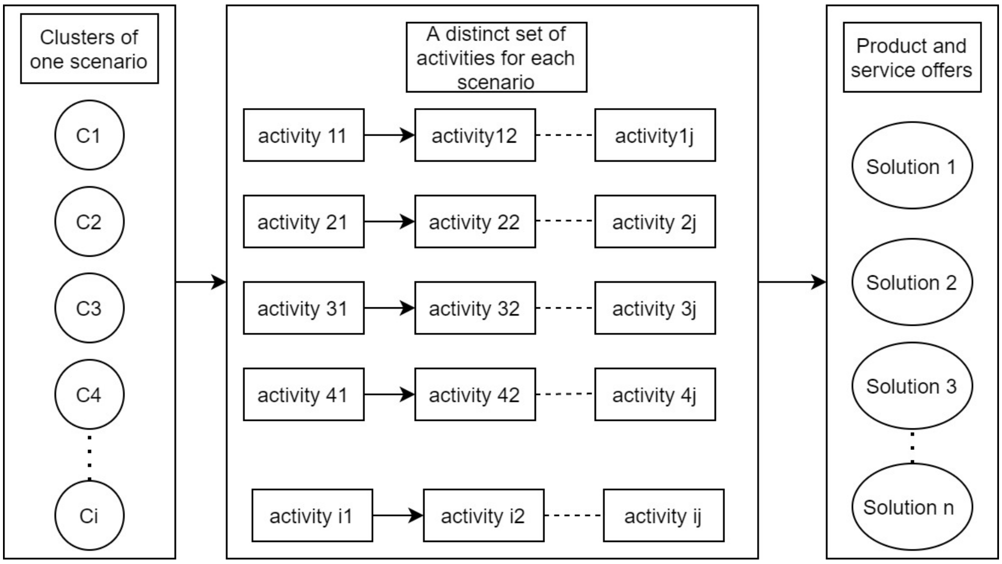


Figure 34. Principle schematic diagram

people who will observe and manage those business processes. BPMN also a notation understandable by different kinds of process modelers and users such as process analysts, process implementers, or business users (White 2004).

BPMN 2.0 will be used in our method to visualize the processes. BPMN 2.0 is the most recent version of the BPMN standard and it is established by the Object Management Group (OMG) to create a unified modeling language that is clear to all business user types. It connects the divergence between business process design and implementation. BPMN 2.0 is simple to understand as it represents the structure and the responsibilities of the organization using the concept of pools and lanes. Activities, gateway and events symbols are designed in logical classes to make it easy to be learned (Allweyer 2016).

Illustration. Each clustering scenario will have its own set of BPMN processes that will be different from other clustering scenarios because of the difference in the structure of clusters. Let's illustrate this step with the case study. We have a total of 4 clustering scenarios that will undergo the evaluation procedures (section 6 in chapter IV). We will take scenarios 1 and scenario 3 as an example to illustrate the BPMN process for cluster 1 for each of the scenarios.

Table 6 in the previous chapter(4) showed 4 different scenarios of formed clusters of our illustrative example. Those were the output clusters that were formed after implementing both hierarchical and partitioning clustering. Cluster 1 in scenario 1 has activities A1, A2, A3, A4, A5, A6, A7, A8, A9 that form one cluster. So those activities will be translated into a BPMN model to form the first cluster. However, cluster 1 of scenario 3 has activities A1, A2, A3, A4, A5, A9. So its BPMN formation model will be different from scenario cluster 1 of scenario 1. Figures 35 and 36 show the BPMN processes for both clusters of both scenarios. These differences occur due to the differences in the clustering formation for each scenario resulting from the strength of the assigned similarity indices among activities that were assigned by the experts. And also due to the usage of different clustering techniques.

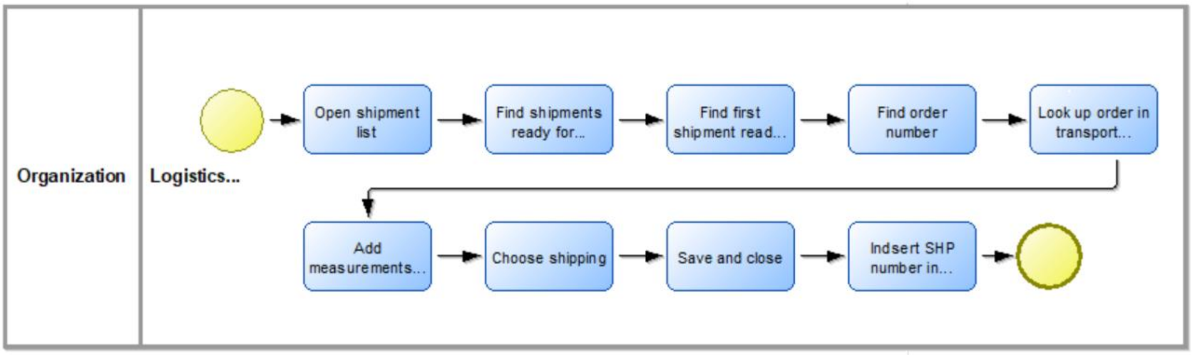


Figure 35. BPMN model of Cluster 1 of scenario 1

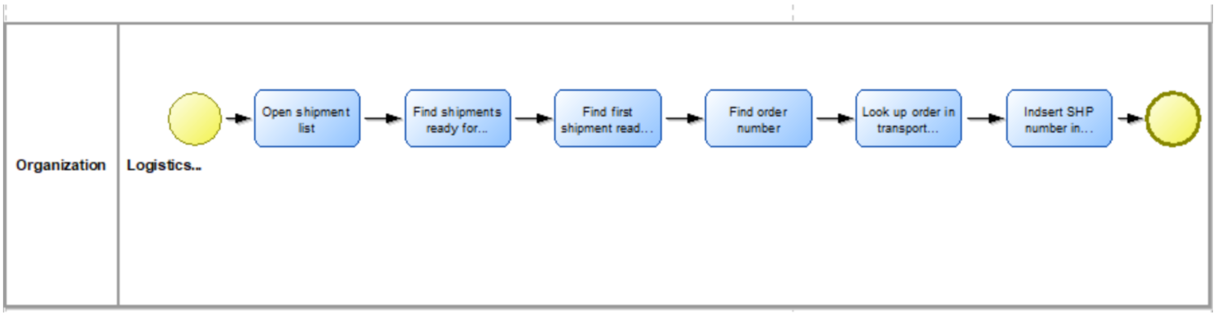


Figure 36. BPMN model of Cluster 1 of scenario 3

V.4. Define evaluation criteria model

Creating the evaluation criteria model is the next step for our method procedure to evaluate the industrial performance of alternative clustering scenarios. The model shows the hierarchy and the relationship between the different dimensions of the indicators. Figure 37 shows the hierarchical model of the evaluation criteria showing all the dimensions of different indicators.

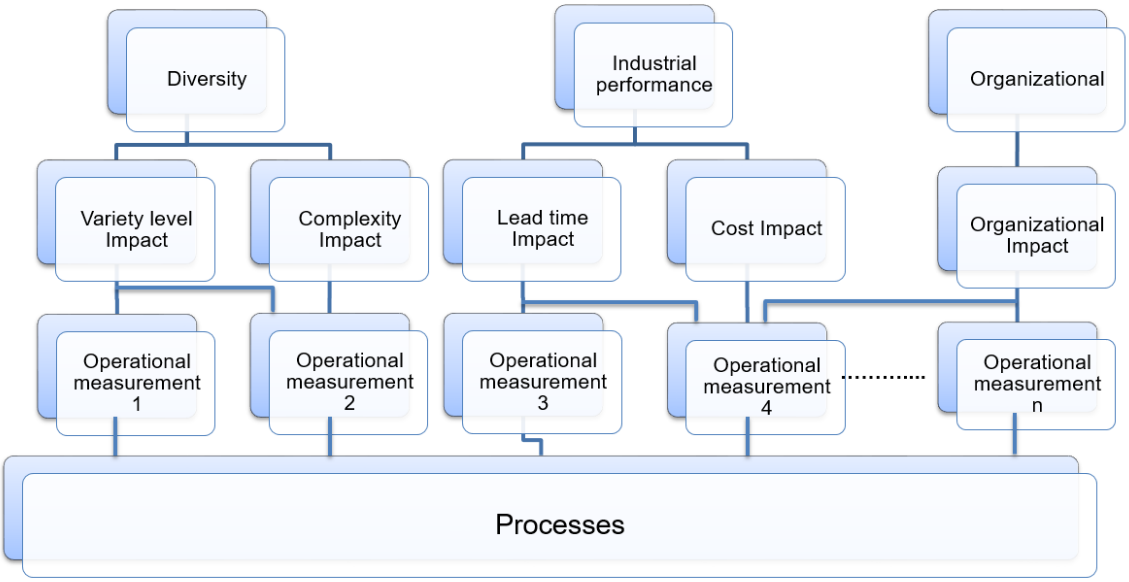


Figure 37. Evaluation criteria model

The evaluation criteria model is structured according to perspectives, impacts, and operational measurements.

Three main perspective criteria are defined as follows

- Organizational perspective: focuses on organizational changes and the impact on the organization.
- Industrial performance perspective: focuses on industrial performance impact on an enterprise.
- Diversity perspective: focuses on the diversity of offers that impact an enterprise.

The three perspectives were identified to be suitable for the case study we are using in our method. There can be more than three perspectives as the evaluation criteria model is considered flexibly and can be modified for each industrial context. For our method, those three perspectives were suitable to identify the differences between the alternative scenarios as we focus on diversity, industrial performance and organizational dimensions.

Impact criteria involve variety level, complexity, organizational change, cost and time. Those impact criteria influence the set of perspectives. Variety level and complexity influence diversity, cost and time influence industrial performance and organization influence the organization perspective. The identified impacts were the result of the literature analysis of measuring the impact of modularity on the performance of the enterprise. The five impacts are the criteria that we would like to evaluate the scenarios in our method. Like the perspective, they are also flexible and can be modified based on the industrial context.

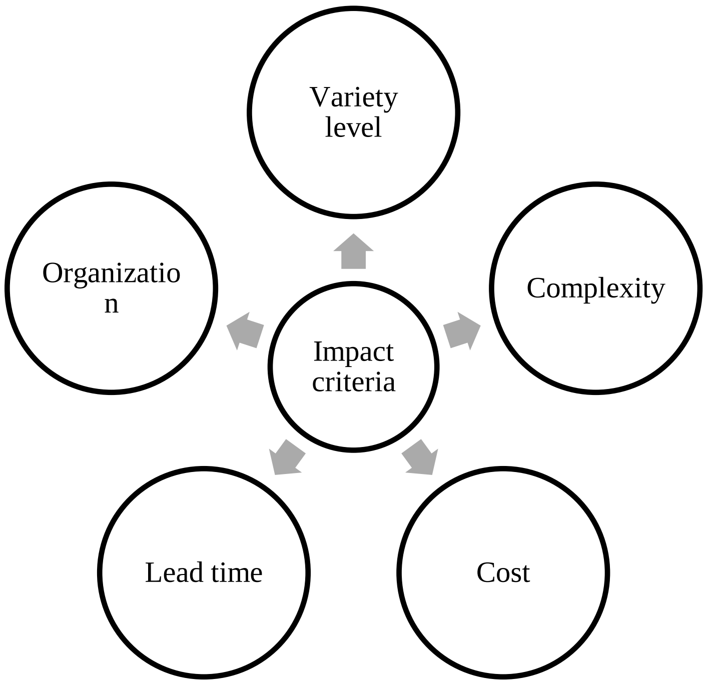


Figure 38. Impact criteria

A set of generic re-usable impact criteria has been identified as candidates for this step. The impact criteria are important to define the area of performance where we can measure the impact of each of the alternative scenarios. They are defined as follows (figure 38):

Complexity impact: evaluates the impact of each clustering scenarios on process complexity. The more complex the process is, the less pertinent will be the scenario for the decision-makers.

Variety level impact: evaluates the impact of each clustering scenarios on the variety level. The higher the level of a variety of the scenario is, the more pertinent will be the scenario for decision-makers.

Lead time impact: evaluates the impact of each clustering scenarios on the lead time of the process. A lower lead time corresponds to a better scenario.

Cost impact: evaluates the impact of each clustering scenarios on the cost of the process. A lower-cost corresponds to a better scenario.

Organizational impact: evaluates the impact of each clustering scenarios on the interaction between the organization (different human resources). The less interaction between different resources each scenario has, the more pertinent will be the scenario for decision-makers.

The operational measurements are required to have an ease of implementation on the BPMN process model. They also need to have easy access and understanding for the experts and decision-makers. Each operational measurement has to influence at least one impact (can influence more than one impact, for example, one operational measurement can have an influence on both cost and lead time)

V.5. Define the operational measurement indicators

The next step in the method is to define the operational measurement indicators required to assess the criteria. They can be either quantitative indicators or qualitative ones. In our proposal below all operational measurement indicators are quantitative, to show the compute numerically all the data, making then easier discriminating among the different clustering scenarios. Table 9 summarizes the operational measurement indicators with their definition, the criteria concerned by each indicator, and some scientific references.

Table 9. Operational measurement indicators

Measurement concept	Symbol	The approach to measuring it	Impact Criteria concerned by an indicator’	Relevant works
Number of activities	I1	Measures the number of activities in the process	• Complexity • Cost	Gonzalez et al. 2010

			• Lead time	
Number of human resources types	I2	Calculates the number of resource types for each process	• Complexity • Cost • Organizational	Gonzalez et al. 2010
Control-flow Complexity Metric (CFC)	I3	Calculates the complexity related to using the gateways in the processes	• Complexity	Cardoso. 2006, Gonzalez et al.2010 and Rolón et al. 2009
Longest path of the process (Diameter)	I4	Measures the longest path between the first and last nodes of a process	• Lead time	González et al. 2012
Percentage of multi-skilled human resources	I5	Measures the percentage of the multi-skilled resources among the total human resource pool for each process	• Complexity • Cost • Lead time • Organizational	Not validated
The flow between activities from a different lane	I6	Calculates the number of sequence flows crossing different lanes of the process	• Complexity	Gonzalez et al. 2006
Number of clusters (modules)	I7	Measures the total number of formed modules for each scenario	• Variety level	Not validated

A total of seven operational measurement indicators have been selected in our method to discriminate between the alternative clustering scenarios. The first operational measurement is the number of activities. It influences the cost, time, and complexity impact as the more the number of activities the more cost, time the scenario will have and more complex the scenario will be.

The second operational measurement is the number of human resource types. It influences the cost and complexity impact as the more the number of human resource types the more cost the scenario will have and the more complex the scenario will be. In the BPMN model, the lanes describe who is executing the set of activities. So the number of human resource types will get the information from the lane. Repeated lanes will not be counted as they will be considered the same human resource type.

The third operational measurement is CFC. It has been defined by (Cardoso 2006) and has been used as a measurement for complexity in the BPMN process in past researches (Cardoso 2006, Gonzales et al.2010 and Rolón et al. 2009). It influences the complexity impact as the larger the metric the more complex is the scenario. The metric is defined with the following equations (8-11):

Equation 8 calculates the metric of CFC. The Control-Flow Complexity metric is mathematically additive. This is done by adding the CFC of all the split constructs. We count the splitting gates and we do not count the merging gates

$$\mathrm{CFC(P)}= \sum_{\mathrm{i} \in \{\mathrm{Xor\text{-}split\ of\ P}\}} \mathrm{CFC_{XOR\text{-}split}(i)} + \sum_{\mathrm{i} \in \{\mathrm{or\text{-}split\ of\ P}\}} \mathrm{CFC_{OR\text{-}split}(i)} + \sum_{\mathrm{i} \in \{\mathrm{AND\text{-}split\ of\ P}\}} \mathrm{CFC_{AND\text{-}split}(i)} \quad (8)$$

XOR-split Control-flow Complexity is defined by the number of situations that are presented with the split (equation 9) where ‘a_i’ is an XOR split activity for XOR_i gateways. i ∊ {1, 2,…m} where m is the total number of XOR gateways. The CFC of the XOR-split is considered as the fan-out of the split. In other words, the number of outputs for each XOR gate. Fan-out is the number of transitions going out of an activity.

$$\mathrm{CFC_{Xor-split}}(\mathrm{a}_i) = \mathrm{fan-out}(\mathrm{a}_i) \quad (9)$$

OR-split Control-flow Complexity is defined by the number of situations that are presented with the split (equation 10). The CFC of the OR-splits is calculated by 2^(n-1), where n is the fan-out of the split. This means that when a designer is building a process he needs to consider 2^{n-1} states that may arise from the execution of an OR-split construct (a_i). i ∊ {1, 2,…m} where m is the total number of OR gateways

$$\mathrm{CFC_{or-split}}(\mathrm{a}_i) = 2^{\mathrm{fan-out}(\mathrm{a}_i)} - 1 \quad (10)$$

In the case of the AND-split, the CFC is considered to be 1(equation 11). One state that arises from the implementation of AND-split is only considered since it is presumed that all the outgoing transitions are being selected. A designer building a process needs only to consider one state that may appear from the implementation of an AND-split construct. It is assumed that all the outgoing transitions are executed and selected. i ∊ {1, 2,…m} where m is the total number of And gateways

$$\mathrm{CFC_{AND-split}}(\mathrm{a}_i) = 1 \quad (11)$$

Figure 39 illustrates the control flow complexity of model P. The result will be as follows:

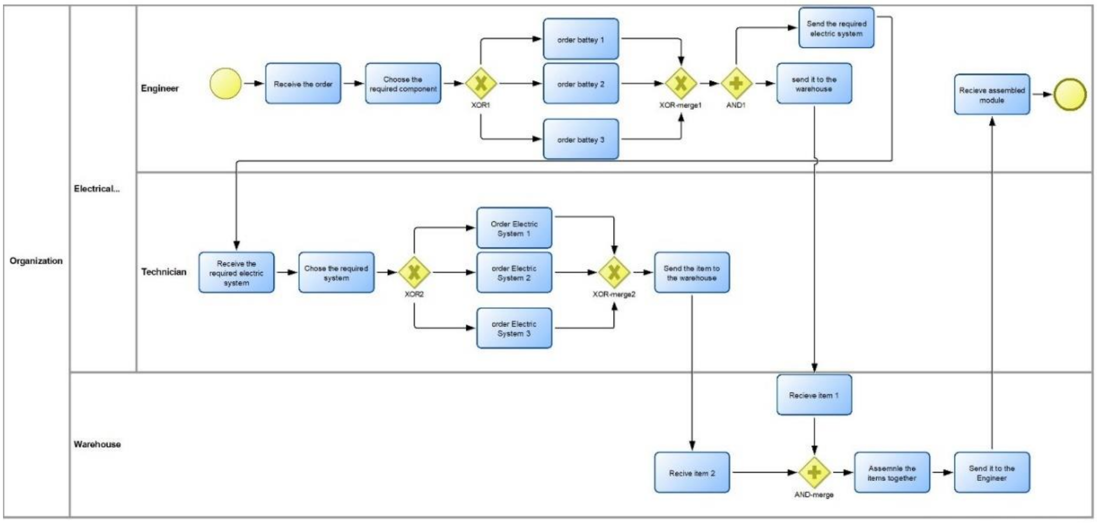


Figure 39. Example of control flow complexity

$CFC_{Xor-split}(\boldsymbol{XOR1}) = 3.$

$CFC_{Xor-split}(\boldsymbol{XOR2}) = 3.$

$CFC_{AND-split}(\boldsymbol{AND1}) = 1.$

$\boldsymbol{CFC}(\boldsymbol{P}) = 7$

The longest path of the process (Diameter) is the fourth operational measurement. (González et al. 2010) defined this indicator to measure the length of the longest path from a start- to an end-node. It influences the time impact as the longer the path of the processes of the scenario the more possibility that the time of the scenario will be increased. It will count all the activities of each cluster for each alternative scenario. We will not put into consideration the splits, so for example if we have XOR split with 3 transactions, we will count only the transaction with the longest number of activities. For AND split, we will count all the transaction splits as they are needed to continue the process. For OR split, we will count the transaction split with the most number of activities.

The fifth measurement indicator is the percentage of multi-skilled human resources. It can influence the complexity and organizational impact. More multi-skilled resources can decrease the complexity of the processes of the scenario as one resource type can do the work of more than two or more resource types. So there will be fewer interactions between different resource types, hence decrease complexity and decrease the organizational impact.

The Flow crossing distinct activity lanes is the sixth measurement indicator. (Rolon et al.2006) discussed this indicator to measure the complexity of the BPMN process. It influences the complexity and organizational impact. The more interaction between different people the more complex will be the scenario and the less favorable impact for the organizational impact.

The last and final measurement indicator is the number of clusters. This is the only operational measurement indicator that is not related to the BPMN process as it is directly related to the alternative clustering scenarios. It influences the variety level impact, as when the number of clusters increases the variety level impact increases. When a company has more input clusters, it may provide more variety of offers to the customers because there will be more options to choose from and integrate them into the final offer.

Illustration. Table 10 shows the operational measurement results of scenarios 1 and 3 of our illustrative example.

Table 10. Operational measurement results

Symbol	Description	S1	S3
I1	Number of activities	71	71
I2	Number of human resources types	2	2
I3	Control-flow complexity	5	4
I4	Longest path of the process (Diameter	69	68
I5	Percentage of multi-skilled human resources	0	0
I6	The flow between activities from a different lane	4	5
I7	Number of clusters (modules)	10	14

V.6. Rank alternative scenarios

Having more than one criterion will make it more complex for decision-makers to choose the most pertinent scenario. In the proposed evaluation model, there are several interrelated criteria. To reduce such complexity and to evaluate the alternative clustering scenarios appropriately, Multi-criteria decision making (MCDM) was chosen.

V.6.1. Multi-Criteria Decision Making

MCDM focuses on solving and structuring decisions involving multiple criteria. MCDM is considered to be a valuable tool when having more than one criterion to evaluate alternative scenarios (Belton and Stewart 2002). They are used in many fields and various disciplines from governmental decisions to industrial strategies. One of the challenges is thus to choose the right method for our context.

Most of the MCDM methods are composed of several steps. (Singh and Malik 2014) presented a generic model of MCDM, setting out the basic concept of the methodology using a series of steps. This is a decision support system that can help in achieving an optimal solution.

There are two principles for the MCDM. The first principle is the compensation principle: it is the fact that, even if a solution has a bad evaluation in a criterion, it can be made up by a good one in other criteria. It exists two levels of compensation: partial and total. Additionnally, 'outranking' is an aggregation way in which solutions preference is not directly defined by their evaluations but by the confirmation (or not) of preference pair-wise hypotheses. For example the hypothesis "the first solution is at least as good as the second one" is valued.

One example of MCDM is ANP. It helps decision-makers to discover the best result that matches their goal and their understanding of the problem. ANP provides a rational and comprehensive framework for constructing a decision problem, for relating the structure's elements to overall goals, for quantifying those elements, and for evaluating alternative solutions. ANP is considered to be a partial compensation principle.

As shown previously with the links among criteria and operational measurements, our decision-making context is characterized by interdependency among the five impact criteria. This situation led us to select among the MCDM method of Analytical Network Process (ANP). ANP provides a comprehensive structure framework for the decision-makers and it does not require interdependency among elements, which is suitable for the network structure of our model. We give an overview of the ANP method in the next section and illustrate why it was chosen.

V.6.2. Detailed explanations of the ANP method

ANP (Saaty 1996) is a comprehensive decision-making technique with the capability to include all the relevant criteria, to support decision-making. ANP structures any decision problem as a network. It uses a system of pairwise comparisons to measure the weights of the components of the structure, and finally to rank the decision alternatives. ANP is considered the first mathematical theory that makes it possible to systematically deal with the dependencies and feedbacks among different criteria (Ozturk 2006).

ANP is considered to be a general form of the analytic hierarchy process (AHP). AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network. AHP designs a decision-making framework that adopts an un-directional hierarchical relationship among different decision levels. While AHP can help in solving complex MCDM problems, it is less effective when applied to problems that involve dependence relationships between criteria (Saaty 1987). Therefore, a new theory was advanced by Saaty that maintains the idea of AHP and develops the ANP method, which raises the analytical ability of ANP. In several cases, interdependence happens between criteria and alternatives. ANP is considered as an effective tool in the cases where interactions among the system's elements produce a network structure through a supermatrix approach (Saaty, 1996).

ANP has been used in several past researches. (Lee and Kim 2001) used ANP for selecting an information system project. (Cheng and Li 2004) applied ANP to a contractor selection. (Poonikom et al.2004) used ANP for university selection decisions. (Piantanakulchai 2005) applied ANP for highway corridor planning. Additionally, Jharkharia and Shankar (2007) used ANP to select logistics service providers. (Hsu and Kuo 2011) applied ANP to select the optimal advertising agency. All of those past researches used ANP to aid them to select the best scenario out of several scenarios, based on a set of criteria that are structured in a network structure model.

There are some advantages that ANP has over other multi-criteria methods: the intuitive appeal of the ANP for the decision-makers, the flexibility of ANP and the ability of ANP to check inconsistencies (Ramanathan 2001). ANP uses the pairwise comparison to evaluate the relationships among criteria for group comparison. Commonly, the pairwise comparison is considered straightforward and convenient. Moreover, the ANP method has another advantage as it breaks down a decision problem into its basic parts and builds networks of criteria and the importance of each criterion becomes understandable (Macharis et al. 2004). ANP helps to capture objective and subjective evaluation measures. ANP provides a beneficial mechanism to check the consistency of the evaluation processes and alternatives. The ANP method helps in group decision−making by calculating the geometric mean of the pairwise comparisons between the decision criteria (Zahir 1999).

Figure 40 illustrates the steps of the ANP method. There are four steps: model construction and problem structuring, pair-wise comparison matrices and priority vectors, supermatrix formation and selection of the best alternatives.

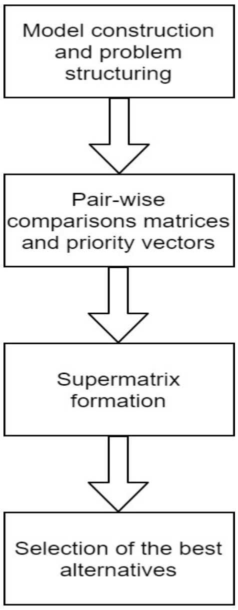


Figure 40. ANP steps

V.6.2.1. Model construction and goal structuring

The goal should be stated clearly and broken down into a rational system as a network. The framework model can be decided based on the opinion of the decision-maker through brainstorming or any other appropriate method. The network model contains a set of clusters (components, nodes or criteria) and elements (sub-criteria) in these clusters.

There are three kinds of components in a network. The source component is defined as the component where there is no arrow to enter. The sink is defined as the component where there are no arrow leaves. The intermediate component is defined as the component in which arrows enter and leave. There are two types of dependency in a network: inner interdependency and outer interdependency. Inner dependency exists when there is a dependency among elements of the same component. Outer dependency exists is when there is a dependency among the elements of different components. Figure 41 illustrates the different types of components and also the type of dependency. C4 and C5 are considered an example of inner dependency. Dependency between (C1and C2), (C1 and C3), (C1 and C4), (C2 and C4) and (C2 and C5) are considered as outer dependency relationships. Outer dependency between C3 and C4 are two

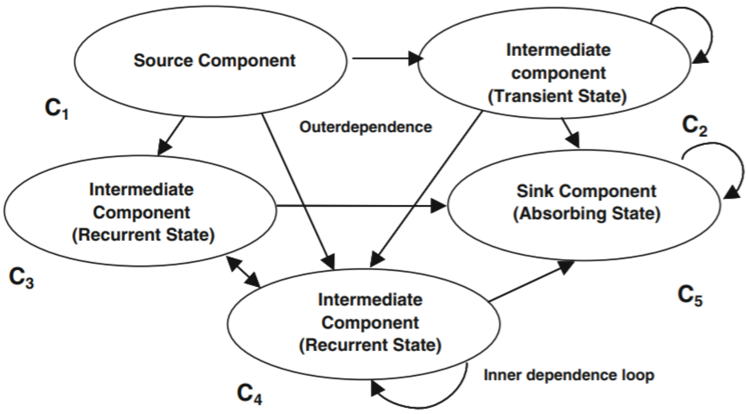


Figure 41.Types of Components in a Network

ways of dependency where C3 impact C4 and C4 impacts C3.

Figure 42 illustrates the component in our method. We have the goal of choosing the best scenario as the source components. The intermediate clusters are the perspective criteria, impact criteria and operational measurement indicators. Last but not least, the sink component is the set of alternative clustering scenarios that we have as an output from applying modularity.

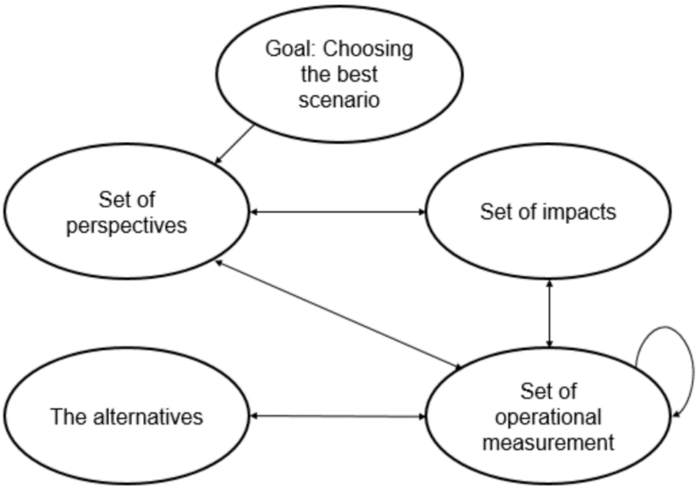


Figure 43. Network's components of our method

Illustration. In our illustrative example, we have 3 main criteria, a goal and a set of alternatives scenarios (Figure 43). The goal in our example is to find the best clustering alternative scenario (1). There are three intermediate components. The first one is the perspective criterion component that consists of three elements (2). The second one is the impact criterion component that consists of five elements (3). And the last intermediate component is the operational measurement criterion that consists of seven elements (4). The sink element is the set of alternative clustering scenarios that was the output of the modularity procedure (5). One directional interdependency is between the goal and the perspective criteria. For perspective criteria and impact criteria, there is a two-directional interdependency between both of them. One directional interdependency between impact criteria and the operational measurement criteria. And lastly, one-directional interdependency between operational measurement criteria and the set of alternatives.

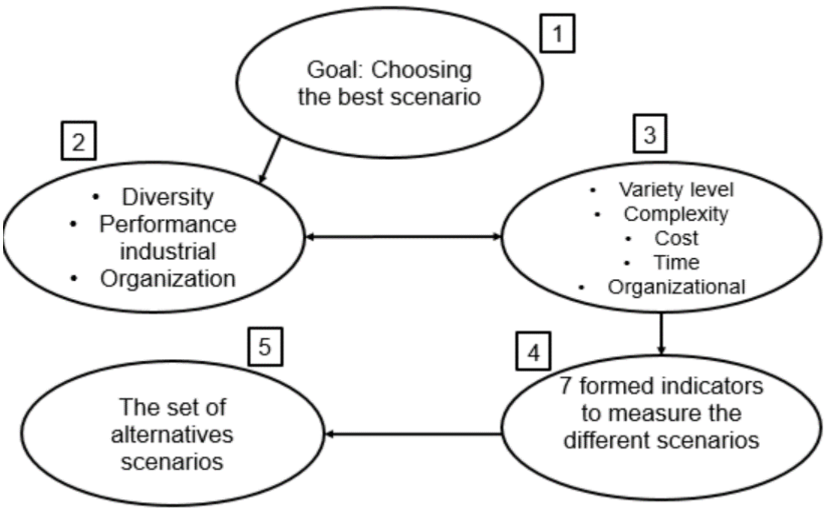


Figure 42. Criteria relationships

V.6.2.2. ANP (Pair-wise comparisons matrices and priority vectors)

The decision element of the ANP at each of the component criteria are compared pair-wise concerning their control criteria, and the components criteria are also compared pair-wise with respect to their contribution to the goal. Decision-makers are generally requested to react to a set of pair-wise comparisons in which two components criteria or elements will be compared at a time concerning how they devote to the particular upper-level criterion (Hsu and Kuo 2011).

The fundamental scale representing the intensities of the importance of judgments is shown in Table 11. This scale has been obtained by stimulus-response theory and was validated for effectiveness in many applications by several people and also by the theoretical justification of what scale one must use in the comparison of homogeneous elements (Saaty and Vargas 2006).

One important aspect of pair-wise comparisons is the reciprocal property. When one element is decided to be x times superior to another one concerning a given property, the inferior one is used as the unit and the more dominant is estimated to be some multiple of that unit. The inverse comparison is done by setting the inferior element the reciprocal value 1/x (Saaty and Vargas 2006).

Table 11. The Fundamental Scale of the comparison matrix (Saaty and Vargas 2006)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Illustration. Table 12 illustrates the pair-wise comparison between the perspective criteria concerning the goal. Experts and decision-makers are gathered to make a brainstorming to assign the importance intensity among the perspectives concerning the contribution to the goal. Diversity criterion is 7 times more important than the organizational criterion and 3 times more important than the performance industrial criterion. Performance industrial criterion is 5 times more important than the organizational criterion. When comparing performance industrial criterion with regards to the diversity criterion, the indices of importance will be 1/3. The importance of organizational criterion is 1/7 to the diversity criterion and 1/5 to the performance industrial criterion. The next step is to obtain the eigenvector of each element of perspective criteria that represent the impacts of each element of perspective criteria on the goal.

Table 12. Pair-wise comparison between perspective

Goal	Diversity	Performance industrial	Organizational
Diversity	1	3	7
Performance industrial	1/3	1	5
Organizational	1/7	1/5	1

Table 13 shows the results of the priority ranking of each of the perspective elements concerning the goal by calculating the eigenvector of the pair-wise comparison matrix in table 12. We calculate the eigenvector through three main steps. First, we square the matrix (which is table 12) as shown in equation 12

$$\begin{matrix} 1 & 3 & 7 \\ 0.333 & 1 & 5 \\ 0.143 & 0.2 & 1 \end{matrix} \times \begin{matrix} 1 & 3 & 7 \\ 0.333 & 1 & 5 \\ 0.143 & 0.2 & 1 \end{matrix} = \begin{matrix} 3 & 7.4 & 29 \\ 1.381 & 2.999 & 12.331 \\ 0.353 & 0.829 & 3.001 \end{matrix} \qquad (12)$$

Then we will sum the total for each row. And finally, we normalize by dividing the row sum by the row total as shown in equation 13. This will get us the result of the eigenvector which is shown in table 13.

$$\begin{matrix} 3 & + & 7.4 & + & 29 & = \\ 1.381 & + & 2.999 & + & 12.331 & = \\ 0.353 & + & 0.829 & + & 3.001 & = \end{matrix} \begin{matrix} 39.4 \\ 16.711 \\ \underline{4.183} \\ 60.295 \end{matrix} \Rightarrow \begin{matrix} 0.65 \\ 0.28 \\ 0.07 \end{matrix} \qquad (13)$$

Table 13. Priorities of perspectives concerning the goal

Perspective	Weight (eigenvector)
Diversity	0.65
Performance industrial	0.28
Organizational	0.07

Table 14 illustrates the pair-wise comparison matrix between elements of impact criteria concerning an element of the perspective criteria which is the diversity criterion. Table 15 shows the results of the priority ranking of variety level impact and complexity impact criteria for the diversity perspective criterion by calculating the eigenvector of the pair-wise comparison matrix in table 14. Other impact criteria are not shown in the pair-wise comparison matrix as they don't influence the diversity perspective that is because the variety level and complexity impact criteria are the only ones that influence the diversity perspective.

Table 14. Pair-wise comparison impact criteria concerning the diversity perspective criterion

C (Diversity)	Variety level	Complexity
Variety level	1	3
Complexity	1/3	1

Table 15. Priorities of impact criteria concerning the diversity perspective criterion

C (Diversity)	Weight (eigenvector)
Variety level	0.75
Complexity	0.25

ANP (The consistency ratio)

The consistency ratio is used to determine how consistent is the decision-makers' opinion. In other words how consistent is the pairwise comparison matrix? Besides, how do decision-makers measure the consistency of subjective judgment? It can be used after forming the pairwise comparison matrix to be able to determine how consistent is the judgment of those priorities. Consistency is closely related to the transitive property. If the consistency ratio's value is smaller or equal to 0.1, the inconsistency of the comparison matrix is acceptable. If the consistency ratio is greater than 0.1, the subjective judgment is needed to be revised. Eqs 14-16 describe how the consistency ratio is calculated

$$\text{CI} = \text{consistency index} = \frac{\lambda_{max} - n}{n-1} \quad (14)$$

$$\lambda_{max} = \max \frac{A_W}{W} \quad (15)$$

$$\text{CR} = \frac{CI}{RI} \quad (16)$$

Where W is the mean average of each line of a_{ij}/sum. A_W is the total of each line of a_{ij}/sum. n is the number. a_{ij} is the value of each coefficient of the pairwise comparison matrix A. The sum is the sum of each column of the pairwise comparison matrix A.

RI is the average value of CI for random matrices. It is based on the Saaty scale that was obtained by (Fomran 1990). The first 9 random index integers are shown in table 16.

Table 16. Random index table (Forman 1990)

n	1-2	3	4	5	6	7	8	9
RI	0.00	0.52	0.89	1.11	1.25	1.35	1.45	1.49

Illustration. To check the consistency we will use the data from table 12. Tables 17-19 illustrate the consistency check for the data in table 12. We are trying to verify whether the decision-makers' opinion for the formed pairwise comparison is consistent or no (Tables 12-15).

Table 17. Pair-wise comparison matrix between perspectives with the sum

A	Diversity	Performance industrial	Organizational
Diversity	1	3	7
Performance industrial	1/3= 0.33	1	5
Organizational	1/7= 0.14	1/5 = 0.2	1
Sum	1.47	4.20	13

Table 18. a_{ij} /sum of each column calculation

A	Diversity	Performance industrial	Organizational
Diversity	1/1.47= 0.68	3/4.2= 0.71	7/13= 0.54
Performance industrial	0.33/1.47= 0.23	1/ 4.2= 0.24	5/13= 0.38
Organizational	0.14/1.47 = 0.1	0.2/ 4.2= 0.05	1/13= 0.08

Table 19. Consistency ratio calculation

a_{ij}/Sum	Diversity	Performance industrial	Organizational	w	A_w	A_w/w
Diversity	0.68	0.71	0.54	0.64	1.93	3
Performance industrial	0.23	0.24	0.38	0.28	0.85	3
Organizational	0.10	0.05	0.08	0.07	0.22	3
Sum	1	1	1			

For column A_w/w, all values are equal to each other so the max of A_w/w is equal 3.

$$\lambda_{max} = \max \frac{Aw}{W} = 3$$

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{3-3}{3-1} = \frac{0}{3-1} = 0$$

RI = 0.52 (table 13 and n=3)

$$CR = \frac{CI}{RI} = \frac{0}{0.52} = 0$$

Therefore the consistency ratio is 0 < 0.1 therefore the pairwise comparison matrix is consistent.

V.6.2.3. ANP (Super matrix formation)

The concept of the supermatrix has the same shape as the Markov chain process that the sum of the probabilities of all conditions equal to one (Saaty, 1996). The idea of supermatrix is to simply aggregate all the pairwise comparisons that were done and integrate them into one big matrix. Each element of the result of the pair-wise comparison matrix is represented at one row and one respective column. (Saaty and Vargas 2006) have improved the supermatrix technique to combine the priority scales of importance. Each priority scale is suitably introduced as a column in a matrix to represent the impact of elements of a cluster on elements of the same cluster (inner dependence) or an element of another cluster (outer dependence). The supermatrix consists of various sub-matrices that each column of the supermatrix is considered a principal eigenvector that represents the importance priority impact of all elements in a cluster on each element in another (or the same) cluster.

With regard to the equation in figure 44, each column of the supermatrix (Wij) is a principal eigenvector of the priority impact of the elements in the ith component of the network decision model on an element in the jth component. Some of the entries of the supermatrix may be zero, which means that those elements have no impact on each other. Thus it is not needed to use all the elements in a component when making the pair-comparison to acquire the eigenvector, but only the elements that have a non-zero impact on other elements. The supermatrix W_{ij} is shown in figure 44.

$$w_{ij} = \begin{bmatrix} W_{i1}^{(j1)} & W_{i1}^{(j2)} & \cdots & W_{i1}^{(jn_j)} \\ W_{i2}^{(j1)} & W_{i2}^{(j2)} & \cdots & W_{i2}^{(jn_j)} \\ \vdots & \vdots & \cdots & \vdots \\ W_{in_i}^{(j1)} & W_{in_i}^{(j2)} & & W_{in_i}^{(jn_j)} \end{bmatrix}$$

Figure 44. Supermatrix W_{ij}

Concerning the equation in figure 45, to build up the supermatrix, the components of a decision system are referred to by C_k with k =1, …, n, where each component C has n_h elements, symbolized by e_{k1}, e_{k2}, …, e_{kmk}. The local priority vectors deduced in Step 2 are grouped and located in suitable positions in a supermatrix based on the flow of the impact from one component to another (outer dependency), or from a component to itself, as in the loop (inner dependency).

For example, the cell C_{21} means that element 2 depends on element 1. That doesn't mean that if C_{21} has a value that C_{12} will have a value since element 1 can be not dependent on element 2. This means that it can be just one-way dependency relation between two elements or 2 ways dependency relation as it depends on the decision-makers (figure 45).

$$
\begin{array}{cc}
 & \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_n \\ e_{11}\cdots e_{1m_1} & \cdots & e_{k1}\cdots e_{km_k} & \cdots & e_{n1}\cdots e_{nm_n} \end{array} \\
W = \begin{array}{cc} & e_{11} \\ C_1 & \vdots \\ & e_{1m_1} \\ \vdots & \vdots \\ & e_{k1} \\ C_k & \vdots \\ & e_{km_k} \\ \vdots & \vdots \\ & e_{n1} \\ C_n & \vdots \\ & e_{nm_n} \end{array} & \begin{bmatrix} W_{11} & \cdots & W_{1k} & \cdots & W_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ W_{k1} & \cdots & W_{kk} & \cdots & W_{kn} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ W_{n1} & \cdots & W_{nk} & \cdots & W_{nn} \end{bmatrix}
\end{array}
$$

Figure 45. supermatrix elements (Hsu and Kuo 2011)

Since interdependence can exist among clusters in a network in a two-way relationship, the columns of a supermatrix can have a total of more than one. The supermatrix must be transformed first to make it stochastic; that is, each column of the matrix sums to unity (total equals to 1 or Zero if all the cells in one column are empty) (Saaty. 2001). If the sum of one column in the composed supermatrix is greater than 1 (there is more than one eigenvector), that column will be normalized by simply divide each cell by the sum of its column.

Saaty (2001) proposed in determining the relative importance of the clusters of criteria in the supermatrix with the column of the cluster criteria considered as the controlling component (Meade and Sarkis 1999). This is considered as the row components with nonzero entries for their clusters in that column cluster are compared based on their influence on the component of that column criteria (Saaty 1996). An eigenvector can be obtained by using a pair-wise comparison matrix of the row components concerning the column component. For each column criteria, the first entry of the corresponding eigenvector is multiplied by all the elements in the first criteria of that column. And the second entry of the corresponding eigenvector is multiplied by all the elements in the second criteria of that column and it will continue like that. The criteria in each column of the supermatrix are therefore weighted, and the result is labeled the weighted supermatrix, which is considered to be stochastic.

Illustration.

$$
\boldsymbol{W} = \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{W_{2,1}} & \mathbf{0} & \boldsymbol{W_{2,3}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{W_{3,2}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{W_{4,3}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{W_{5,4}} & \mathbf{0} \end{pmatrix} \tag{17}
$$

In the above matrix (eq 17), 1 belongs to the goal which is choosing the best scenario, 2 belongs to the perspectives cluster, 3 belongs to the impacts cluster, 4 belongs to the operational measurement cluster and 5 belongs to the list of alternatives. From the network model hierarchy we can find that 2 depends on 1, 3 depends on 2, 4 depends on 3, 5 depends on 4. As well, there is a dependency relationship that 2 depends on 3 and 3 depends on 4. Since we have two-way relationships between clusters 2,3. This matrix collects the resulted value of the pairwise comparison formed between different criteria clusters. They will be positioned as shown in the matrix.

Before building up the supermatrix, some points have to be considered to avoid problems:

- For $W_{5,4}$ which is the relationship between the alternatives and the operational measurement, the weight of each of the columns has to be normalized and the sum should be equals to 1 before adding it in the supermatrix. And that's not the case in table 10 where we calculated the operational measurement for each of the scenarios. So to solve this issue, The result values of the indicators have to be normalized to put them in the supermatrix cells.
- As well what needs to be considered is the sense of measurement of the indicators(to be able to show that the lower the value is the better the scenario is). Therefore, to be able to do that we will divide all the values by 1 ($\frac{1}{I_n}$) where I_n is the operational measurement for n scenarios and n is the total number of scenarios, n ϵ (1,2,3,….n). Then do the normalization that is taking the total of all the values of the scenarios and divide each value by the total. This will make it able to change so that it shows that the lower value will have the highest weight ($\frac{I_n}{I_T}$) I_T is the total value of all the scenarios for each indicator.

Table 20 and Table 21 illustrates those two steps of the procedure.

Table 20. Operational measurement with sum

Symbol	I1	I2	I3	I4	I5	I6	I7
Description	Number of activities	Number of human resources types	Control-flow complexity	Longest path of the process (Diameter	Percentage of multi-skilled human resources	The flow between activities from a different lane	Number of clusters (modules)
S1	71	2	5	69	0	4	10
S2	71	2	4	68	0	5	10
S3	71	2	7	65	0	4	14
S4	71	2	5	68	0	4	14
Sum	284	8	21	270	0	17	52

Table 21. Normalized operational measurement

Symbol	I1	I2	I3	I4	I5	I6	I7

Description	Number of activities	Number of human resources types	Control-flow complexity	Longest path of the process (Diameter	Percentage of multi-skilled human resources	The flow between activities from a different lane	Number of clusters (modules)
S1	0.25	0.25	0.24	0.26	0	0.24	0.21
S2	0.25	0.25	0.19	0.25	0	0.29	0.21
S3	0.25	0.25	0.33	0.24	0	0.24	0.29
S4	0.25	0.25	0.24	0.25	0	0.24	0.29

After having all the relationships dependency between the criteria and sub-criteria (Perspectives, impacts and operational measurement) and between the perspective and the goal. Also after having the normalized operational measurement for all the scenarios, forming the supermatrix that combined all of those relationships is the next step. Figure 46 shows the supermatrix that connects all the relationships together.

		Criteria(Perspectives)			Sub-criteria(Impact)					Indicators(Operational measurement)							Alternatives (Scenario)			
	Goal	Diversity	Industrial Performance	Orgaanizational	Variety	Complexity	Cost	Time	Organizationa	I1	I2	I3	I4	I5	I6	I7	S1	S2	S3	S4
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diversity	0.65	0	0	0	1	0.77	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Performance	0.28	0	0	0	0	0.17	0.88	0.88	0	0	0	0	0	0	0	0	0	0	0	0
Orgaanizational	0.07	0	0	0	0	0.06	0.13	0.13	1	0	0	0	0	0	0	0	0	0	0	0
Variety	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Complexity	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost	0	0	0.67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizational	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I1	0	0	0	0	0	0.12	0.11	0.2	0	0	0	0	0	0	0	0	0	0	0	0
I2	0	0	0	0	0	0.08	0.37	0	0.16	0	0	0	0	0	0	0	0	0	0	0
I3	0	0	0	0	0	0.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I4	0	0	0	0	0	0.12	0.33	0.68	0	0	0	0	0	0	0	0	0	0	0	0
I5	0	0	0	0	0	0.10	0.19	0.12	0.30	0	0	0	0	0	0	0	0	0	0	0
I6	0	0	0	0	0	0.23	0	0	0.54	0	0	0	0	0	0	0	0	0	0	0
I7	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0	0	0	0.25	0.25	0.24	0.26	0	0.24	0.21	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0.25	0.25	0.19	0.25	0	0.29	0.21	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0.25	0.25	0.33	0.24	0	0.24	0.29	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0.25	0.25	0.24	0.25	0	0.24	0.29	0	0	0	0

Figure 46. Unweighted supermatrix

The formed supermatrix is unweighted which means the sum of columns is not unity (equals 1) or zero. Therefore it is needed to be normalized by simply dividing each coefficient by the sum of each column (only for columns that their sum is not 1 nor 0). Figure 47 shows the weighted supermatrix after it has been normalized.

Selection of the best alternatives

The Limit Matrix is the weighted Super matrix, taken to the power of k+1, where k is an arbitrary number (Saaty 1996). The limit supermatrix has the same form as the weighted supermatrix, but all the columns of the limit supermatrix are the same. Normalizing each block of this supermatrix can obtain the final priorities of all the elements in the matrix. Raising the weighted supermatrix to the power k + 1 allows the convergence of the matrix, which means the row values converge to the same value for each column of the matrix. In other words, the limit supermatrix is calculated by raising continuously the supermatrix until the value in each column in a row is the same. The priority weights of alternatives scenarios can be found in the column of alternatives in the normalized supermatrix.

		Criteria(Perspectives)			Sub-criteria(Impact)					Indicators(Operational measurement)							Alternatives (Scenario)			
	Goal	Diversity	Industrial Performance	Orgaanizational	Variety	Complexity	Cost	Time	Organizational	I1	I2	I3	I4	I5	I6	I7	S1	S2	S3	S4
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diversity	0.65	0	0	0	0.5	0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Performance	0.28	0	0	0	0	0.09	0.44	0.44	0	0	0	0	0	0	0	0	0	0	0	0
Orgaanizational	0.07	0	0	0	0	0.03	0.06	0.06	0.5	0	0	0	0	0	0	0	0	0	0	0
Variety	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Complexity	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost	0	0	0.67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizational	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I1	0	0	0	0	0	0.06	0.05	0.10	0	0	0	0	0	0	0	0	0	0	0	0
I2	0	0	0	0	0	0.04	0.19	0	0.08	0	0	0	0	0	0	0	0	0	0	0
I3	0	0	0	0	0	0.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I4	0	0	0	0	0	0.06	0.16	0.34	0	0	0	0	0	0	0	0	0	0	0	0
I5	0	0	0	0	0	0.05	0.09	0.06	0.15	0	0	0	0	0	0	0	0	0	0	0
I6	0	0	0	0	0	0.11	0	0	0.27	0	0	0	0	0	0	0	0	0	0	0
I7	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0	0	0	0.25	0.25	0.24	0.26	0	0.24	0.21	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0.25	0.25	0.19	0.25	0	0.29	0.21	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0.25	0.25	0.33	0.24	0	0.24	0.29	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0.25	0.25	0.24	0.25	0	0.24	0.29	0	0	0	0

Figure 47. Weighted supermatrix

Illustration. Figure 48 shows the result of the limit supermatrix. This limit supermatrix shows the final priorities of the scenarios.

We can distinguish the rankings of the scenarios from the column of goal with the lines of each scenario. S4 has the highest priority followed by S3 then S1 with value equals then the least priority scenario S2. So the ranking of the scenarios will be: S4>S3>S1>S2. S4 and S3 are the scenarios with more clusters since both have 14 clusters.

		Criteria(Perspectives)			Sub-criteria(Impact)					Indicators(Operational measurement)							Alternatives (Scenario)			
	Goal	Diversity	Industrial Performance	Orgaanizational	Variety	Complexity	Cost	Time	Organizational	I1	I2	I3	I4	I5	I6	I7	S1	S2	S3	S4
Goal	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Diversity	0,000	0,223	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Industrial Performance	0,000	0,021	0,194	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Orgaanizational	0,000	0,009	0,056	0,250	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Variety	0,230	0,000	0,000	0,000	0,177	0,138	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Complexity	0,077	0,000	0,000	0,000	0,059	0,046	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Cost	0,092	0,000	0,000	0,000	0,008	0,032	0,130	0,130	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Time	0,045	0,000	0,000	0,000	0,004	0,016	0,064	0,064	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Organizational	0,057	0,000	0,000	0,000	0,004	0,023	0,056	0,056	0,250	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I1	0,000	0,009	0,029	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I2	0,000	0,008	0,061	0,040	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I3	0,000	0,021	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I4	0,000	0,012	0,097	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I5	0,000	0,009	0,044	0,075	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I6	0,000	0,015	0,016	0,135	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
I7	0,000	0,354	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
S1	0,170	0,000	0,000	0,000	0,093	0,084	0,052	0,052	0,042	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
S2	0,164	0,000	0,000	0,000	0,092	0,084	0,051	0,051	0,049	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
S3	0,173	0,000	0,000	0,000	0,124	0,109	0,050	0,050	0,042	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
S4	0,193	0,000	0,000	0,000	0,122	0,107	0,051	0,051	0,042	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

Figure 48. Limit supermatrix

V.6.3. Sensitivity analysis

To understand how the priorities intensities of the criteria may affect the outcome of alternative rankings, a sensitivity analysis needs to be conducted. Sensitivity analysis is involved with some questions that are related to“what if” to verify if the final ranking is stable to some changes in the inputs that are either judgments or priorities intensities. Sensitivity analysis is usually accomplished by adjusting the criteria weights one at a time (WAT), i.e. changing the value for one criterion and keeping values of the relative weights of the other criteria constant. The final priorities of the alternative scenarios are highly dependent on the weights of the main criteria. Therefore, small changes in the relative weights of criteria may generate considerable changes in the final ranking. Sensitivity analysis is used to examine the effects of having variations in judgments on the stability of the final ranking of the alternatives (Saaty and Vargas 2006).

Since the intensity importance weights are based on highly subjective judgments, the stability of the ranking of the alternatives while adjusting criteria weights have to be tested. Therefore, sensitivity analysis can be performed based on different views on the relative importance of the criteria or sub-criteria. By increasing or decreasing the weight of a criterion, some changes can be observed in the priority importance intensity of criteria and also the ranking of the alternatives. Therefore, sensitivity analysis presents information on the stability of the ranking of the alternatives. In our method sensitivity analysis is important to show how the ranking is changing when we change the weight of perspective.

Illustration. We can change the weight of one of the perspectives and figure out how much the alternatives will be varying and check how it will affect the output (putting into consideration to change the other perspective priority value as the total weight has to be 1). For example, here the perspective 'diversity' has 0,65 as a priority weight and it is considered the dominant perspective. Therefore, the ranking will be: S4 then followed by S3 then S1and then S2 being the least favorite scenario (figure 49a) on the left of the figure. We can change the weight of the perspectives and make the 'industrial performance' as the dominant perspective. The ranking of the scenarios will be S1, S4 S3 and S2 (figure 49b). The preferred scenario now is S1 not S4 when we put the 'industrial performance 'perspective as the dominant one. If the 'organizational perspective' is the dominant perspective, the ranking will be: S1 followed by S4 then S3 and the last ranked scenario will be S2. Figure 49c shows the ranking when the weight of the organization perspective is the dominant one. The ranking will be: S4 then S1 then S3 and the least ranked will be S2.

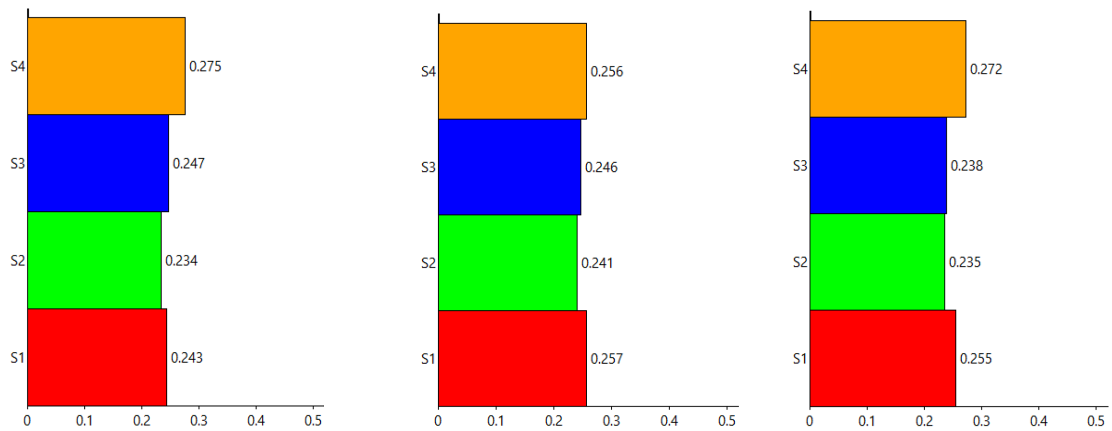


Figure 49. Ranking results with a) diversity as the most important b) industrial performance as the most important c) organization as the most important

This can help decision-makers to choose the best scenario, based on the perspective they would like to emphasize, in their proper industrial context. It is considered a helpful tool to aid the decision-makers to analyze the results of the ranked scenarios.

V.7. Conclusion

Implementing modularity for products and services is considered to have a potentially positive impact on the performance of the company. Past researchers, in the literature review that was discussed in chapter 2, support the idea of using modularity as a driver to improve the performance of the company while applying the mass customization strategy in service-oriented systems.

This chapter focused on illustrating the procedure of measuring the impact of modularity on the industrial performance of the company. A new method was proposed for measuring the impact of modularizing products and/or services on the industrial performance of a company. The method addresses evaluating different output clustering scenarios for offering a variety of product and service elements using several criteria indicators.

The method provides a decision-support model to rank the scenarios and propose the best solution based on a set of criteria that are based on the industrial context of the company. Evaluating the performance supports the comparison of different modularity scenarios, which will have valuable support for decision-makers of variety management.

MCDM methods in general and the ANP method, in particular, are considered as an effective tool to be able to rank the alternative scenarios based on several criteria. ANP is more flexible because one can maintain any relation interdependency between any element in the network model structure. So even if it is more complex to implement, it solves important issues related to network structures. It is suitable for our model structure because there is a network dependency relationship among some of the elements of the model.

In the next chapter, a case study is provided to illustrate the applicability of the method that was demonstrated in chapter four and chapter five. The main objective of the case study is to validate the applicability of applying modularity on service-oriented systems and also to validate measures of the impact of modularity on industrial performance, by comparing different clustering output scenarios.

Chapter VI. **CASE STUDY**

VI.1. Introduction

In this chapter, a case study is provided to illustrate the applicability of the modularity procedure on a service-oriented industrial system. We will discuss also the impact of modularity on industrial performance by comparing the result of different alternative clustering scenarios.

The objective of the case study is to verify the feasibility of applying the whole method on a service-oriented system that offers varieties of both products and services and to discuss the lessons learned from this experimentation, notably concerning the applicability, added-value of the method and limitations. In this perspective, we first provide a brief description of the case study (Section 2) together with a presentation of the implementation tools and software that are needed to apply the method to the case study and to generate the required outputs (Section 3). Second, in section 4, we apply step by step the method defined to specify the modularity problem and to generate a set of alternative clustering scenarios. Then, the third and last step (section 5) is dedicated to rank and measure the industrial performances of the output clustering scenarios. These results are discussed in section 6.

VI.2. The description of the case study

In this section, the case study is described in detail and the main objective of the case study is presented.

VI.2.1. Data of the case study

The case study originally has been applied in an industrial context to reinforce the full process design of a robotic PSS solution which was developed via the national funded French (FUI) project with the name of 'Clean Robot'. The Clean Robot is a project of innovative development of an autonomous industrial cleaning service. This research work was developed in collaboration with the company INNVOTEC Industries, as an industrial leader of the project (Boucher et al.2018). The design process covers the qualitative design phase of the robot and the services opportunities throughout the full life-cycle, the configuration of the value chain, the specification of the PSS offer for industrial cleaning and the study of alternative economic models for market deployment. The consortium includes four stakeholders (figure 50 shows the organization view with the sets of involved actors):

- The provider (E1): A small-sized company manufacturing batteries that has a key role and impact on the PSS delivery.
- Manufacturer (E2): a small-sized company manufacturing special machines including robotics and providing customized solutions. It plays a central role in the delivery of the envisioned PSS solutions.

- Service Intermediary (E3): it is a facilitator agent or enterprise in charge of cleaning services in the customer places as well as maintenance activities for the equipment (Cleaning robot), in some scenarios where the manufacturer does not expect to provide them.
- Customer/End-user (E4): a medium-sized company from the meat transformation industry

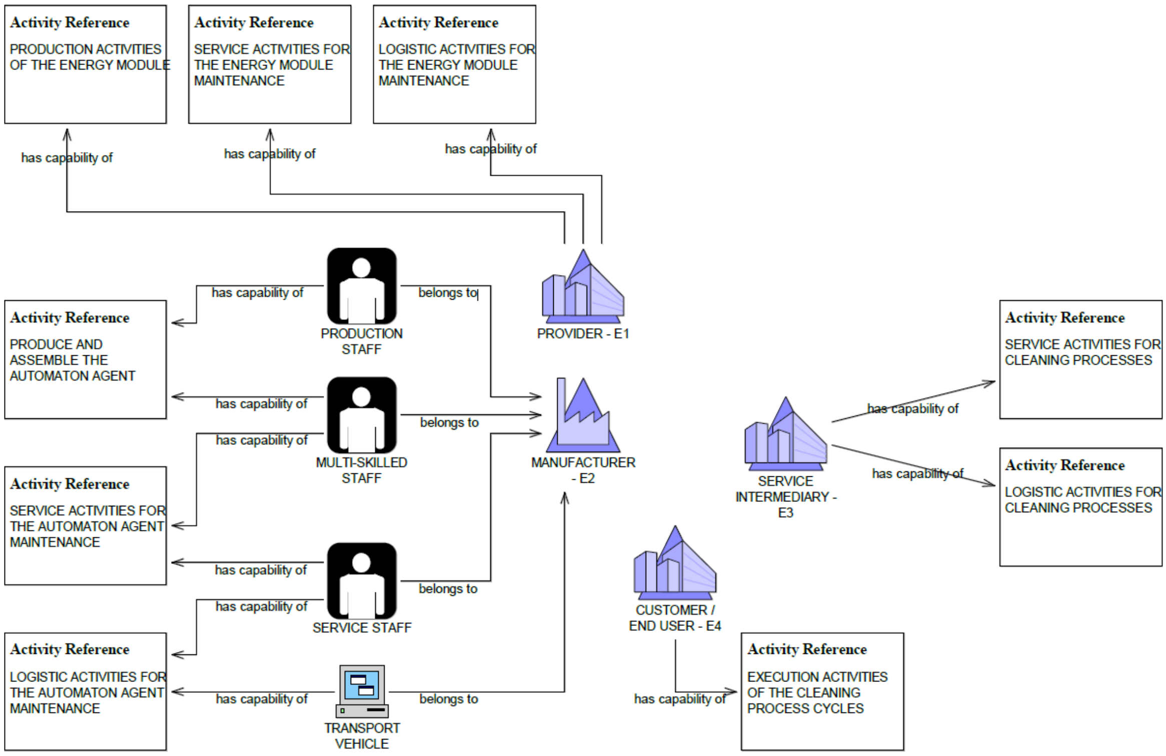


Figure 50. Organization view (Boucher et al.2018)

Some prospects are expected from the end-user company needs to be suppressed:- Ensure autonomous cleaning services in cold warehouses without removing the meat carcasses; reduce meat contamination risks; diminish exposure to chemical substances; night cleaning to avoid production disruptions and increase the frequency of cleaning processes. That is why the interest in developing a PSS solution was popped out which is named cleaning robot (Boucher et al. 2018).

The cleaning robot consists of 4 main product modules (security, energy, cleaning and displacement) and a set of services that is related to the product lifecycle (figure 51).

For the thesis, we decided not to limit the study to just the mead industry application but to extend the case study to additional application fields. In the project, one autonomous robot was included with a set of product modules and a set of services. In the thesis, those product modules and services were extended to have more variety of products and services that can illustrate and validate the method. Two more products were added with the original cleaning robot that leads to an additional variety of product modules and also new services were added to the case study.

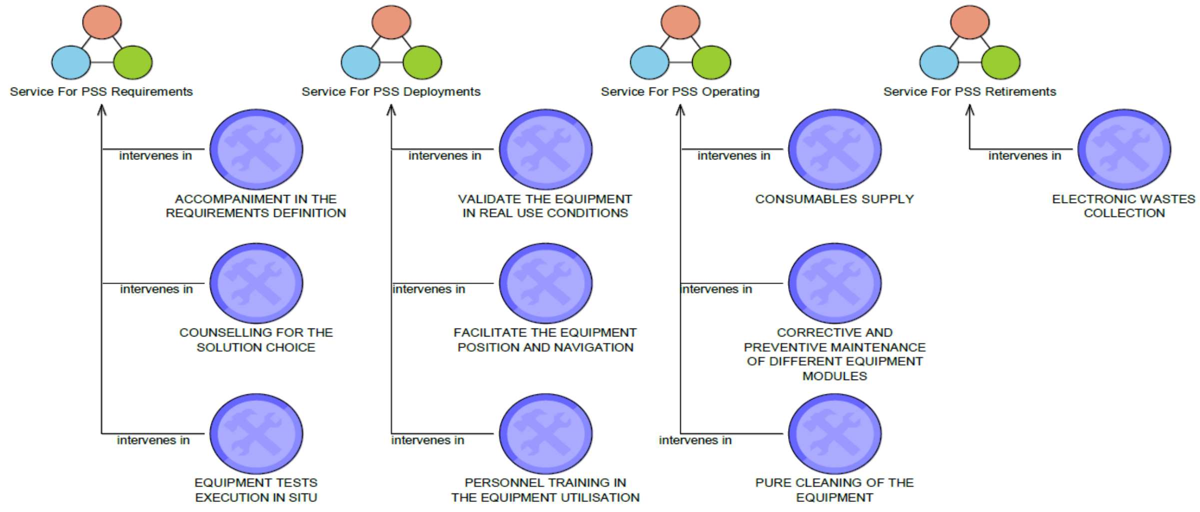


Figure 51. Service view of cleaning robot (Boucher et al.2018)

In this regard, three different applications are considered, cleaning fridges in the meat industry, cleaning for swimming pools, and lastly, train interior cleaning. For each of these applications, the offer consists of an autonomous robot with a set of services.

VI.2.2. Challenges and requirements of the case study

There are several types of PSS (Tukker 2004): "*product-oriented PSS*", where the customer still buys the product and some additional services are delivered by the provider; "*use oriented PSS*" where the ownership of the tangible product remains to the PSS provider and the customer buys a service contract including utilization of the solution together with usage-oriented services; and lastly,"*result-oriented PSS*" where the customers contracts the provider for a given level of expected performance. In our case study, we are addressing the service-oriented system where the system can address either services or products or integration of both. That means that the customer can have just a product or service or integration of both. It is close to the PSS type of product-oriented PSS. The service provided can appear in three different phases of the lifecycle of the system. Requirement phase where it is a presale service to consult and test the required solution for the company. The deployment phase where it happened during the sales of the solution offer that includes the installation and training steps. Lastly, the operation phase where it happened during the period of after-sales of the solution offer that includes maintenance and providing the needed consumable supplies.

The extension of the case study to several application fields of the cleaning solution increases the diversity of the offer's elements. For instance, for the product elements, the variety of energy modules is increased because the energy module in different application fields will require distinct battery systems. One energy module can have a battery that has a longer lifespan and can charge slower. Another energy module can have a shorter lifespan but can charge faster. The same idea will occur for other product modules. For service elements, an example of diversity will be the maintenance service. There can be a general maintenance service for the whole cleaning robot or several maintenance services for each module of the cleaning robot.

Also, there is an option of checking in the robot in distance or have a full check-in service on-site. Having much diversity will make it more complex for the provider company, that’s why the idea of modularity came. By studying the similarity relationships between product modules and services, modules can be formed that can decrease the complexity resulting from this higher variety. Modularity between product, service or integration of both will be established based on a set of criteria that define the similarity relationships among different product modules and services. The challenge will be to find the criteria that can help us in defining these similarity measures.

Some initial industrial data inputs are necessary to implement our modularity method: a data table with the product modules and the list of services; the list of the required human resources for the production activities of each service or product module; the tools and flow of information needed to implement these production processes; the functionality of each of the service and the product modules (in order to find the similarity relationships based on the set of criteria defined in chapter 4). And lastly, we need the industrial processes to implement both the product modules and the services. This is needed to measure the performance of the clustering scenarios in the method that is proposed in chapter 5. The performance that will be analyzed in this case study is not dependent on this case study but it is a general proposal that can be used in other industrial case studies.

A technical hypothesis was used while identifying the similarity relationship between the elements of products and services: there will be no similarity indices between two product modules that have the same functionality. For example, two energy modules that are different in the lifespan of the energy system but have the same functionality of providing the whole system with energy. They will not have a similarity relationship between them as we they are considered as alternative solutions of energy modules, not expected to be modularized.

Figure 52 illustrates the experimentation procedures from the case study. It consists of four main steps. It starts with formalizing the modularity solution where we gathered the data from the research project and a workshop was created with the experts to extend the data and form a more variety of scenarios of products and services. The second step is to generate and evaluate clustering scenarios. A second workshop was made with the experts to assign the similarity indices between the elements of products and services. Design structure matrix (DSM) was used to form several matrices based on each similarity criterion. RStudio software was used to upload the matrices data and aggregate them to generate clustering using the two clustering techniques. The third step is to evaluate and compare the performances of the alternative clustering scenarios. Adonis software was used to translate the clustering scenarios into BPMN models constituted with a set of activities and resources. Multi-criteria decision making (MCDM) was used to compare different scenarios using the ANP method procedure. A third workshop was created to calculate the pairwise comparison indices between the different criteria indicators. RStudio software was used to implement the pairwise comparison and to form the step of the supermatrix for the ANP method. Lastly, interpretation between the experts is constructed to analyze the output ranking and give some explanation for the output ranking.

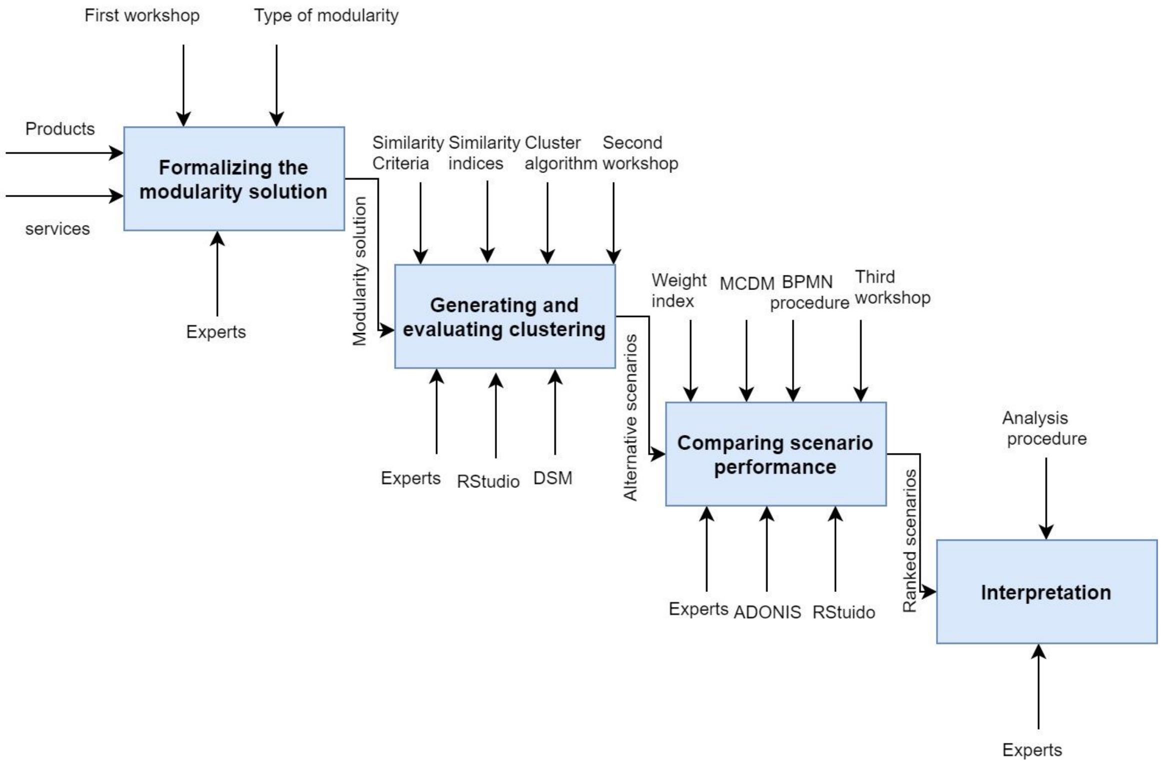


Figure 52. Experimentation procedures

VI.3. Implementation tools

This section discusses the tools and the software that were used to implement the procedures of our method. Those tools are used to help in implementing the procedures of the method either implementing modularity on the service-oriented system or measuring the impact of modularity on the industrial performance.

Two software were used, RStudio and Adonis community edition. We will have a brief introduction to both of them in the following sections.

VI.3.1. RStudio, to implement a clustering approach

It is a software that is mainly used to implement the programming language R. It is considered to be an integrated development environment software. R is considered as an environment of programming language that is generally used for graphics and statistical computing and it is supported by the R Foundation for Statistical Computing. The R language is commonly used amongst data miners and statisticians to be able to develop data analysis and statistical software (RStudio Team 2020).

RStudio is used in our method to implement the mathematical computation related to building the numerical DSM and computing the aggregated matrix. It is used to compute the hierarchical clustering and partitioning clustering required for implementing the modularity procedure conceptualized previously. It supports also the visualization of the resulting clusters and computes the silhouette method for the output clustering scenarios that are used, in our method, to measure the consistency of the clustering.

Later in the method deployment, Rstudio is also used to compute some steps that are done for the ANP method. It computes the pairwise comparison, using decision-makers' points of view to rank the importance of the criteria. It is used also to compute the steps to form the supermatrix and limit supermatrix to rank the alternative clustering scenarios.

VI.3.2. Adonis, to support performance asssessement

ADONIS is considered to be a Business Process Management (BPM) and Business Process Analysis (BPA) tool. ADONIS supports business process management based on the Business Process Management System (BPMS) framework that was created at the University of Vienna. The tool of ADONIS has been developed by BOC Information Technologies Consulting GmbH. ADONIS offers an array of functionalities, including web-based business process modeling, using BPMN 2.0 notations, graphical analysis capabilities and process simulation & optimization (BOC Information Technologies Consulting GmbH n.d).

ADONIS is used in the second phase of our method in the step to translate the clusters scenarios into a set of processes that include resources and activities. We decided to use the BPMN 2.0 technique as a rather standardized process modeling method, commonly used in industries. This will ease in applying the operational measurement indicators for each of the clustering scenarios. The process models will contain both qualitative and quantitative information on the organization and structuring of the processes which will allow the necessary measurements to be carried out for the expected performance evaluation.

VI.4. Applying the modularity method

VI.4.1. Identifying the elements

The first step of the method is to identify the raw input of the method which are the elements (section 3, chapter 4). In the current case study, services are assumed to be already identified, filtered, and defined. These main elements were the results of the first step of the experimentation procedure. Product modules were derived from customer needs in a way to have a mapping between the system functions (resulting from the needs) and the modules (e.g. Body1 resists cold temperature and Body 2 has a function of water-resistance). Each product module has specific functionality that is different from other product modules. An example is provided by the energy module: Energy module 3 has a higher life span of the battery system more than energy 2. And Energy 2 has a higher life span of battery system more than energy 1. The functionality of each of the elements will be shown in appendix II. The list of services is considered here as already defined based on customer needs (e.g. supplying the customer with the required consumables): service definition is not in the scope of this research. The product modules and the list of services are treated as components of the offer. They are shown in table 22.

Table 22. List of product and service elements

Elements (product modules)	**Description**	**Elements (Services)**	**Description**
E1	Energy1	E15	Consulting service
E2	Security	E16	Equipment tests
E3	Cleaning1	E17	Battery Maintenance
E4	Displacement1	E18	Cleaning module maintenance
E5	Body1	E19	Displacement maintenance
E6	Cleaning 2	E20	Pure cleaning Equipment
E7	Body2	E21	Emergency maintenance
E8	Energy2	E22	Preventive maintenance
E9	Microcontroller module	E23	Consumables supply
E10	Displacement 2	E24	Training battery
E11	Cleaning 3	E25	Training security
E12	Body 3	E26	Installation
E13	Displacement 3	E27	Upgrade
E14	Energy 3	E28	Check up from a distance
E29	Monitor module		

VI.4.2. Forming the similarity DSM

After identifying the elements, it is necessary to identify which relevant criteria can be used to compute the similarity indices forming the DSM (chapter 4 section 4). The analysis of the input data from the company, concerning the list of customer needs, a list of process models and the list of potential final PSS solution, is the basis to identify the similarity indices based on the four criteria defined before in chapter 4, section 4 (functional requirement, human resource, commonality, and information & technology). Examples of customer needs are ‘regular maintenance’, ‘avoid hitting or crashing’, ‘withstand cold temperature’, and ‘adapt to the cleaning environment’. Experts use the data in table 4 in chapter 4 as a guideline to quantify the similarity indices among the elements based on each criterion. The table describes the value of indices for each of the criteria used. A single value is assigned to each index based on agreements among the experts.

The second workshop between the experts was done to collect the data about the similarity indices between the elements. Since there can be more than one opinion of experts on every similarity index, we relied on having a brainstorming between the experts to assign the similarity indices among the elements

5 experts were in the workshop. It took two meetings to be able to assign all the similarity indices among the elements of products and services. We discussed how similar is each element to the other element concerning the criterion given and decided specific indexes based on available data and collegial discussions (functionality table, human resources table, tools and information,…).

Table 23 shows part of the indices among the elements based on the experts' point of view in terms of functional requirement criterion. The indices among the elements can be measured with values 0, 1, 2, and 3 according to table 4. The full matrices for each criterion can be shown at the end of the thesis report in appendix II.

The 4 formed DSM matrices were uploaded into RStudio in order to compute the aggregated matrix while assigning each of the matrices a specific weight based on its criterion.

Table 23. Functionality DSM

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
E1	3	1	2	1	2	1	0	0	1	1
E2	1	3	0	2	0	0	0	1	3	2
E3	2	0	3	2	0	0	0	1	1	2
E4	1	2	2	3	0	1	0	1	2	0
E5	2	0	0	0	3	0	0	1	0	0
E6	1	0	0	1	0	3	0	2	1	2
E7	0	0	0	0	0	0	3	2	0	0
E8	0	1	1	1	1	2	2	3	1	1
E9	1	3	1	2	0	1	0	1	3	1
E10	1	2	2	0	0	2	0	1	1	3

VI.4.3. Building the aggregated DSM

The aggregated DSM results from the weighted sum of the DSMs built for each of the criteria (Section 5 in chapter 4). The weights are determined using brainstorming among the experts. The experts see the functionality criterion as the most important with a weight of 0.5. They assumed that commonality importance can be represented with a weight of 0.3. They also agreed on assigning equal weights to human resources and information & technology with a weight of 0.1. The aggregated DSM A is shown in table 24.

RStudio was used to compute the aggregated matrix A and the output of the full aggregated matrix will be in appendix II

Table 24. Aggregated matrix A

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
E1	3.0	1.3	2.0	2.0	2.2	1.2	0.3	0.0	1.3	0.9
E2	1.0	3.0	0.6	1.4	0.5	0.6	0.5	1.0	2.9	1.4
E3	2.0	0.9	3.0	1.8	1.6	0.0	0.3	1.2	1.4	1.5
E4	2.0	1.7	1.8	3.0	1.7	1.0	0.4	0.9	1.7	0.0
E5	2.2	0.8	1.6	1.7	3.0	0.3	0.0	0.8	0.7	0.4
E6	1.2	0.9	0.0	1.0	0.3	3.0	1.6	2.0	2.4	1.8
E7	0.3	0.5	0.3	0.4	0.0	1.6	3.0	2.6	0.7	0.7
E8	0.0	1.0	1.2	0.9	0.8	2.0	2.6	3.0	2.3	1.2
E9	1.3	2.9	1.4	1.7	0.7	2.4	0.7	2.3	3.0	1.2
E10	0.9	1.4	1.5	0.0	0.4	1.8	0.7	1.2	1.2	3.0

VI.4.4. Clustering the aggregated matrix

The aggregated matrix A will be now rearranged to form the initial clusters that can present the modules using hierarchical and partitioning clustering using *k*- medoids. The two clustering techniques are implemented using Rstudio to compute their respective results (Section 6 in chapter 4). For hierarchical clustering, ward.D method is used to calculate the distance between the two elements to form the hierarchical dendrogram. While observing the dendrogram output, there can be several different scenarios for the quality level of the clustering based on the cutting level of the dendrogram.

For the *k*-medoids technique, a PAM algorithm is used to implement the *k*-medoids clustering technique. The number of clusters has to be defined before implementing the algorithm. The Silhouette method, which indicates the optimum number of clusters, is presented for *k*-medoids clustering techniques to help in deciding on the number of clusters. It is used as a starting point for having an input for the K number in *k*-medoids clustering.

Figures 53 and 54 show respectively optimal numbers of clusters using k-medoids (13 clusters) and hierarchical clustering (13 clusters).

Those numbers of clusters will be the inputs for both hierarchical and k-medoids techniques for deciding the quality level of clustering results.

Figure 55a shows the dendrogram formed with 13 clusters resulting from the hierarchical clustering and figure 55b shows the clusters formed using k-medoids. By studying figures 53 and 54 and comparing the silhouette width with other numbers of clusters, we can conclude that 12, 13, 15 and 16 clusters can also be used for the comparison since their values are close to the

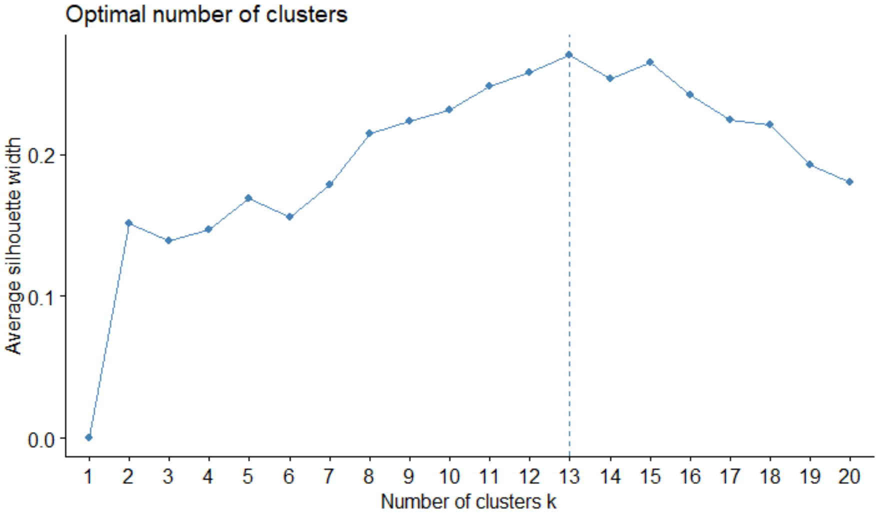


Figure 54. Optimum number of clusters (PAM)

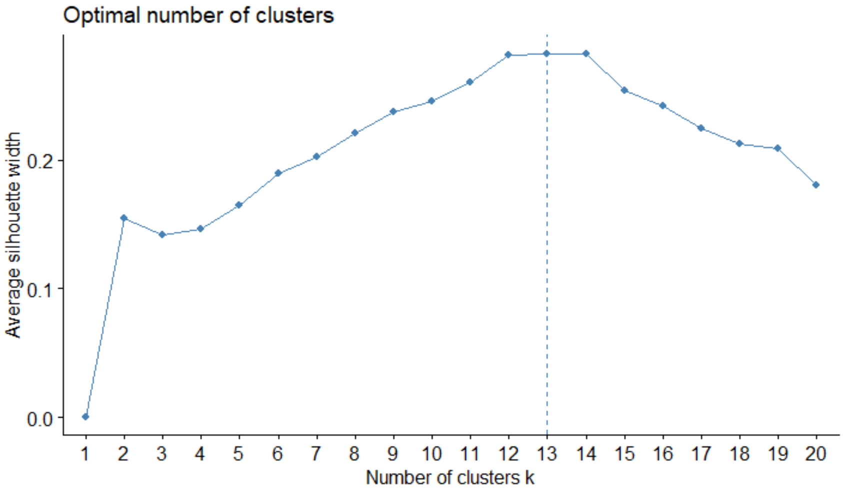


Figure 53. Optimum number of clusters (hierarchical)

optimum value of 13 clusters. Those numbers of clusters will be the inputs for both hierarchical and k medoids techniques for deciding the quality level of clustering. So there will be a total of 4 scenarios with a total of 12, 13, 14, and 15 clusters. Those scenarios will be implemented through both clustering techniques. Therefore in total, there will be 8 scenarios as follows:

Scenario 1 (S1): 12 clusters with hierarchical clustering

Scenario 2 (S2): 12 clusters with *k*-medoids clustering

Scenario 3 (S3): 13 clusters with hierarchical clustering

Scenario 4 (S4): 13 clusters with *k*-medoids clustering

Scenario 5 (S5): 14 clusters with hierarchical clustering

Scenario 6 (S6): 14 clusters with *k*-medoids clustering

Scenario 7 (S7): 15 clusters with hierarchical clustering

Scenario 8 (S8): 15 clusters with *k*-medoids clustering

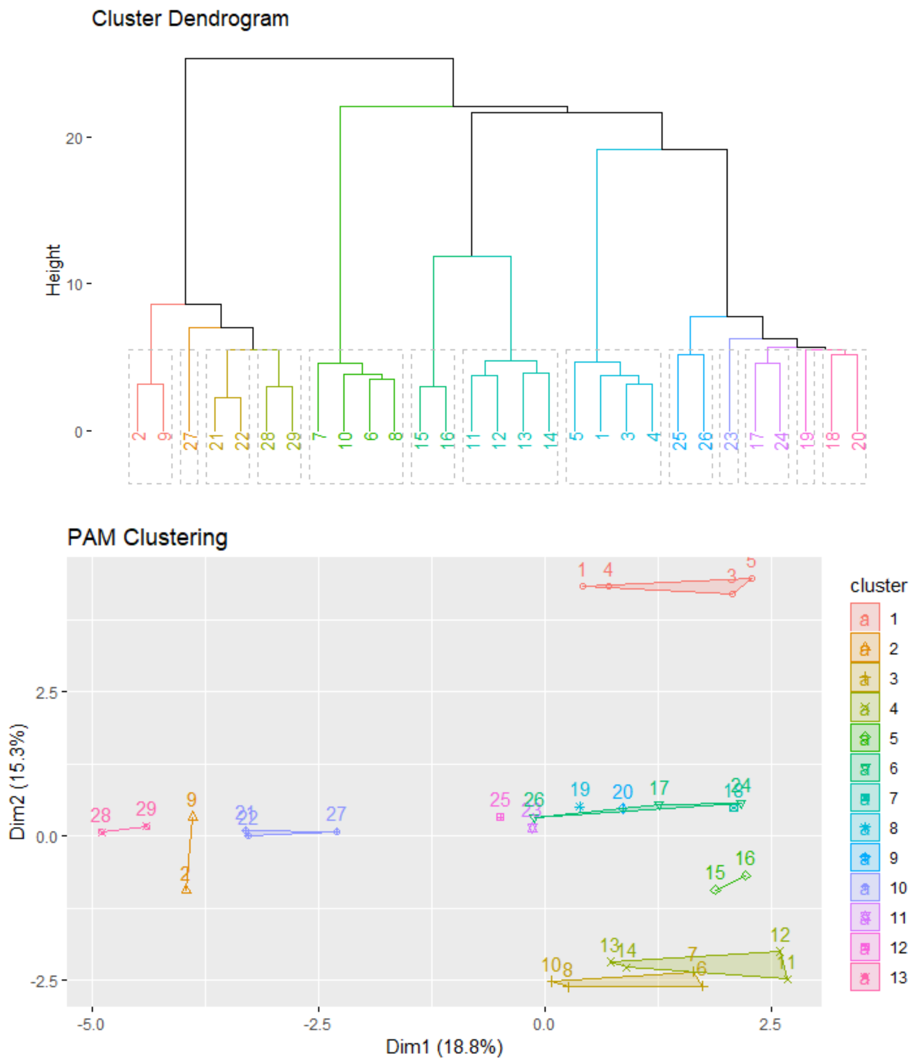


Figure 55. a) Dendrogram with 13 clusters b) k-medoids with 13 clusters

Table 25 shows the clusters formed in each scenario case.

Table 25. Cluster scenarios

Clusters	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
1	E1,E3,E4, E5	E1,E3,E4, E5	E1,E3,E4, E5	E1,E3,E4, E5	E1,E3, E4, E5	E1,E3,E4, E5	E1,E3,E4, E5	E1,E3,E4, E5
2	E2,E9	E2,E9	E2,E9	E2,E9	E2,E9	E2,E9	E2,E9	E2,E9
3	E6,E7,E8,E10	E6,E7,E8,E10	E6,E7,E8,E10	E6,E7,E8,E10	E6,E7, E8,E10	E6,E7,E8,E10	E6,E7,E8,E10	E6,E7,E8,E10
4	E11,E12, E13, E14	E11,E12, E13, E14	E11,E12, E13, E14	E11,E12, E13, E14	E11,E12, E13, E14	E11,E12, E13, E14	E11,E12, E13, E14	E11,E12, E13, E14
5	E15,E16	E15,E16	E15,E16	E15,E16	E15,E16	E15,E16	E15,E16	E15,E16

6	E17,E24	E17,E24, E26	E17,E24	E17,E24, E26	E17,E24	E17,E24	E17,E24	E17,E24
7	E18, E20	E18	E18, E20	E18	E18, E20	E18	E18	E18
8	E19	E19	E19	E19	E19	E19	E19	E19
9	E21,E22, E28,E29	E20	E21,E22	E20	E21,E22	E20	E20	E20
10	E23	E21,E22, E27,E28, E29	E23	E21,E22, E27	E23	E21,E22, E27	E21,E22	E21,E22, E27
11	E25,E26	E23	E25,E26	E23	E25	E23	E23	E23
12	E27	E25	E27	E25	E26	E25	E25	E25
13			E28,E29	E28,E29	E27	E26	E26	E26
14					E28, E29	E28,E29	E27	E28
15							E28, E29	E29

It can be observed that some elements have strong interdependency among each other, as they are proposed simultaneously (e.g. E1, E3, E4 and E5), therefore they can be considered as good candidates to form modules. Some elements can be considered as outliers since they form single element clusters (e.g. E19). This could direct the decision-makers into some preliminary decisions on what elements, products, and/or services to put together.

Clusters 1, 3 and 4 show that the formation of the main modules of each product. In the beginning, we had three different cleaning modules, three different body modules, three different energy modules and three different displacement modules. After assigning similarity indices between the element and formation of numerical DSM and aggregated DSM, 3 different clusters that contain each of energy, cleaning displacement and body module of the robot. Cleaning1, Energy1, Displacement1 and Body1 of cluster 1 has strong similarity indices between each other so they can be treated as one module as they will always be together in term of the final solution of a product. The same concept goes for the other main modules.

Cluster 5 shows the cluster formed between elements 15 and 16. They are both services of consulting the best solution and equipment test execution. Since they are formed together, a multi-skilled resource will be formed that will be an engineer who can do both jobs. The cluster can be named ‘before sales services’ that includes the consulting of the product and the equipment test execution.

There is a cluster formed between product and service that is between the monitor module and the check-up in distance (cluster 13 in scenarios 3 and 4).

VI.4.5. Evaluating the Cluster output

This step helps to point out clustering scenario differences through indicators to select ultimately a preferred scenario from the decision-makers' point of view. Figures 56 and 57 report on the consistency measure of both hierarchical clustering and the PAM algorithm using the silhouette measure with 12 clusters. The dotted line shows the average silhouette index for all the elements. The bars refer to the silhouette index for each of the elements within the clusters. A zero silhouette index means that the element is part of a single element cluster.

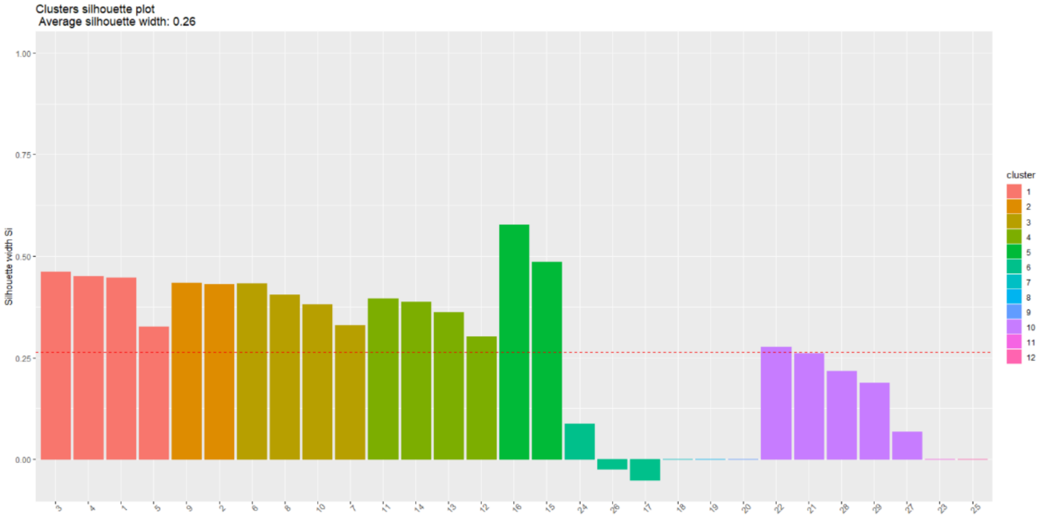


Figure 56. Consistency of hierarchical clustering (S1)

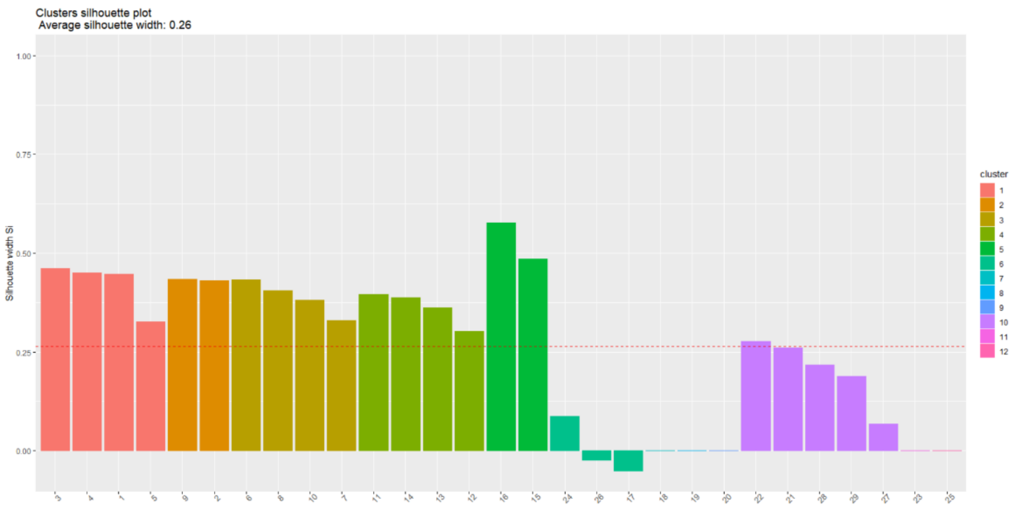


Figure 57. Consistency of PAM clustering (S2)

Complementary, figure 58 reports on the indicators evaluating the eight clustering scenarios. Figure 58a (the left figure) shows the number of elements under the average index (Indicator B). Indicator C is related to the number of non-applicable clusters. Indicator D is related to the number of applicable clusters formed. Each cluster includes more than one element.

It can be observed that S8 and S7 have the least number of elements under the average index of the silhouette measurement with 3. S1 has the highest number (10) of elements under

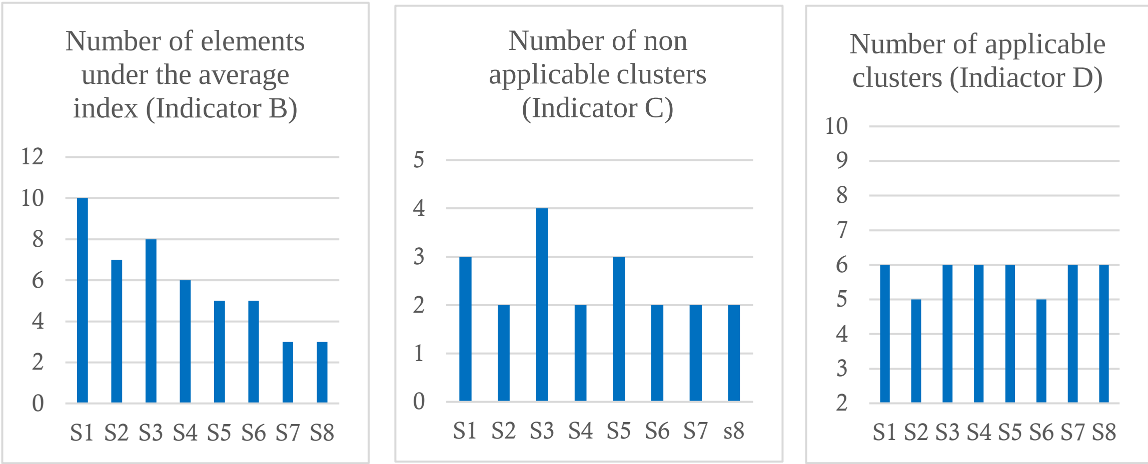


Figure 58. (a) Indicator B ; (b) Indicator C ; (c) Indicator D

the average index followed by S3. Regarding the indicator of non-applicable clusters, S2, S4, S6, S7, S8 are considered the best case scenario with only 2 non-applicable clusters. S3 represents the worst case scenarios with 4 non-applicable clusters followed by S1 and S5 with 3 clusters. The last indicator shows that S2 and S6 have the least number of applicable clusters with a total of 5.

It can be distinguished from indicator B that the more number of clusters that each scenario has the fewer the number of elements under the average index. The reason for this that there are several clusters done that consist of only one element. Figure 59 shows the number of clusters formed that have just one element for each scenario. S7 and S8 have the most formed clusters that include just one element in the cluster. Each one has a total of 7 clusters. While S1 and S3 each have fewer clusters that consist of 1 element. Each one has a total of 3 clusters.

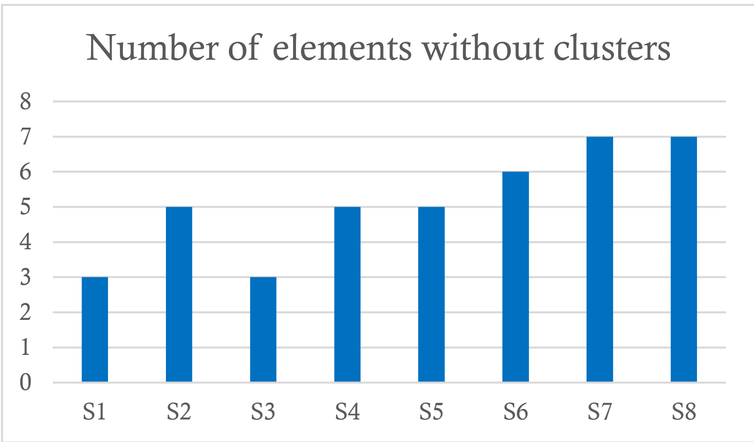


Figure 59. Number of elements without clusters

Based on the above results and due to the small differences between the scenarios, all the scenarios are considered good candidates. This is a special case here but in more general cases, some clustering of insufficient quality could be ruled out. This clearly shows that the usual indicators of clustering quality are insufficient to differentiate the possible scenarios and that the second evaluation is all the more necessary. Therefore, the output scenarios will undergo another evaluation procedure to measure their impact on the performance of the company.

The above evaluation is used to evaluate the consistency of the clusters and how well each cluster is formed. Another evaluation is proposed to be able to choose the most suitable scenario for the industrial context.

VI.5. Measuring the impact of modularity on performance

After having a set of scenarios that are considered to be good candidates to be the most suitable modularity scenario for the case study, an evaluation of performance has to be carried out for each of the alternative clustering scenarios (section 2 chapter 5).

VI.5.1. Translate the scenarios into BPMN processes

In our case study, we are having 8 scenarios that are needed to undergo thorough the evaluation process. So we will have 8 different BPMN processes (one for each scenario) and each cluster for each scenario will have its own BPMN with the needed activities and the resources. A part of the BPMN process for cluster 5 is shown in figures 60 and the rest will be shown in appendix III. This BPMN corresponds to the cluster {E15; E16}. Thus the BPMN process describes the integrated processes to produce these two elements. E15 is a consulting service and E16 is an equipment test service. So instead of doing each of the services separately, our method proposes to realize these two services with one integrated process. The figure includes 3 swimlanes corresponding to 3 distinct types of actors required to execute the services. Data information on the site of the customer is required. This way of modeling supports the indicator measurements. Indicator I6 can be an example as it measures the flow between activities from a different lane. In the figure, there is 3 interaction flows among the 3 different actors. The cluster will start with receiving the order from the customer by the consulting engineer. Then he will contact the customer to exchange with him about the requirement and the needs that the customer would like to have. The consulting engineer will propose a solution to the customer. After that, he will send information to the electrical engineer and to the maintenance engineer. The electrical engineer will prepare the required configuration and the required elements. And after preparing all the needed equipment, the electrical engineer will send to the maintenance engineer the required configured equipment. The maintenance engineer will receive information from the consulting engineer to prepare an order to go for the customer to test the equipment and will have another information from the electrical engineer that the equipment is ready and configured. The maintenance engineer will test the equipment on the customer site. And after finalizing the test, he will send the information to the consulting engineer.

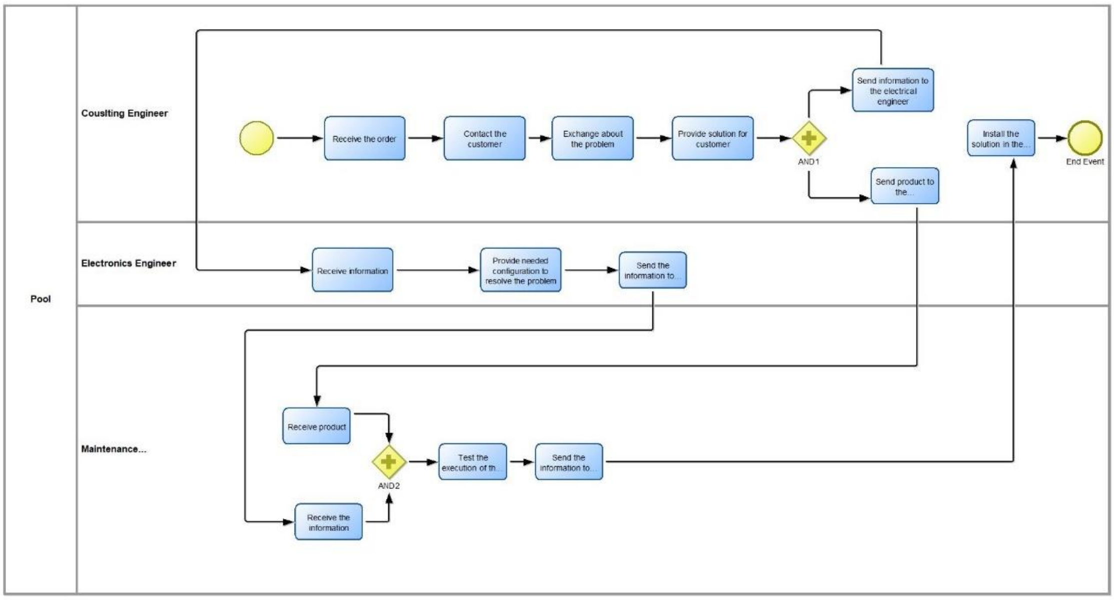


Figure 60. Cluster 5 (E15 & E16)

VI.5.2. Operational measurement results

Table 26 shows the results of each of the operational measurement indicators for each alternative clustering scenario. The seven operational measurements were used to discriminate between each of the scenarios (Section 5 in chapter 5).

Table 26. Operational measurement results

Symbol	Description	S1	S2	S3	S4	S5	S6	S7	S8
I1	Number of activities	214	210	220	223	222	225	227	228
I2	Number of human resources types	8	8	9	9	9	9	9	9
I3	Control-flow complexity	40	36	44	42	44	40	42	38
I4	Longest path of the process (Diameter	188	181	190	192	192	195	197	199
I5	Percentage of multi-skilled human resources	25%	25%	11.1%	11.1%	11.1%	0	11.1%	0
I6	The flow between activities from a different lane	33	36	34	38	33	37	31	38
I7	Number of clusters (modules)	12	12	13	13	14	14	15	15

VI.5.3. The evaluation criteria model

After identifying the scenarios, it is necessary to identify which relevant criteria dimension can be used to evaluate the different alternative scenarios. Figure 61 shows the model of the evaluation criteria with all the levels of dimensions and each criterion used. The three perspective criteria (industrial performance, diversity and organization) are needed for the evaluation of the alternative scenarios. Then five different impact (Variety level, Cost, Lead time, Complexity, Organizational) dimensions that each one influences each of the perspectives are needed. The seven operational measurement indicators that influence each of the impacts. Influences are depicted by arrows

The criteria evaluation model was suitable for the case study. We used all the three dimensions of evaluation that were described in section 6 in chapter 5. The descriptive information of the processes is sufficient for measurements on these 3 different dimensions.

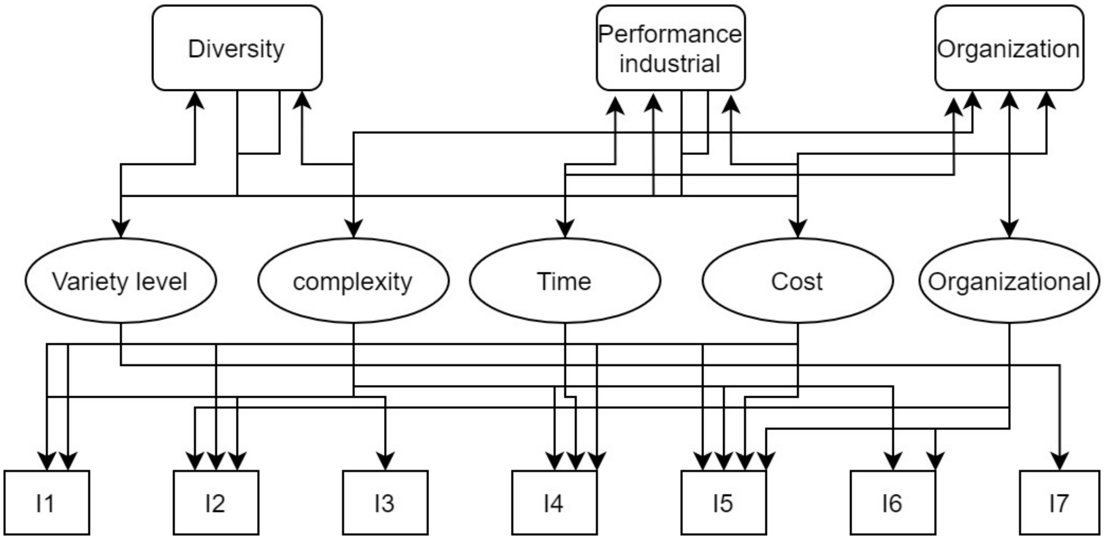


Figure 61. Criteria evaluation model

For the relationship between operational measurement indicators and impacts it will be as follows:

- I1,I2,I3,I4,I5,I6 influence the complexity impact.
- I1,I2,I4,I5 influence the cost impact
- I1,I4, I5 influence the time impact
- I2,I5,I6 influence the organizational impact
- I7 influences the variety level impact

VI.5.4. Rank the alternatives scenarios

The last step is to rank the alternative scenarios based on the evaluation model. ANP method is used to rank the scenarios using the evaluation criteria model to prioritize the scenarios (Section 7 in chapter 5).

VI.5.4.1. Model and goal construction

The first step for applying the ANP method is to create the model criteria structure and to define the goal or the problem. Our goal is to be able to choose the optimal clustering alternative scenarios for the industrial test case. The next step is to define the model for ANP that illustrates the relationship and dependency between the criteria, the goal and the alternatives. The model for ANP usually consists of a set of clusters that each one has the elements that are either the different criterion or the alternatives scenarios. In our case, we have 5 clusters. The first cluster is the main goal that is choosing the best scenario. The second cluster is the 3 perspective criteria. The third cluster is the 5 impact criteria. The fourth cluster is the 7 operational measurement indicators. And the last cluster is the 5 alternative clustering scenarios that we have as a result of implementing modularity. This is shown in figure 62.

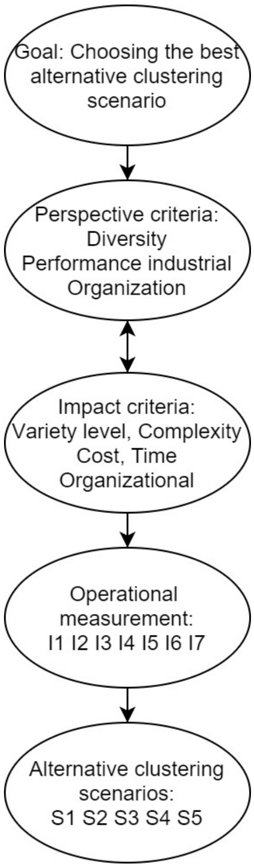


Figure 62. ANP model

VI.5.4.2. Pair-wise comparisons matrices and priority vectors

A workshop was conducted between researchers to make the pairwise comparison of the decision criteria and assign the relative scores. The researchers worked for 3 years in direct and close collaboration with manufacturers, they were, therefore, able to play roles to represent industrial points of view. In the workshop, the objective was to select a pairwise comparison between the different dimensions of the evaluation model. They need to prioritize the importance of each criterion indicator related to the other criteria. The number of experts was 5. The first step is to do the pairwise comparison between the perspectives.

$$W = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ W_{2,1} & 0 & W_{2,3} & 0 & 0 \\ 0 & W_{3,2} & 0 & 0 & 0 \\ 0 & 0 & W_{4,3} & 0 & 0 \\ 0 & 0 & 0 & W_{5,4} & 0 \end{pmatrix} \qquad (16)$$

The above matrix (eq 16) describes the relationship that is included among the criteria and sub-criteria clusters, in our case among (goals (1), perspectives(2), impacts(3), operational measurements(4) and alternatives scenarios(5)). It is important to study this matrix to define the pairwise comparison between the elements of the criteria and sub-criteria clusters. $W_{2,1}$ describes the pairwise comparison between the elements of the perspective dimension concerning the goal. $W_{2,3}$ defines the pairwise comparison between the elements of the perspective dimension with regards to the impact criteria. The following tables will show the pairwise comparison weight of each element in eq 16.

To measure the eigenvector and the consistency for the pairwise comparison of each element of the matrix in eq 16, RStudio software was used.

Table 27 shows the pairwise comparison of the first element in the matrix in equation 16 (W_{21}). It shows the pairwise comparison between the perspectives with regards to the goal which choosing the best clustering scenario. For example, Diversity is 3 times more important than industrial performance and 9 times more important than the organization perspective. The consistency ratio was performed and it shows that table 27 is consistent with a value equals to 0.

Table 27. Pairwise comparison ($W_{2,1}$) between the goal and the perspectives

Perspectives	Diversity	Industrial performance	Organization	Weight (eigenvector)
Diversity	1	3	9	0.66
Industrial performance	1/3	1	7	0.29
Organization	1/9	1/7	1	0.05
$\lambda_{max} = 3$ CI = 0 CR= 0 ≤0.1 Consistency				

Table 28 shows the pairwise comparison of the second element in the matrix ($W_{3,2}$) It shows the pairwise between the impacts criteria while putting into consideration each of the perspectives. Variety level and complexity impacts influence the diversity perspective and both have the same importance. For the industrial performance perspective, it is influenced by cost and time impacts. The organization perspective is only influenced by the organizational impact. The matrix is consistent as the consistency ratio is less than 0.1.

Table 28. Pairwise comparison (W3,2) between the perspectives and the impacts

Diversity perspective (P1)	Industrial performance perspective (P2)

Impact	Variety level	Complexity	Weight (Eigenvector)
Variety level	1	1	0.5
Complexity	1	1	0.5
$\lambda_{max} =$ 2 CI = 0 CR= 0 ≤0.1 Consistency			

Impact	Cost	Time	Weight (Eigenvector)
Cost	1	3	0.75
Time	1/3	1	0.25
$\lambda_{max} =$ 2 CI = 0 CR= 0 ≤0.1 Consistency			

Organization perspective (P3)

Impact	Organizational	Weight (Eigenvector)
Organizational	1	1

[redacted]

Table 29 shows the pairwise comparison of the third element in the matrix (W2,3).

Table 29.Pairwise comparison ($W2,3$) between the impacts and the perspectives

Complexity impact (C1)

Perspective	P1	P2	P3	Weight (Eigenvector)
P1	1	7	9	0.77
P2	1/7	1	5	0.17
P3	1/9	1/5	1	0.06
$\lambda_{max} =$ 3 CI = 0 CR= 0 ≤0.1 Consistency				

Variety level (C2)

Perspective	P1	[redacted]	Weight (Eigenvector)
P1	1	[redacted]	1
[redacted]			

Cost impact(C3)

Perspective	[redacted]	P2	P3	Weight (Eigenvector)
[redacted]				
P2	[redacted]	1	7	0.875
P3	[redacted]	1/7	1	0.125
$\lambda_{max} =$ 2 CI = 0 CR= 0 ≤0.1 Consistency				

Time impact (C4)

Perspective	[redacted]	P2	P3	Weight (Eigenvector)
[redacted]				
P2	[redacted]	1	7	0.875
P3	[redacted]	1/7	7	0.125
$\lambda_{max} =$ 2 CI = 0 CR= 0 ≤0.1 Consistency				

Organizational (C5)

Perspective	[redacted]	P3	Weight (Eigenvector)
[redacted]			
P3	[redacted]	1	1
[redacted]			

It shows the pairwise between the perspectives criteria while putting into consideration each of the impacts.

Diversity, industrial performance and organization perspectives influence the complexity impact. Variety level impact is only influenced by the diversity perspective. Cost and time are influenced by industrial performance and organization perspective. The organizational impact is only influenced by the organization perspective.

Table 30 shows the fourth element in the matrix ($W_{4,3}$). It shows the pairwise comparison between the impacts criteria and the operational measurement indicators. I7 is the only indicator that influences the variety level impact. I1, I2, I3, I4, I5, I6 are the indicators that influence the complexity impact and the pairwise comparison was calculated between them. The cost impact is influenced by I1, I2, I4, I5. The time impact is influenced by indicators I1, I4, I5, and lastly the organizational impact is influenced by indicators I2, I5, I6. The pairwise comparison is calculated between the indicators with regards to each of the impacts

Table 30. Pairwise comparison ($W_{4,3}$) between the impacts and the operational measurement

Variety level impact							
Indicators	I7						Weight (eigenvector)
I7	1						1
Complexity impact							
Indicators	I1	I2	I3	I4	I5	I6	Weight (eigenvector)
I1	1/1	3/1	1/5	1/1	3/1	1/5	0.1
I2	1/3	1/1	1/5	1/1	1/5	1/3	0.05
I3	5/1	5/1	1/1	5/1	5/1	3/1	0.41
I4	1/1	1/1	1/5	1/1	3/1	1/3	0.1
I5	1/3	5/1	1/5	1/3	1/1	1/5	0.08
I6	5/1	3/1	1/3	3/1	5/1	1/1	0.26
$\lambda_{max} =$ 6 CI = 0 CR = 0 ≤0.1 Consistency							
Cost impact							
Indicators	I1	I2	I4	I5			Weight (eigenvector)
I1	1/1	1/3	1/7	1/3			0.08
I2	5/1	1/1	1/1	3/1			0.42
I4	7/1	1/1	1/1	1/3			0.35
I5	3/1	1/3	1/5	1/1			0.15

λ_{max} = 4 CI = 0 CR= 0 ≤0.1 Consistency					
Time impact					
Indicators	I1	I4	I5	[redacted]	Weight (eigenvector)
I1	1/1	1/7	3/1	[redacted]	0.15
I4	7/1	1/1	9/1	[redacted]	0.78
I5	1/3	1/9	1/1	[redacted]	0.07
λ_{max} = 3 CI = 0 CR= 0 ≤0.1 Consistency					
Organizational impact					
Indicators	I2	I5	I6	[redacted]	Weight (eigenvector)
I2	1/1	1/3	1/5	[redacted]	0.1
I5	3/1	1/1	1/3	[redacted]	0.26
I6	5/1	3/1	1/1	[redacted]	0.63
λ_{max} = 3 CI = 0 CR= 0 ≤0.1 Consistency					

The last element in matrix 16 is W5,4 that is the relationship dependency between the alternative cluster and the operational measurement indicator cluster. It is the normalized result of the operational measurement indicator for each of the alternative clustering scenarios to be able to put them in the supermatrix cells. Table 31 shows the normalized operational measurement indicators.

Table 31. Normalized operational measurement indicators

Symbol	Description	S1	S2	S3	S4	S5	S6	S7	S8
I1	Number of activities	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12
I2	Number of human resources types	0.14	0.14	0.12	0.12	0.12	0.12	0.12	0.12
I3	Control-flow complexity	0.21	0.13	0.1	0.11	0.1	0.11	0.11	0.12
I4	Longest path of the process (Diameter	0.18	0.19	0.09	0.17	0.09	0.09	0.09	0.09
I5	Percentage of multi-skilled human resources	0.27	0.27	0.12	0.12	0.12	0	0. 12	0

I6	The flow between activities from a different lane	0.2	0.1	0.11	0.16	0.11	0.1	0.12	0.1
I7	Number of clusters (modules)	0.14	0.14	0.13	0.13	0.12	0.12	0.11	0.11

VI.5.4.3. Supermatrix formation

Forming the supermatrix is the next step. It gathers all the pairwise comparison matrices that have been done in the last step and put them in one big matrix. The matrix in equation 16 shows how will be the shape of the matrix and where each of the pairwise comparisons will lie in the matrix. Figure 63 shows the resulting supermatrix.

		Criteria(Perspectives)			Sub-criteria(Impact)					Indicators(Operational measurement)							Alternatives (Scenario)							
	Goal	Diversity	Industrial Performance	Orgaanizational	Variety	Complexity	Cost	Time	Organizational	I1	I2	I3	I4	I5	I6	I7	S1	S2	S3	S4	S5	S6	S7	S8
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diversity	0.66	0	0	0	1	0.77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Performance	0.29	0	0	0	0	0.17	0.875	0.875	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orgaanizational	0.05	0	0	0	0	0.06	0.125	0.125	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Variety	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Complexity	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	0	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizational	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I1	0	0	0	0	0	0.1	0.08	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I2	0	0	0	0	0	0.05	0.42	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I3	0	0	0	0	0	0.41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I4	0	0	0	0	0	0.1	0.35	0.78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I5	0	0	0	0	0	0.08	0.15	0.07	0.26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I6	0	0	0	0	0	0.26	0	0	0.63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I7	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0	0	0	0.13	0.14	0.21	0.18	0.27	0.2	0.14	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0.13	0.14	0.13	0.19	0.27	0.1	0.14	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0.13	0.12	0.1	0.09	0.12	0.11	0.13	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0.12	0.12	0.11	0.17	0.12	0.16	0.13	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0.12	0.12	0.1	0.09	0.12	0.11	0.12	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0	0	0.12	0.12	0.11	0.09	0	0.1	0.12	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0	0	0.12	0.12	0.11	0.09	0.12	0.12	0.11	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0.12	0.12	0.12	0.09	0	0.1	0.11	0	0	0	0	0	0	0	0

Figure 63. Unweighted supermatrix

The formed supermatrix is unweighted. Therefore normalizing the supermatrix is needed, by simply dividing each coefficient by the sum of each column (only for columns that their sum is not 1 nor 0). Figure 64 shows the weighted supermatrix after normalization.

		Criteria(Perspectives)			Sub-criteria(Impact)					Indicators(Operational measurement)							Alternatives (Scenario)							
	Goal	Diversity	Industrial Performance	Orgaanizational	Variety	Complexity	Cost	Time	Organizational	I1	I2	I3	I4	I5	I6	I7	S1	S2	S3	S4	S5	S6	S7	S8
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diversity	0.66	0	0	0	0.385	0.385	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Performance	0.29	0	0	0	0.085	0.085	0.4375	0.4375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orgaanizational	0.05	0	0	0	0.03	0.03	0.0625	0.0625	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Variety	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Complexity	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	0	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizational	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I1	0	0	0	0	0.05	0.05	0.04	0.075	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I2	0	0	0	0	0.025	0.025	0.21	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I3	0	0	0	0	0.205	0.205	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I4	0	0	0	0	0.05	0.05	0.175	0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I5	0	0	0	0	0.04	0.04	0.075	0.035	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I6	0	0	0	0	0.13	0.13	0	0	0.315	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0	0	0	0.13	0.14	0.21	0.18	0.27	0.2	0.14	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0.13	0.14	0.13	0.19	0.27	0.1	0.14	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0.13	0.12	0.1	0.09	0.12	0.11	0.13	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0.12	0.12	0.11	0.17	0.12	0.16	0.13	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0.12	0.12	0.1	0.09	0.12	0.11	0.12	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0	0	0.12	0.12	0.11	0.09	0	0.1	0.12	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0	0	0.12	0.12	0.11	0.09	0.12	0.12	0.11	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0.12	0.12	0.12	0.09	0	0.1	0.11	0	0	0	0	0	0	0	0

Figure 64. Weighted supermatrix

VI.5.4.4. Selecting the best alternatives

The limit supermatrix is formed by squaring up the matrix until reaches convergence (section 7 chapter 5) Figure 65 shows the result of the limit supermatrix. This limit supermatrix shows the final priorities of the scenarios.

		Criteria(Perspectives)			Sub-criteria(Impact)					Indicators(Operational measurement)							Alternatives (Scenario)							
	Goal	Diversity	Industrial Performance	Orgaanizational	Variety	Complexity	Cost	Time	Organizational	I1	I2	I3	I4	I5	I6	I7	S1	S2	S3	S4	S5	S6	S7	S8
Goal	0.00000000	0.00000000	0.00000000	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diversity	0.00000000	0.14822500	0.00000000	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Performance	0.00000000	0.06991250	0.19140625	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orgaanizational	0.00000000	0.03186250	0.05859375	0.2500	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Variety	0.12705000	0.00000000	0.00000000	0.0000	0.07411250	0.07411250	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Complexity	0.12705000	0.00000000	0.00000000	0.0000	0.07411250	0.07411250	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost	0.04574375	0.00000000	0.00000000	0.0000	0.01747813	0.01747813	0.04785156	0.04785156	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time	0.13723125	0.00000000	0.00000000	0.0000	0.05243438	0.05243438	0.14355469	0.14355469	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizational	0.06292500	0.00000000	0.00000000	0.0000	0.03186250	0.03186250	0.05859375	0.05859375	0.250000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I1	0.00000000	0.02488125	0.02898437	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I2	0.00000000	0.01558750	0.02609375	0.0250	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I3	0.00000000	0.07892500	0.00000000	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I4	0.00000000	0.04783125	0.14710937	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I5	0.00000000	0.02312500	0.02781250	0.0650	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I6	0.00000000	0.05950000	0.01968750	0.1575	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I7	0.00000000	0.00000000	0.00000000	0.0000	0.00000000	0.00000000	0.00000000	0.00000000	0.000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1	0.09012332	0.00000000	0.00000000	0.0000	0.05360069	0.05360069	0.05118828	0.05118828	0.066200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0.07421982	0.00000000	0.00000000	0.0000	0.04181500	0.04181500	0.05069062	0.05069062	0.050450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S3	0.05752154	0.00000000	0.00000000	0.0000	0.02407863	0.02407863	0.02258281	0.02258281	0.020975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S4	0.06859102	0.00000000	0.00000000	0.0000	0.03142056	0.03142056	0.03504609	0.03504609	0.028850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S5	0.05610239	0.00000000	0.00000000	0.0000	0.02382981	0.02382981	0.02229297	0.02229297	0.020975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6	0.04951022	0.00000000	0.00000000	0.0000	0.02379281	0.02379281	0.02181797	0.02181797	0.018750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S7	0.05650947	0.00000000	0.00000000	0.0000	0.02521406	0.02521406	0.02248984	0.02248984	0.022550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S8	0.04856729	0.00000000	0.00000000	0.0000	0.02458206	0.02458206	0.02181797	0.02181797	0.018750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 65. Limit supermatrix

The relationship between the scenarios and the goal shows the ranking of the scenarios related to the goal. The limit supermatrix shows that the ranking of the scenarios will be as follows: S1>S2>S4>S3>S7 >S5>S6>S8. S1 is the scenario that has the smaller number of clusters with a total number of clusters equals 12 same as scenario 2 that has the same total number of clusters but using a different clustering technique (k-medoids). Scenarios 1 and 2 have more modularized elements than other scenarios.

More than one dimension affects the output of the ranking. The results of the operational measurement show that scenarios 1 and 2 have the best value of most of the operational measurements. Also having a fewer number of clusters makes the number of activities lower (I1). I1 has a high influence on several criteria impacts based on the pairwise comparison explained before. The difference between S1 and S2 is the clustering technique (S1 is the output of hierarchical clustering and S2 is the output of *k*-medoids clustering) as both have the same number of clusters but the arranging of the clusters is different because of the difference of algorithms.

In S1, 12 clusters were formed. There are 3 clusters formed that they have just one element in the cluster, so we can understand that they do not share similarity indices with other elements. In other words, they will not form a cluster with other elements and it is better to keep it alone. S1 has three different types of formed clusters (modules): product clusters where we can have clusters of product modules (cluster 1, cluster 2), service clusters where we can have clusters of services (cluster 6, cluster 7) and one cluster where we can have both product and services (cluster 9). Other scenarios can have different structures of clusters either because of the clustering algorithm or because of the breaking down of some clusters to smaller clusters (since we increase the number of output clusters).

This method gives an idea of the scenarios' ranking from a performance evaluation point of view. The decision-makers can use the outputs to decide whether they should take the whole scenario and change the way to organize the elements of products or services. Or the decision-makers can have some clusters be developed from some elements of products and services while keeping the other remaining elements without clusters. The first five clusters formed can be an example as they are repeated in every clustering scenarios. That means that there are strong similarity indices among elements of those clusters.

Decision-makers should use the output data of this method and start to analyze and discuss the change in the structure of elements of both products and services. The output is considered as a guideline of how the clusters should be and how will be its impact on the industrial performance of the company.

Our final ranking was based on the pairwise comparison index assigned to each perspective and impact that was decided throughout the case study by the decision-makers. The importance rate for each criterion helps in defining the ranking as it is related to the pairwise comparison between different criteria of the decision-makers. Changing the priority index may change the order of the final ranking.

We can then propose a first sensitivity analysis concerning this priority index. All weights of indicators in our method could influence the final ranking. But first, we can consider that the relative weights of key perspectives (Diversity, Industrial performance, Organisational) should have a major influence, compared to more specific impacts. Thus, we propose to test the sensitivity of the ranking, with regards to the priorities among these perspectives.

We will change the weight of one of the perspectives to figure out how much the alternatives will be changing and check how it will change the ranking output with relation to the goal index (putting into consideration to change the other perspective priority value as the total weight has to be 1). In the previous experimentation, the perspective diversity had 0.66 as a priority weight and it is considered the dominant perspective in terms of importance. This resulted in S1 ranked the first one (figure 66a on the left side). We will change the weight of the importance of the perspective and make industrial performance the dominant perspective. The result shows a change in the order of the scenarios but still, S1 is the most preferred one (figure 66b). Alternatively, we can test to position the organizational perspective as the dominant one. Again the order of the scenarios changes but S1 remains the best scenario (figure 66c).

Impact criteria are considered as variables particularly important for the company that would like to follow the decision-making approach. Defining the criteria will be based upon the industrial context of the company and which criteria the company emphasizes when evaluating the alternative clustering scenarios and choosing the more pertinent for their industrial context. The five chosen criteria were sufficient for this case study as they focus on several areas and can help distinguish which scenario is the best in which area. The managerial implications of the execution of ANP are factors that vary from organization to organization, but that need to be taken into consideration for effective and efficient use of decision-making resources.

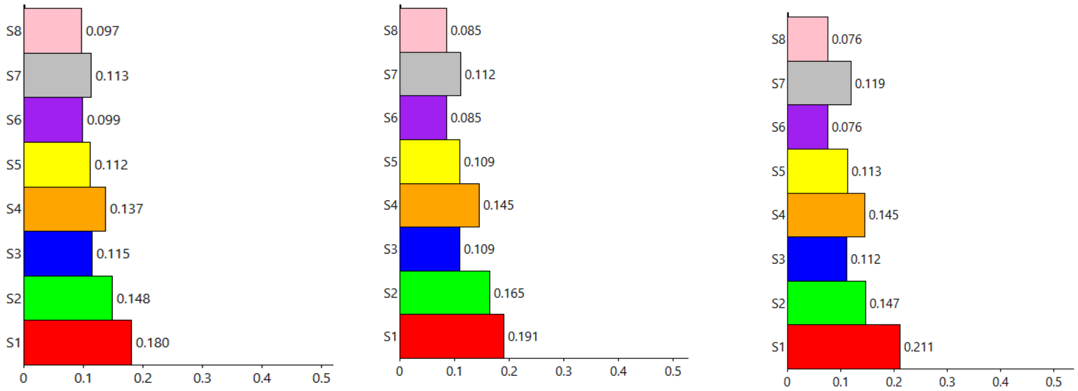


Figure 66. Ranking alternatives with (a) diversity as the most important (b) industrial performance as the most (c) organization as the most important

VI.6. Conclusion

This chapter shows the usage of the proposed methods of applying modularity on a service-oriented system and on measuring the impact of modularity on the industrial context. The industrial case study helps in building and verifying the usage of the methods proposed. The tools used in the case study help building up the steps of the method and to visualize the the output results. The two algorithms (partitioning and hierarchical) were helpful to build several scenarios of clustering that can support decision-makers in choosing the scenario that suits their industrial context.

The indicators were used to help engineers and decision-makers in analyzing the different output scenarios. For instance, they pointed out the applicable and non-applicable output clusters. This helps in identifying and rejecting candidates to build modules. S1 was shown to be the best-ranked scenario. From the industrial point of view, it has less complexity since it will have the fewest number of clusters and it is shown to have a fewer number of processed activities. Also, S1 has more multi-skilled resources than other scenarios, which can help in getting the industrial system more flexible.

According to these first experimentations, the method is shown to be applicable to a system that has both services and products and needs to be modularized. The method is not complicated to be implemented but requires several decision-making processes. The required input data appeared easy to understand and to follow up with it, but it takes some time for the people to gather it. Three workshops were necessary, each one with two sessions of 1.5 hours for each. For the first part of the method (which is to implement the modularity), it required two workshops and some data analysis and statistical work on Rstudio to get the required output. It took around one week to apply the method when all the data input is ready. For the second part (which is to evaluate the modularity impact), it requires some time to translate the clusters into a set of processes. Applying the method in an industrial context in a company would require a person who is familiar with clustering algorithms to implement it on the software. And another person who would be able to model all the clusters into a set of processes. And, of course, interactions with the decision-makers who manage modularity in their company would also be necessary.

The case was considered a service-oriented system. The method was able to form modules of products, services and modules of products and services. 'Check-up in distance' service and 'the monitor product module' formed one cluster of product and service elements. So instead of providing a solution that has those two elements separated, they will always be integrated into one unique offer. Our method provides a practical solution for the ability to make modularity of both product and service together, pertinent for most of nowadays industrial manufacturer which integrate services into their offers. This modular integration helps in decreasing the internal complexity of the company.

Relevant cases in other industries could involve a larger number of elements and a higher variety of products and services components than in the current case study. However, the method will remain fully applicable to such an increased number of elements, and the modularity benefits should even become higher. Regarding the implementation of the method at industrial manufacture, the method is beneficial because the techniques used are relatively well acknowledged in the industry (DSM, clustering, BPMN, ANP,..) and supporting software for implementation is widely available.

In the next chapter, we will discuss the impacts of the case study and the findings of our method. We will provide a full conclusion of the whole method. Future perspectives and limitations will also be discussed in the next chapter.

Chapter VII. CONCLUSION AND PERSPECTIVES

VII.1. Findings & results

The main research issue that was addressed in our thesis is how modularity management can be formalized then implemented for service-oriented systems, to help mitigating industrial complexity while ensuring a high variety level of products and services, so as to capture as many customer preferences as possible. We proposed a method for modularizing a service-oriented system, embedding either products, services or integration of both. The method helps in identifying and visualizing similarity indices among the elements expected to be modularized according to several predefined criteria. These criteria will provide valuable support for decision making for modularizing the elements contributing to the company's offering and ultimately promoting variety management. The method helps in identifying the similarity relationships among products and services according to (i) a distinct mix of the predefined criteria and (ii) various clustering techniques, resulting in different cluster alternatives. The clustering and performance evaluation contributes to the comparison of the modularity scenarios and provides valuable support for the decision-makers on variety management. The evaluation criteria addressed in the method help decision-makers in choosing suitable alternative clustering scenarios representing the product and/or service modules, based on the industrial context and assess the impact of modularity on operational performance (e.g. complexity, variety level, cost, time…etc)

According to the proposed method, the service-oriented system is defined in the case study with 30 different elements, evolving different product modules and a set of services. Similarity indices were calculated based on different predefined criteria. The indices are then combined into one aggregated DSM, on which two basic clustering algorithms were applied. The subsequent clusters have been evaluated using silhouette measures. Compared with other traditional methods, this method was found effective to modularize a service-oriented system in a systematic manner (offering products, services, and supporting processes).

Modularizing a service-oriented system makes it possible to achieve the integration between the products and services and to accomplish the needed quality, variety, and efficiency for the industrial context based on several predefined criteria that include the customer requirements. It also enhances the ability of the system to adapt to requirement changes and to reduce both lead time and costs. It will likely ease the operational management of products and services in the subsequent phase and can also have the potential to boost economies of scale thus supporting mass customization implementation in product and service domains.

The two clustering techniques (partitioning and hierarchical) were helpful to build several scenarios of clustering that can support decision-makers in choosing the scenario that suits their industrial context. The method applied modularity practically on service-oriented systems using both techniques. Each of them provides different ways of clustering the input elements (using different clustering algorithms), resulting in having different constructions of clusters as an output.

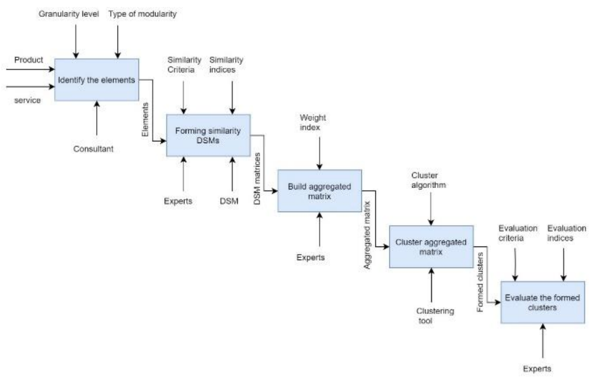
BPMN has been used to visualize the different activities and resources and be able to discriminate between different clustering scenarios from the perspective of industrial process organization. Defining the resources, tools and information manipulated for the production of each element (product modules or services) helped in defining the business processes of each of the clustering scenarios, making them possible a structural and comparative assessment.

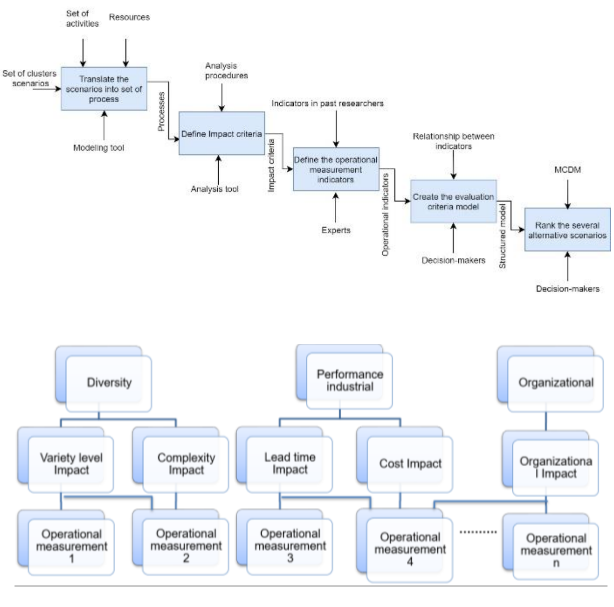
ANP method is considered an effective tool to be able to rank our alternative scenario based on several criteria. It is more flexible because we can have any relation interdependency among any element of criteria in the model structure so, even if, it is more complex to be implemented, it covers complex models where the relationships among the elements of the decision criteria are more complex. It was suitable for our model structure as we have network relationships among all the elements of the model.

Two different applications were addressed in the thesis to demonstrate and illustrate the thesis's approach. An illustrative example of a company that is addressing service modularity by modularizing service production activities into a set of modules. This illustrative example was used to ease the understanding of the methodological step. The other application was a larger case study related to a PSS industrial project, used for a feasibility verification. This case study is based on a service-oriented robotic system that includes both products and services required to be modularized to form modules of either products or services or integration of both.

Table 32 illustrates the main contribution of the thesis. It shows the main research questions that were addressed in the thesis and how we answered those questions.

Table 32. Contribution of the thesis

Research question	Solution	Framework
How to modularize offers of products and/or services?	A modularity procedure for a service-oriented system that can modularize either input of product and/or service using DSM and clustering to create several output scenarios.	

How to evaluate and compare the industrial performance impact of several alternative modularity scenarios?	A modularity impact procedure to measure modularity impacts on industrial performance by evaluating and comparing different alternative scenarios.	

VII.2. Research implication

Our contributions to the thesis have both scientific implications and practical implications. The scientific implication is related to the thesis's contribution to the research gap that was addressed before. The practical implication is related to the thesis's contribution to the designers and decision-makers in industrial companies.

VII.2.1. Scientific implication

Most of the methods that address modularity in the literature are addressed to the product domain and to some extent to the service domain. The methods that are applied to the service domain are related to the conceptual aspects not to a practical one. Our method is different from the traditional methods that were addressed in the literature review that addresses either product domain or service domain or integration of both (which is rarely addressed). Our method addressed the gap by implementing the approach of modularity on service-oriented systems. It is a unique method that can address any type of tangible/intangible system, so making it easier acceptability for industrials. The method was developed conceptually and was applied to two applications in our thesis. One that addresses the service modularity where we modularize the activities into a set of modules and another application that addresses a service-oriented system.

The method is also academically new, as it extends the usage of clustering and DSM to apply to modularization of the domain of service-oriented system by defining service and product components. The discussion of how modularization of service-oriented systems was performed concretely also advances scientific insights in literature.

The method allowed interaction similarity interactions for service and product components based on customer needs, commonality, human resources, tools and information. Those similarity interactions provide a new perspective to be quantified between product and service elements, which does not appear in other literature previously. This is critical to the modularization of service-oriented systems because it affects the way the elements of the system bundled into modules. The method is flexible and open to some changes that are related to each industrial case. The similarity criteria can be changed or chosen based on the industrial context of each case. Different similarity criteria can still be integrated and mixed to adapt to each scientific context.

The method addresses the usage of clustering techniques in developing the modules. We used one algorithm of each technique to illustrate and validate our method. The method is considered also open to new advances in clustering algorithms since the methodological procedure makes it possible to integrate any new clustering technique then compare the various resulting scenarios.

We defined in our method an evaluation model that consists of indicators and criteria to measure the impact of modularity on industrial performance. We identified several impacts and indicators that The evaluation model is considered flexible when addressing the indicators and the criteria as we can integrate new indicators and/or criteria based on each industrial context.

We can conclude that our overall methodology is considered to be flexible and open to changes and incremental improvements of the technical components in the future while respecting the same overall methodological framework that was identified.

VII.2.2. Practical implications

Addressing the variety management on service-oriented systems was the main challenge for our thesis as nowadays service is considered as an important factor in the offers that the company provides to its customers. Generally, in most companies an organizational frontier appears between service activities and manufacturing activities and each type of activity is managed separately. In our approach, these two types of processes are not considered separate from a closed frontier, but the method looks for efficiency improvement based on the integration of both types of activities. Our method considered high integration among service production and product manufacturing by allowing having modules that integrate both product and service components. Additionally, a lack of research has been recognized on the integration between product and service modularity in an integrated product and service system context Our method can manipulate similarity measures among service and product elements where the method can be flexible so it could address only products, only services or both of them

The clustering indicators were used to help engineers and decision-makers in analyzing the outputs of the different scenarios. For instance, they pointed out the applicable and non-applicable output clusters. This helps in identifying and rejecting candidates to build modules.

For example, in our case study in chapter 6, E19 forms its own cluster in all the scenarios which means it can't form a module with other elements. This is ultimately useful in restructuring the products and services for improving efficiency.

Applying modularity to the system enhances the ability of the manufacturing decision-makers to adapt to requirement changes and to boost the company's performance, by reducing the complexity induced by a high level of variety. Therefore it is important to show how applying a modularity scenario affects the performance of the industry. Impacts can affect several dimensions of industrial performance, like process complexity, variety level, cost efficiency, production lead time, or organizational efficiency.

The method was found practically useful. According to the experts, it brings, in a scientific and standardized manner, reasonable modularization that may be different from how methods of modularity are applied in practice at present.

The whole method is used to emphasize the capacity to contextualize the method when adapting it to a specific company, by integrating the pragmatical expertise of experts of the firms at different levels of the method: criteria, preferences, clustering algorithm, performance dimensions and impacts. This reinforces its usability among engineers and decision-makers at large and makes it easy to modularize the system.

The method has the capacity to be contextualized when adapting it to a specific company, by integrating the pragmatical expertise of experts of the firm at different levels of the method: criteria, preferences, clustering algorithm, performance dimensions and impacts. This gives the method to be modified based on each industrial context for each company and reinforces its usability among engineers and decision-makers at large and makes it easy to modularize the system.

VII.3. Limitation and Future perspective

The main thesis contributions are linked with modularity implementation on a service-oriented system and measuring the impact of applying modularity. However, there is additional work that needs to be implemented in the future.

The main issue at the beginning of our thesis is to addresses the challenges of providing variety management for product and service offers and how to decrease the complexity that arises with increasing the offer varieties. In our thesis, we did not address the whole issue of variety management as our approach focused on addressing the issue of providing a modularity method for service-oriented systems. We came up with modularity as a method to mitigate this complexity and consider it as a first step approach to help in providing a variety of offers of products and services while keeping the performance efficiency of the enterprise. Our modularity approach can help engineers and decision-makers defining the foundation design for the variety offers of products and services which will reduce the internal complexity that impacts the performance of the company while maintaining the variety of offers that satisfy the market demands. The proposed procedure is required to be further validated utilizing its applicability in different contexts and industries to verify the contributed results.

VII.3.1. Regarding modularity implementation

Some additional works are needed to be implemented in the future for the first part of the method that is related to implementing modularity. Four main future perspectives are considered that can be done in future research to improve the method.

- Similarity indices in DSM were applied by implementing a workshop with the experts and using brainstorming where the experts discuss together to choose the required similarity indices among elements. Even though the workshop did not face any issues or problems, there can be some discrimination in the future among the experts to assign the value of the similarity index. In the future, each expert can give his own opinion and we can use Multi-criteria decision-making methods to have the required similarity indices.
- Another challenge is to involve several people from different backgrounds (service, production, design…etc.) in the case study. Gathering and integrating the points of view of each person of different departments is considered to be challenging yet it would benefit the application of the method for different departments with different points of view. It impacts the assigning of the similarity indices between the elements as each one may have a different assignment based on his own background. In our case study, the workshop made was by people from the same department. An approach of having one person of each department as a representative in the workshop to apply the similarity indices would help in having different backgrounds and points of view.
- Our method can be applied to either product, service or integration of product and service. In our thesis, we addressed two applications for our method. One is related to the service modularity that modularizes the service activities into a set of modules and the other is related to the PSS project that modularizes products and services into modules of product, services and integration of both. In section IV.2 we addressed two strategies of applying modularity, we used the first strategy where we broke down services and products. There is a need to test the second strategy where we pre-modularized products and services.
- One other perspective is concerning the enlargement of the case study application. Three points can be considered: (i) currently we have only a first feasibility verification, but the organizational and human context could be impacting: this requires a larger panel of experimentation and a protocol to analyze the impact ; (ii) There are certainly different contexts of service and PSS offers where the potential of modularity could be quite different: a study with applications in various sectors and context could

bring insights on such issue (iii) depending on the variety level of the offer, the applicability of the method may differ. So validation of the applicability of the method on a larger case study is considered a future perspective.

VII.3.2. Regarding modularity's impact on industrial performance.

The purpose of the second part of the method to measure the impact of modularity on industrial performance. Three main additional points are considered to be implemented in the future.

- We evaluate the performance of alternative scenarios that have the same aggregated matrix. A distinct aggregated matrix could happen when we change the weight of each similarity criterion. In the future, it would be interesting to evaluate the scenarios that have different aggregated matrices to see the effect of having alternative weights of the similarity criteria that will result in alternative aggregated matrices then develop a sensibility analysis with regards to the influence of similarity criteria during the aggregation. For example, adding the weight of one criterion while decreasing others may change the formation of the aggregated matrix which will result in the different formation of clusters. It could be useful for decision-makers to see the difference that can help them in building the most suitable modules for their industrial context. Such comparative analysis would be based on assessing industrial performance impacts.
- Additional factors can be added when associating the clusters to a set of industrial processes. Some of those factors can be the cost and the time of each of the activities of the process. Also, the labor cost of each of the human resources can be considered as an additional challenge to add while defining the set of processes. It can help in defining in detail some of the indicators that can help in discriminating in details the different clustering scenarios. It is difficult to implement in our method as it is necessary to access very fine and precise information on the manufacturing processes and services process and it has lower applicability on the method.
- More indicators can be added that are related to the variety level impact and organizational impact. We did not address indicators for the variety level impact except the number of clusters. A future perspective would be to address more indicators that can influence the variety level impact. Also, the organizational impact was not addressed sufficiently in our method and more deeply and detailed interaction in the organization can help in evaluating the modularity scenarios

RESUME DE THESE EN FRANÇAIS

Chapitre 1. Contexte et problématiques de recherche

Le concept principal de l'approche de personnalisation de masse (MC) est de fournir des produits et services qui répondent aux demandes de personnalisation des clients tout en essayant de répondre aux normes de coût et d'efficacité de la production de masse (Mitchell et Jianxin 1996). La personnalisation de masse vise à atteindre une grande diversité de produits et de services pour répondre aux besoins personnalisés de différents types de clients. Cependant, la diversification de l'offre est corrélée à une augmentation de la complexité interne du système de production et de l'ensemble de la chaîne d'approvisionnement de l'entreprise. Cette complexité est accrue lorsqu'on considère à la fois les produits et les services conjointement dans une même offre (Wang et al. 2011).

Dans ce domaine, la modularité est apparue comme l'une des méthodes permettant de contribuer à gérer le problème de la complexité. L'idée de base de la modularité est de regrouper les composants en utilisant un groupe de critères qui aboutiront à offrir une grande variété tout en atténuant la complexité interne (Sun et al.2017). La modularité a été largement utilisée comme méthode appliquée dans le domaine des produits (Lau Antonio et al.2007, J. K. Gershenson et al.2003, Danese et Filippini 2013). Elle a été récemment abordée dans le domaine des services au cours des dernières années (Mattos et al., 2019, Brax et al., 2017). Bien que certaines méthodes de modularité soient abordées dans la littérature, elles ont été principalement appliquées au domaine du produit et dans une certaine mesure au domaine du service. La plupart des méthodes appliquées au domaine des services sont liées aux aspects conceptuels des cadres de modularité (Song et al. 2015). C'est également le cas pour le domaine du système intégré de produits et de services. Les travaux de recherche développés dans cette thèse relèveront précisément le défi de la modularité appliquée aux systèmes orientés services. Le système orienté services est un système qui peut avoir des offres de produits ou de services uniquement ou une intégration réelle des deux par composants « système produit-service ».

Ce chapitre est dédié à la construction du contexte de cette étude de recherche et présente les recherches décrites dans cette thèse. Il décrit les problèmes qui résultent de la diversité des offres de produits et de services. Sur cette base, les principaux défis pour atténuer ces problèmes sont discutés avant de définir le but de notre étude et les questions de recherche. Enfin, la conception de la recherche pour résoudre ce problème est détaillée dans la dernière section.

Chapitre 2. Bases de la personnalisation de masse et de la modularité

Ce chapitre a examiné le concept principal et la revue de la littérature sur la personnalisation de masse et la modularité. L'étude de la littérature a soutenu l'idée d'utiliser la modularité comme moteur pour implémenter avec succès la MC dans le système orienté services. La méthode DSM et l'analyse de regroupement sont présentées dans la revue de la littérature comme un potentiel à appliquer pour la modularisation du système orienté services. Nous avons appris de la littérature que les entreprises manufacturières ont commencé à intégrer des services dans leur offre personnalisée pour être en mesure de générer une valeur élevée pour les besoins des clients.

Nous avons également abordé l'impact de la modularité sur les performances industrielles et la manière dont les recherches antérieures l'ont abordé. Alors que certaines méthodes de modularité sont abordées dans la littérature, elles ont été principalement appliquées au domaine du produit et dans une certaine mesure au domaine du service. La plupart des méthodes appliquées au domaine des services apportent de précieuses contributions à la modularité des services à partir du cadre et du processus des aspects conceptuels (Song et al. 2015). Cela s'applique également au domaine du système intégré de produits et de services. Les méthodes pratiques pour appliquer efficacement la modularité dans les systèmes orientés services ont rarement été abordées. Les méthodes abordées dans la littérature ne s'appliquent qu'au domaine du produit ou au domaine du service ou rarement aux deux. Ils n'abordent pas la flexibilité de leurs méthodes pour l'appliquer à d'autres domaines.

L'analyse de clustering est une étape clé du processus de modularisation d'un système. Bien que plusieurs techniques soient disponibles pour exécuter l'algorithme de clustering, il n'existe pas de technique exclusivement la meilleure. Chaque technique donnera lieu à des extrants différents : leur analyse comparative peut aider à la rechercher du meilleur résultat en fonction du contexte industriel de l'entreprise (Ezzat et al.2019). Par conséquent, l'approche rigoureuse de la thèse est d'avoir une méthode qui fournit les meilleurs résultats de modularisation pour un système orienté services, dans un contexte donné. De plus, il est important de disposer d'indicateurs pour évaluer les différents résultats car ils fournissent un soutien précieux pour l'analyse comparative des scénarios alternatifs de regroupement. Alors qu'une partie de la littérature a abordé les indicateurs d'évaluation soit du clustering, soit de la performance, aucune recherche n'a abordé à la fois la qualité du cluster formé et son impact sur la performance industrielle qui peut aider les décideurs à comprendre la cohérence du cluster et à identifier l'impact de modularité sur la performance industrielle.

Chapitre 3. Proposition d'un cadre méthodologique pour la gestion de la modularité des produits et services

Sur la base de la revue de la littérature, l'approche de la thèse se concentre sur la mise en œuvre d'une méthode de modularité pouvant être appliquée à un système orienté services. Cette approche vise à diminuer la complexité interne résultant de la génération d'une variété d'offres de produits et de services. L'approche démontre efficacement l'utilisation de la modularité comme moteur pour aider à atténuer la complexité industrielle. Notre méthode vise à accompagner les décideurs dans le choix du scénario de modularité de sortie adapté en fonction du contexte industriel de l'entreprise et de l'impact de la modularité sur la performance de l'entreprise en évaluant et en comparant plusieurs scénarios de sortie alternatifs. Cela facilitera probablement la gestion opérationnelle des produits et services dans la phase suivante et peut également avoir le potentiel de stimuler les économies d'échelle.

La méthode proposée est divisée en deux parties principales basées sur nos deux questions de recherche. La première partie aborde la première question de recherche en démontrant l'approche pour implémenter la modularité sur un système orienté services. Il traite des procédures nécessaires pour mettre en œuvre avec succès la modularité avec des entrées qui peuvent être des éléments de produits et / ou de services. Le résultat sera plusieurs scénarios de modularité alternatifs, dont l'un d'entre eux peut être un scénario approprié pour l'entreprise. Pour choisir le scénario le plus adapté, une approche d'évaluation de ces scénarios en fonction de leur impact sur la performance industrielle de l'entreprise est proposée. Cela nous amènera à la deuxième partie où nous pouvons mesurer l'impact de la modularité sur la performance de l'industrie qui est notre deuxième question de recherche.

Ce chapitre présente le cadre méthodologique général de la méthode proposée pour modulariser le système orienté services. Le chapitre est divisé en deux parties principales. La première partie décrit deux phases de la méthode : tout d’abord, le cadre général de la méthode et les étapes requises de notre méthode pour la mise en œuvre d'une méthode de modularité sur un système orienté services ; puis, l'évaluation des scénarios de sortie des alternatives et de la mesure de l'impact de la modularité sur la performance de l'entreprise. Le chapitre 4 discutera en détail de l'approche de mise en œuvre de la modularité sur un système orienté services et le chapitre 5 discutera de l'approche pour mesurer l'impact de la modularité sur les performances industrielles d'une entreprise.

La deuxième partie décrit l'exemple illustratif qui sera utilisé pour bien illustrer et décrire la méthode proposée. Cet exemple illustratif est différent de notre étude de cas qui sera discutée au chapitre 6. Cet exemple illustratif vise à démontrer les étapes détaillées de la méthode.

Chapitre 4. Méthode pour appliquer la modularité aux systèmes orientés services

La mise en œuvre de la modularité a été proposée comme solution pour surmonter la complexité interne résultant de l'offre de produits et services personnalisés. La méthode consiste généralement en plusieurs modules créés à partir de plusieurs composants. La modularité émerge de la partition d'un système en plusieurs ensembles indépendants de composants. Cette indépendance renforce l'utilisation des composants standardisés tout en maintenant la possibilité pour les concepteurs de créer facilement une large gamme de systèmes variés en utilisant un ensemble de composants d'entrée beaucoup plus petit. Cela s'applique aux domaines de produits et de services et contribue à atténuer la complexité induite par la variété ainsi qu'à soutenir un processus de configuration fluide du côté du client final.

Notre méthode se concentre sur la mise en œuvre de la modularité sur un système orienté services comme spécifié au chapitre III. La méthode proposée est différente des autres méthodes qui se concentrent sur la modularité des services ou des produits en étudiant une relation de similitude entre les produits et services. Cela facilitera probablement la gestion opérationnelle des produits et services dans la phase suivante et peut également avoir le potentiel de stimuler les économies d'échelle.

Ce chapitre se concentre sur une approche de modularisation d'un système orienté services. Il décrit en détail les étapes nécessaires pour implémenter la modularité sur un système orienté services. Il est divisé en cinq étapes principales qui comprennent: l'identification des éléments, la formation de la matrice numérique de structure de conception (DSM), la forme et la matrice agrégée, le regroupement de la matrice et enfin, l'évaluation des différents résultats pour les deux techniques utilisées pour identifier le nombre et la qualité de la sortie de clustering. Différents indicateurs de mesure sont utilisés pour évaluer chaque scénario de sortie et pour évaluer les grappes formées.

La méthode de ce chapitre a été illustrée par un exemple illustratif pour mettre en évidence, étape par étape, l'application de la méthode. Cela souligne son applicabilité. Avec l'exemple, dans tout le potentiel de la méthode a été exploité: il sera développé plus avant avec une étude de cas étendue au chapitre 6.

La méthode aide à identifier la relation de similitude entre les produits et les services selon différents critères prédéfinis et différentes techniques de regroupement, résultant en différentes alternatives de clusters. La méthode aide également à identifier une comparaison entre différents scénarios de clustering en termes de cohérence et de qualité du clustering. Ceci n'est pas suffisant car cela ne prend pas en considération les performances de l'entreprise et quel est l'effet de chaque scénario de modularité sur les performances de l'entreprise. C'est pourquoi une approche comparative complémentaire basée sur l'évaluation des performances est nécessaire. C'est ce dont nous parlerons dans le prochain chapitre de notre thèse.

Chapitre 5. Impact de la modularité sur les performances industrielles

Selon la revue de la littérature abordée dans le chapitre 2, la modularité du produit est considérée comme un avantage potentiel tout en traitant des produits complexes car elle limite l'interaction entre les composants du produit ou les fonctions du produit. Il a le potentiel de réduire le temps de cycle qui se produit dans un processus de production ou de conception. Cela réduit également le cycle de développement pour atteindre le cycle de vie plus court du produit avec des coûts de développement plus faibles (Baldwin et Clark 2000).

(Lin et al. 2010) ont discuté d'une réduction de la complexité du service et d'une augmentation de la réactivité pour offrir une variété de services. La mise en œuvre de la logique de modularité au processus de conception est considérée comme un moyen rentable et également flexible de créer de nouveaux services de processus. La revue de la littérature nous a permis de conclure que la modularité a un impact potentiellement positif sur la performance de l'entreprise et cela doit être mesuré pour pouvoir différencier / prioriser les scénarios d'amélioration.

La mise en œuvre de la modularité sur les systèmes orientés services dans notre méthode a conduit à disposer de plusieurs scénarios de clustering qui doivent être évalués pour trouver le scénario le plus approprié ayant l'impact optimal sur les performances de l'entreprise.

Ce chapitre évalue l'impact des scénarios de modularité sur la performance de l'entreprise en termes de plusieurs indicateurs. Cela aidera à trouver le scénario le plus approprié en fonction du contexte industriel de chaque cas industriel. Cette partie de la méthode constituera un ensemble d'indicateurs pertinent et configurera une méthode d'évaluation des performances soutenant une analyse rigoureuse des impacts de modularité.

La méthode comprend cinq étapes principales illustrées. La méthode commence par la traduction des scénarios de clustering de sortie en un ensemble de processus, la définition des critères d'impact nécessaires, la définition de la mesure opérationnelle nécessaire pour mesurer les processus, la création du modèle de critères d'évaluation et enfin le classement des scénarios de clustering alternatifs.

La méthode fournit un modèle d'aide à la décision pour classer les scénarios et fournir la solution optimale basée sur un ensemble de critères basés sur le contexte industriel de l'entreprise. L'évaluation de la performance permet de comparer différents scénarios de modularité, ce qui apportera un soutien précieux aux décideurs de la gestion des variétés.

Les méthodes MCDM en général et la méthode ANP en particulier sont considérées comme un outil efficace pour pouvoir classer notre scénario alternatif en fonction de plusieurs critères. ANP est plus flexible car elle permet de traiter des relations d'interdépendance entre des éléments de la structure du modèle de réseau. Ainsi, même si elle est plus complexe à mettre en œuvre, elle résout les problèmes liés aux structures du réseau. Elle convient à notre structure de modèle car nous avons certaines relations de dépendance de réseau entre des éléments du modèle.

Chapitre 6. Étude de cas

Dans ce chapitre, une étude de cas est fournie pour illustrer l'applicabilité de la procédure de modularité sur un système industriel orienté services. Nous aborderons également l'impact de la modularité sur les performances industrielles pour cette étude de cas en comparant le résultat de différents scénarios de clustering alternatifs.

L'objectif de l'étude de cas est de vérifier la faisabilité de l'application de l'ensemble de la méthode sur un système orienté services qui offre des variétés de produits et de services, puis de discuter des leçons tirées de cette expérimentation, notamment en ce qui concerne l'applicabilité, la valeur ajoutée de la méthode et ses limites. Dans cette perspective, nous fournissons d'abord une brève description de l'étude de cas accompagnée d'une présentation des outils et logiciels de mise en œuvre nécessaires pour appliquer la méthode à l'étude de cas et générer les résultats requis. Deuxièmement, nous appliquons étape par étape la méthode spécifiée pour spécifier le problème de modularité et pour générer un ensemble de scénarios de clustering alternatifs. Ensuite, la troisième et dernière étape est consacrée au classement et à la mesure des performances industrielles des scénarios de clustering de sortie. Ces résultats seront discutés à la fin du chapitre.

Chapitre 7. Conclusion

Le principal problème de recherche qui a été abordé dans notre thèse est de savoir comment la gestion de la modularité peut être formalisée puis mise en œuvre pour les systèmes orientés services, pour aider à atténuer la complexité industrielle tout en garantissant un niveau élevé de variété de produits et de services, afin de capturer autant de préférences des clients que possible. Nous avons proposé une méthode de modularisation d'un système orienté services, intégrant soit des produits, des services ou l'intégration des deux. Le procédé aide à identifier et à visualiser les indices de similarité parmi les éléments censés être modularisés selon plusieurs critères prédéfinis. Ces critères apporteront une aide précieuse à la prise de décision pour la modularisation des éléments contribuant à l'offre de l'entreprise et, à terme, la promotion de la gestion des variétés. La méthode aide à identifier les relations de similitude entre les produits et services selon (i) un mélange distinct des critères prédéfinis et (ii) diverses techniques de regroupement, résultant en différentes alternatives de cluster. Le regroupement et l'évaluation des performances contribuent à la comparaison des scénarios de modularité et fournissent un soutien précieux aux décideurs sur la gestion des variétés. Les critères d'évaluation abordés dans la méthode aident les décideurs à choisir des scénarios de clustering alternatifs appropriés représentant les modules de produit et / ou de service, en fonction du contexte industriel et évaluent l'impact de la modularité sur les performances opérationnelles (par exemple, complexité, niveau de variété, coût, temps …etc)

Selon la méthode proposée, le système orienté services est défini dans l'étude de cas avec 30 éléments différents, faisant évoluer différents modules de produits et un ensemble de services. Les indices de similarité ont été calculés sur la base de différents critères prédéfinis. Les indices sont ensuite combinés en un DSM agrégé, sur lequel deux algorithmes de clustering de base ont été appliqués. Les grappes suivantes ont été évaluées à l'aide de mesures de silhouette. Par rapport à d'autres méthodes traditionnelles, cette méthode s'est avérée efficace pour modulariser un système orienté services de manière systématique (offrant des produits, des services et des processus de soutien).

La modularisation d'un système orienté services permet de réaliser l'intégration entre les produits et services et d'obtenir la qualité, la variété et l'efficacité nécessaires pour le contexte industriel en fonction de plusieurs critères prédéfinis qui incluent les exigences du client. Cela améliore également la capacité du système à s'adapter aux changements d'exigences et à réduire à la fois les délais et les coûts. Cela facilitera probablement la gestion opérationnelle des produits et services dans la phase suivante et peut également avoir le potentiel de stimuler les économies d'échelle, soutenant ainsi la mise en œuvre de la personnalisation de masse dans les domaines des produits et des services.

Les deux techniques de clustering (partitionnement et hiérarchique) ont été utiles pour construire plusieurs scénarios de clustering qui peuvent aider les décideurs à choisir le scénario qui convient à leur contexte industriel. La méthode a appliqué la modularité pratiquement sur des systèmes orientés services utilisant les deux techniques. Chacun d'eux fournit différentes façons de regrouper les éléments d'entrée (en utilisant différents algorithmes de clustering), ce qui permet d'avoir différentes constructions de clusters en sortie.

Le BPMN a été utilisé pour visualiser les différentes activités et ressources et être capable de distinguer les différents scénarios de clustering du point de vue de l'organisation des processus industriels. La définition des ressources, outils et informations manipulés pour la production de chaque élément (modules produits ou services) a permis de définir les processus métiers de chacun des scénarios de clustering, permettant ainsi une évaluation structurelle et comparative.

La méthode ANP est considérée comme un outil efficace pour pouvoir classer notre scénario alternatif en fonction de plusieurs critères. Il est plus flexible car nous pouvons avoir n'importe quelle relation d'interdépendance entre n'importe quel élément de critère dans la structure du modèle donc, même si, il est plus complexe à mettre en œuvre, il couvre des modèles complexes où les relations entre les éléments des critères de décision sont plus complexes . Il convenait à notre structure de modèle car nous avons des relations de réseau entre tous les éléments du modèle.

Deux applications différentes ont été abordées dans la thèse pour démontrer et illustrer l’approche de la thèse. Un exemple illustratif d'une entreprise qui aborde la modularité des services en modularisant les activités de production de services en un ensemble de modules. Cet exemple illustratif a été utilisé pour faciliter la compréhension de l'étape méthodologique. L'autre application était une étude de cas plus large liée à un projet industriel PSS, utilisée pour une vérification de faisabilité. Cette étude de cas est basée sur un système robotique axé sur les services qui comprend à la fois des produits et des services devant être modularisés pour former des modules de produits ou de services ou l'intégration des deux.

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APPENDICES

Appendix I. Illustrative example

Appendix I.1.List of resources

Activities	Human resource	Technological tools /material	Information
A1	Logistics representative	Computer, Excel	Shipment list
A2	Logistics representative	Computer, Excel	Shipment list
A3	Logistics representative	Computer, Excel	Shipment list
A4	Logistics representative	Computer, Excel	Shipment list
A5	Logistics representative	Computer, transport management system	
A6	Logistics representative	Computer, transport management system	
A7	Logistics representative	Computer, transport management system	
A8	Logistics representative	Computer, transport management system	
A9	Logistics representative	Computer, Excel	Shipment list
A10	N/A		
A11	Warehouse operative		
A12	N/A		
A13	N/A		
A14	Logistics representative	Computer, Excel	Shipment list
A15	Logistics representative	Computer	Shipment list
A16	Logistics representative	Computer	Shipment list
A17	Logistics representative	Computer, ERP system	
A18	Logistics representative	Computer, ERP system	
A19	Logistics representative	Computer, ERP system	
A20	Logistics representative	Computer, transport management system	
A21	Logistics representative	Computer, transport management system	
A22	Logistics representative	Computer, transport management system	
A23	Logistics representative	Computer, Email	
A24	Logistics representative	Computer, Email	
A25	Logistics representative	Computer, transport management system	
A26	Logistics representative	Computer, Email	
A27	Logistics representative	Computer, transport management system	
A28	Logistics representative	Computer, transport management system	
A29	Logistics representative	Computer, transport management system	
A30	Logistics representative	Computer, transport management system	
A31	Logistics representative	Computer, transport management system	
A32	Logistics representative	Computer, transport management system	

A33	Logistics representative	Computer, Printer	
A34	Logistics representative	Computer, Printer	
A35	Logistics representative, Warehouse operative	Labels, CMR papers	
A36	Warehouse operative	Plastic pockets, labels	
A37	Warehouse operative	Pallets with products, Labels	
A38	Logistics representative		
A39	Logistics representative	Computer, Email	
A40	Logistics representative	Computer, Email	
A41	Logistics representative	Computer, Email	
A42	Logistics representative	Computer, Email	
A43	Logistics representative	Computer, Customer's delivery portal	
A44	Logistics representative	Computer, Customer's delivery portal	
A45	Logistics representative	Computer, Customer's delivery portal	
A46	Logistics representative	Computer, Customer's delivery portal	
A47	Logistics representative	Computer, Customer's delivery portal	
A48	Logistics representative	Computer, Customer's delivery portal	
A49	Logistics representative	Computer, Customer's delivery portal	
A50	Logistics representative	Computer, Customer's delivery portal	
A51	Logistics representative	Computer, Email	
A52	Logistics representative	Computer Email	
A53	Logistics representative	Computer	Shipment lists
A54	Logistics representative	Computer	Shipment lists
A55	Logistics representative	Computer	Shipment lists
A56	Logistics representative	Computer, ERP system	
A57	Logistics representative	Computer, ERP system	
A58	Logistics representative	Computer, ERP system	
A59	Logistics representative	Computer, Email	
A60	Logistics representative	Computer, ERP system	Delivery note
A61	Logistics representative	Computer	Delivery note
A62	Logistics representative	Computer, Email	
A63	Logistics representative	Computer, Email	Delivery note
A64	Logistics representative	Computer	Shipment lists
A65	Logistics representative	Computer	Shipment lists
A66	Logistics representative	Computer, Email	
A67	Logistics representative	Computer, Email	
A68	Logistics representative	Computer, Email	
A69	Logistics representative	Computer, Email	
A70	Logistics representative	Computer, Email	
A71	Logistics representative	Computer, Email	
A72	Logistics representative	Computer, Email	

Appendix II. Case study

Appendix II.1. Prerequisite tables

Elements description

Element	Description
Energy 1	The basic energy system is mainly responsible for the energy system for other modules. It consists of the main battery and in this module its lifetime is normal
Cleaning 1	A module that contains mainly of all the cleaning tools (brushes ….) that are used mainly to clean the fridges
Security	This module is mainly used to secure the robot from having problem in the current of electricity (overcurrent or other related stuff) and as well regarding the movement which is to avoid hitting something and avoid crashing as well
Displacement 1	It is the module that is responsible for the movement of the robot (this one mainly is used to be able to move in a normal ground to be able to clean fridges or other stuff on the normal surface)
Body 1	The body that is responsible for the robot. It is nonresistant to anything
Cleaning 2	A module that contains mainly of all the cleaning tools (brushes ….) that are used mainly to clean the swimming pool. It is adaptable to the different environment as it can clan small pools and bigger ones
Displacement 2	The module is responsible for the movement of the robot. This one mainly is used to be adaptable for the different surface to be able to clean different environment for different kinds of swimming pool
Energy 2	It is mainly responsible for the energy system for other modules. It consists of a battery and it should be water-resistant and chemical resistant as well
Body 2	The body that is used to protect the robot from water and chemical
Cleaning 3	A module that contains mainly of all the cleaning tools (brushes ….) that are used mainly to clean the interior of the train.
Displacement 3	The module is responsible for the movement of the robot. This one mainly is used to be able to climb upstairs and clean dirty stuff above the surface
Energy 3	It is mainly responsible for the energy system for other modules. It consists of a battery and it should have a higher battery life than other energy modules
Body 3	The body that is used to protect the robot from impact so it is impact-resistance
Counseling for the solution choice	A service of consulting with the customer to be able to have the best solution for him
Equipment test execution	A service to make a test of the equipment before buying it

Training battery	Make personal training for utilizing the battery
Training security	Make personal training for utilizing the usage of the security module
Pure cleaning Equipment	A service to clean the whole equipment
Emergency maintenance	A service of maintenance whenever there is an incident or breakdown problem with the equipment
Preventive maintenance	Maintenance that is scheduled each period to avoid breaking down
Consumables supply	A service to supply the customer with consumables or part of the robot that its life span ended
Installation	The installation service that installs the equipment in the customer's place
Check up in distance	A service that can check up the equipment in the distance
Monitor module	The module responsible for monitoring and controlling all the modules together and is responsible to send signals for each part of the robot.
Upgrade	Make an upgrade of the system for the whole modules
Battery Maintenance	A maintenance service that is required for the energy module
Cleaning module maintenance	A maintenance service that is required for the cleaning module with its components
Displacement maintenance	A maintenance service that is required for the displacement module

Functionality of elements

Element	**Needs (functionality)**
Energy1	Validate that the equipment is in a good use condition frequently Goot batter life to be able to power all the elements
Security1	Guarantee safety for the people around Avoid hitting or crashing
Cleaning1	Guarantee for changing supplies for the first 2 years and fix anything Validate that the equipment is in a good use condition frequently Be able to upgrade the program for any new inquires Install the equipment with the component surrounding it Cleaning robot or fridges of factory
Displacement1	Avoid hitting or crashing Validate that the equipment is in a good use condition frequently Install the equipment with the component surrounding it
Body1	Guarantee for changing supplies for the first 2 years and fix anything Be able to withstand cold temperature
Cleaning 2	Waterproof cleaning Pressure resistant Chemical resistant Adoptable cleaning
Body2	Waterproof cleaning Pressure resistant Chemical resistant Being Anti-steam screen

	Being Anti-slip in a soaked environment
Energy2	Working with battery Waterproof cleaning Higher battery life
Microcontroller module	Being remote control Being able to maintain it in distance
Displacement 2	Being remote control
Cleaning 3	Reach hard cleaning area Controlling the quality of the cleaning Absorbing dust when cleaning Multiple cleaning
Body 3	Climbing up and down the stairs Keep the balance on an inclined surface Impact resistance
Displacement 3	Climbing up and down the stairs Reach hard cleaning area Keep the balance on an inclined surface
Energy 3	Higher battery life
Counseling for the solution choice	Validate the suitability for installing the equipment
Equipment test execution	Validate the suitability for installing the equipment Guarantee safety for the people around
Personal training for battery	Training for users for utilizing the battery
Personal training for security	Training for users for utilizing the security module
Pure cleaning Equipment	Cleaning the equipment service
Emergency maintenance	Fix anything and anytime (even incident and breakdown)
Preventive maintenance	Regular maintenance
Consumables supply	Regular maintenance Guarantee for changing supplies for the first 2 years and fix anything
Installation	Install the equipment with the component surrounding it
Check up in distance	Be able to check up the robot in distance
Update	Ability to update the equipment for new requirements
Monitor module	Being remote control Being able to maintain it in distance Being able to see the surrounding area
Battery Maintenance	Have service maintenance just for the energy module
Cleaning module maintenance	Have service maintenance just for the cleaning module
Displacement maintenance	Have service maintenance just for the displacement module

Technological and material information

Element	Tools and material needed	Information needed
Energy1		Working environment Battery life Maintenance data
Security1	Software installation	Data of the place
Cleaning1	Software installation	Working environment
Displacement1	Software installation	Working environment Regulations
Body1		Data o the place
Cleaning 2	Software installation	Working environment
Body2		Data o the place
Energy2		Working environment Battery life

		Maintenance data
Monitoring module	Software programming Monitoring equipment	Data requirement
Microcontroller module	Software programming	Data requirement
Displacement 2		Working environment Regulations
Cleaning 3	Software installation	Working environment
Body 3		Working environment
Displacement 3		Working environment Regulations
Energy 3		Working environment Battery life Maintenance data
Counseling for the solution choice		Installation guide Installation requirement
Equipment test execution	Installation software	Installation guide Installation requirement
Personal training for battery utilization	Training manual Working manual Installation software	
Personal training for security utilization	Training manual Working manual Installation software	
Pure cleaning Equipment	Cleaning tool	Robot data
Emergency maintenance maintenance	Maintenance manual	Maintenance history Upgrade and installation history
Preventive maintenance	Maintenance manual	Maintenance history Upgrade and installation history
Consumables supply	Maintenance manual	Maintenance history Upgrade and installation history
Installation	Installation software	Installation guide Working environment
Check up in distance	Programming software	Data of the robot
Battery module maintenance	Maintenance manual	Maintenance history Upgrade and installation history
Displacement maintenance	Maintenance manual	Maintenance history Upgrade and installation history
Cleaning maintenance	Maintenance manual	Maintenance history Upgrade and installation history
Upgrade	Installation software	Installation guide Working environment

Human resources

Element	**Human resources**
Energy1	Electronics engineer/ Warehouse
Security1	Electronics engineer/ Warehouse

Cleaning1	Electronics engineer/ Warehouse
Displacement1	Mechanical/Warehouse
Body1	Electronics engineer/ Warehouse
Cleaning 2	Electronics engineer/ Warehouse
Body2	Electronics engineer/ Warehouse
Energy2	Electronics engineer/ Warehouse
Microcontroller module	Electronics engineer/ Warehouse
Displacement 2	Mechanical/Warehouse
Cleaning 3	Electronics engineer
Body 3	Electronics engineer/ Warehouse
Displacement 3	Mechanical/Warehouse
Energy 3	Electronics engineer/ Warehouse
Counseling for the solution choice service	Consulting Engineer/Electronics Engineer/ Maintenance engineer
Equipment test execution	Consulting Engineer/Electronics Engineer/ Maintenance engineer
Battery Maintenance	Maintenance engineer /warehouse /technician
Cleaning module maintenance	Maintenance engineer/warehouse/ technician
Displacement maintenance	Maintenance engineer /warehouse /technician
Pure cleaning Equipment	Technician
Emergency maintenance	Maintenance engineer/technician
Preventive maintenance	Maintenance Engineer /Technician /warehouse
Consumables supply	Warehouse /Maintenance engineer
Training battery	Maintenance Engineer
Training security	Electronics engineer
Installation	Electronics engineer/ Technician/ Maintenance engineer/ warehouse
Upgrade	Electrical engineer/ Technician
Check up from a distance	Maintenance engineer
Monitor module	Electrical engineer

Appendix II.2. Criteria DSMs

Functionality DSM

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E29
E1	3	1	2	1	2	1	0	0	1	1	1	0	1	0	1	2	2	0	0	0	1	1	1	3	0	0	0	2	2
E2	1	3	0	2	0	0	0	1	3	2	0	0	2	1	1	2	0	0	0	0	2	2	0	0	3	0	2	3	3
E3	2	0	3	2	0	0	0	1	1	2	0	0	2	1	2	2	0	2	0	0	1	1	3	0	0	0	0	0	0
E4	1	2	2	3	0	1	0	1	2	0	1	0	0	1	1	2	0	0	3	0	1	1	0	0	0	0	2	1	0
E5	2	0	0	0	3	0	0	1	0	0	0	0	0	1	1	1	0	0	0	3	1	1	0	0	0	0	0	0	0
E6	1	0	0	1	0	3	0	2	1	2	0	0	1	1	2	2	0	2	0	0	1	1	3	0	0	0	0	0	0
E7	0	0	0	0	0	0	3	2	0	0	0	0	0	0	1	1	0	0	0	3	1	1	0	0	0	0	0	0	0
E8	0	1	1	1	1	2	2	3	1	1	1	1	1	0	2	2	2	0	0	0	1	1	2	3	0	0	0	2	2
E9	1	3	1	2	0	1	0	1	3	1	0	0	1	1	1	2	0	0	0	0	2	2	0	0	3	2	2	3	3
E10	1	2	2	0	0	2	0	1	1	3	1	0	0	1	1	2	0	0	2	0	1	1	0	0	0	0	2	1	0
E11	1	0	0	1	0	0	0	1	0	1	3	0	2	1	2	2	0	2	0	0	1	1	3	0	0	0	0	0	0
E12	0	0	0	0	0	0	0	1	0	0	0	3	0	1	1	1	0	0	0	3	1	1	0	0	0	0	0	0	0
E13	1	2	2	0	0	1	0	1	1	0	2	0	3	1	1	2	0	0	2	0	1	1	0	0	0	0	2	1	0
E14	0	1	1	1	1	1	0	0	1	1	1	1	1	3	2	2	2	0	0	0	1	1	2	3	0	0	0	2	2
E15	1	1	2	1	1	2	1	2	1	1	2	1	1	2	3	3	0	0	0	0	1	1	2	0	0	1	1	2	2
E16	2	2	2	2	1	2	1	2	2	2	2	1	2	2	3	3	0	0	0	0	0	0	0	0	0	2	2	2	2
E17	3	0	0	0	0	0	0	3	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	1	1	0
E18	0	0	3	0	0	3	0	0	0	0	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	1	0
E19	0	0	0	3	0	0	0	0	0	3	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	1	1	2
E20	0	0	0	0	3	0	3	0	0	0	0	3	0	0	0	0	0	0	0	3	1	1	0	0	0	0	2	1	0
E21	2	2	2	2	1	2	1	2	2	2	2	1	2	2	2	0	0	0	0	1	3	2	2	0	0	1	1	3	2
E22	2	2	2	2	1	2	1	2	2	2	2	1	2	2	2	0	0	0	0	1	2	3	2	0	0	1	1	3	2
E23	2	0	3	0	0	3	0	2	0	0	3	0	0	2	2	0	0	0	0	0	2	2	3	0	0	0	2	1	1
E24	3	0	0	0	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0
E25	0	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0
E26	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	2	0	0	0	0	1	1	0	1	1	3	2	0	0
E27	0	2	0	2	0	0	0	0	2	2	0	0	2	0	1	2	1	1	1	2	1	1	2	0	0	2	3	2	2
E28	2	3	0	1	0	0	0	2	3	1	0	0	1	2	2	2	1	1	1	1	3	3	1	0	0	0	2	3	3
E29	2	3	0	0	0	0	0	2	3	0	0	0	0	2	2	2	0	0	2	0	2	2	1	0	0	0	2	3	3

Commonality DSM

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E29
E1	3	2	2	2	2	1	1	0	2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E2	1	3	1	1	1	1	1	1	3	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	3	1	2	1
E3	2	2	3	2	2	0	1	1	2	1	0	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E4	2	2	2	3	2	1	1	1	2	0	1	1	0	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E5	2	2	2	2	3	1	0	1	2	1	1	0	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E6	1	2	0	1	1	3	2	2	2	2	0	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E7	1	1	1	1	0	2	3	2	2	2	1	0	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E8	0	1	1	1	1	2	2	3	2	2	1	1	1	0	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E9	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	1	2	1
E10	1	1	1	0	1	2	2	2	2	3	1	1	0	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E11	1	1	0	1	1	0	1	1	2	1	3	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E12	1	1	1	1	0	1	0	1	2	1	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E13	1	1	1	0	1	1	1	1	2	0	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E14	1	1	1	1	1	1	1	0	2	1	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	1	2	1
E15	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	2	2	2	2	2	2	2	2	2	1	1	1
E16	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	2	2	2	2	2	2	2	2	2	1	1	1
E17	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2	3	2	2	2	1	2	1
E18	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2	3	2	2	2	1	2	1
E19	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2	3	2	2	2	1	2	1
E20	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	1	1	2	1	1	2
E21	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	1	1	2	2	1	1
E22	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	1	1
E23	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2	3	2	2	2	1	2	1
E24	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2	3	3	2	1	2	1
E25	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2	3	3	2	1	2	1
E26	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	1	1
E27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	3	3	1	1
E28	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2	2	1	1	1	2	2	2	1	1	3	2
E29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	2	3

Human resources DSM

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E29
E1	3	2	3	0	0	3	0	0	2	0	3	0	0	0	1	1	1	0	0	1	0	0	0	2	2	1	3	0	0
E2	2	3	2	0	0	2	0	2	3	0	2	0	0	2	2	1	2	1	1	0	0	0	0	3	3	1	2	0	0
E3	3	2	3	0	0	0	0	3	2	0	0	0	0	3	1	1	2	1	2	1	0	0	0	2	2	1	3	0	0
E4	0	0	0	3	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	1	3	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
E6	3	2	0	0	0	3	0	3	2	0	0	0	0	3	1	1	2	1	2	1	0	0	0	2	2	1	3	0	0
E7	0	0	0	1	0	0	3	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
E8	0	2	3	0	0	3	0	3	2	0	3	0	0	0	1	1	1	0	0	1	0	0	0	2	2	1	3	0	0
E9	2	3	2	0	0	2	0	2	3	0	2	0	0	2	2	1	2	1	1	0	0	0	0	3	3	1	2	0	0
E10	0	0	0	0	1	0	1	0	0	3	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
E11	3	2	0	0	0	3	0	3	2	0	3	0	0	3	1	1	2	1	2	1	0	0	0	2	2	1	3	0	0
E12	0	0	0	1	0	0	0	0	0	1	0	3	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
E13	0	0	0	0	1	0	1	0	0	0	0	1	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
E14	0	2	3	0	0	3	0	3	2	0	3	0	0	3	1	1	1	0	0	1	0	0	0	2	2	1	3	0	0
E15	1	2	1	0	0	1	0	1	2	0	1	0	0	1	3	2	1	0	0	0	0	0	0	2	2	1	1	0	0
E16	1	1	1	0	0	1	0	1	1	0	1	0	0	1	2	3	2	1	1	0	1	1	1	2	2	2	1	1	0
E17	1	2	2	0	0	2	0	1	2	0	2	0	0	1	1	2	3	2	1	0	2	2	1	2	2	2	1	1	0
E18	0	1	1	0	0	1	0	0	1	0	1	0	0	0	0	1	2	3	2	0	3	3	2	0	0	1	0	3	0
E19	0	1	2	1	1	2	1	0	1	1	2	1	1	0	0	1	1	2	3	0	2	2	1	0	0	1	0	2	0
E20	1	0	1	0	0	1	0	1	0	0	1	0	0	1	0	0	0	0	0	3	0	0	0	0	0	1	1	0	0
E21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	2	0	3	3	2	0	0	1	0	3	0
E22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	2	0	3	3	2	0	0	1	0	3	0
E23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	1	0	2	2	3	0	0	1	0	2	0
E24	2	3	2	0	0	2	0	2	3	0	2	0	0	2	2	2	2	0	0	0	0	0	0	3	3	1	2	0	0
E25	2	3	2	0	0	2	0	2	3	0	2	0	0	2	2	2	2	0	0	0	0	0	0	3	3	1	2	0	0
E26	1	1	1	0	0	1	0	1	1	0	1	0	0	1	1	2	2	1	1	1	1	1	1	1	1	3	2	1	0
E27	3	2	3	0	0	3	0	3	2	0	3	0	0	3	1	1	1	0	0	1	0	0	0	2	2	2	3	0	0
E28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	2	0	3	3	2	0	0	1	0	3	0
E29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3

Technology DSM

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E29
E1	3	0	1	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E2	0	3	1	1	2	1	2	0	2	1	1	2	1	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	0
E3	1	1	3	2	0	0	0	1	1	2	0	0	2	1	0	1	0	0	0	0	0	0	0	1	1	2	1	1	0
E4	1	1	2	3	0	2	0	1	1	0	2	0	0	1	0	1	0	0	0	1	0	0	0	1	1	2	1	1	0
E5	0	2	0	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E6	1	1	0	2	0	3	0	1	1	2	0	0	2	1	0	1	0	0	0	0	0	0	0	1	1	2	1	1	0
E7	0	2	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E8	0	0	1	1	0	1	0	3	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E9	0	2	1	1	1	1	1	0	3	1	1	1	1	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	0
E10	1	1	2	0	0	2	0	1	1	3	2	0	0	1	0	1	0	0	0	1	0	0	0	1	1	2	1	1	0
E11	1	1	0	2	0	0	0	1	1	2	3	0	2	1	0	1	0	0	0	0	0	0	0	1	1	2	1	1	0
E12	0	2	0	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E13	1	1	2	0	0	2	0	1	1	0	2	0	3	1	0	1	0	0	0	1	0	0	0	1	1	2	1	1	0
E14	0	0	1	1	0	1	0	0	0	1	1	0	1	3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	1	1	1	0	1	1	1	1	1	1	0	0	0
E16	0	1	1	1	0	1	0	0	1	1	1	0	1	0	2	3	1	1	1	0	1	1	1	3	3	2	1	1	0
E17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	0	3	3	3	1	1	1	1	1	1
E18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	0	3	3	3	1	1	1	1	1	1
E19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	0	3	3	3	1	1	1	1	1	1
E20	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	1	0	0	0
E21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	0	3	3	3	1	1	1	1	1	1
E22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	0	3	3	3	1	1	1	1	1	1
E23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	0	3	3	3	1	1	1	1	1	1
E24	0	1	1	1	0	1	0	0	1	1	1	0	1	0	1	3	1	1	1	0	1	1	1	3	3	2	1	1	0
E25	0	1	1	1	0	1	0	0	1	1	1	0	1	0	1	3	1	1	1	0	1	1	1	3	3	2	1	1	0
E26	1	1	2	2	1	2	1	1	1	2	2	1	2	1	1	2	1	1	1	1	1	1	1	2	2	3	1	1	0
E27	0	1	1	1	0	1	0	0	1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	3	3	1
E28	0	1	1	1	0	1	0	0	1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	3	3	1
E29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	1	1	3

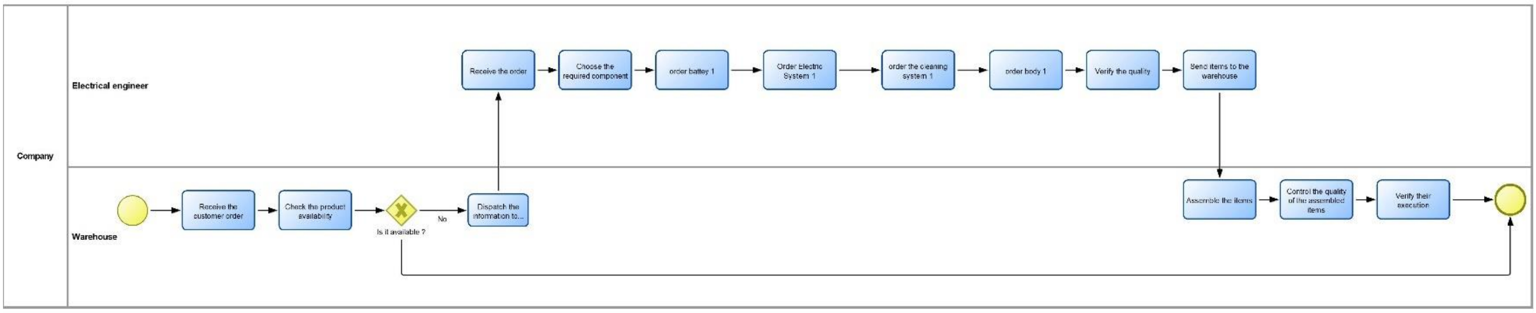
Aggregated DSM

E	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27	E28	E29
E1	3	1	3	3	3	0	0	0	1	0	0	0	0	0	1	2	1	0	0	0	1	1	1	1	0	0	0	2	2
E2	1	3	0	0	0	0	0	1	3	2	0	0	2	1	1	2	0	0	0	0	2	2	0	0	3	0	2	3	3
E3	3	0	3	3	3	0	0	0	1	0	0	0	0	0	2	2	0	1	0	0	1	1	1	0	0	0	0	0	0
E4	3	1	3	3	3	0	0	0	1	0	0	0	0	0	1	2	0	0	1	0	1	1	0	0	0	0	2	1	0
E5	3	0	3	3	3	0	0	0	0	0	0	0	0	0	1	1	0	0	0	3	1	1	0	0	0	0	0	0	0
E6	0	0	0	0	0	3	3	3	1	3	0	0	0	0	2	2	0	1	0	0	1	1	1	0	0	0	0	0	0
E7	0	0	0	0	0	3	3	3	1	3	0	0	0	0	1	1	0	0	0	3	1	1	0	0	0	0	0	0	0
E8	0	1	0	0	0	3	3	3	1	3	0	0	0	0	2	2	1	0	0	0	1	1	1	1	0	0	0	2	2
E9	1	3	1	1	1	1	0	1	3	1	0	0	1	1	1	2	0	0	0	0	2	2	0	0	3	2	2	3	3
E10	0	2	0	0	0	3	3	3	1	3	0	0	0	0	1	2	0	0	1	0	1	1	0	0	0	0	2	1	0
E11	0	0	0	0	0	0	0	0	0	1	3	3	3	3	2	2	0	1	0	0	1	1	1	0	0	0	0	0	0
E12	0	0	0	0	0	0	0	0	0	0	3	3	3	3	1	1	0	0	0	3	1	1	0	0	0	0	0	0	0
E13	0	2	0	0	0	0	0	0	1	0	3	3	3	3	1	2	0	0	1	0	1	1	0	0	0	0	2	1	0
E14	0	1	0	0	0	0	0	0	1	0	3	3	3	3	2	2	1	0	0	0	1	1	1	1	0	0	0	2	2
E15	1	1	2	1	1	2	1	2	1	1	2	1	1	2	3	3	0	0	0	0	1	1	1	0	0	1	1	0	0
E16	2	2	2	2	1	2	1	2	2	2	2	1	2	2	3	3	0	0	0	0	0	0	0	0	0	1	1	0	0
E17	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	1	1	0
E18	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	1	0
E19	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	3	0	0	0	0	0	0	0	1	1	2
E20	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	3	1	1	0	0	0	0	2	1	0
E21	1	2	0	0	0	0	0	1	2	0	0	0	0	1	1	0	0	0	0	1	3	2	2	0	0	1	1	3	2
E22	1	2	0	1	0	0	0	1	2	1	0	0	1	1	1	0	0	0	0	1	2	3	2	0	0	1	1	3	2
E23	1	0	1	0	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	2	2	3	0	0	0	2	0	0
E24	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0
E25	0	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0
E26	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	1	0	0	0	0	1	1	0	1	1	3	2	0	0
E27	0	2	0	2	0	0	0	0	2	2	0	0	2	0	1	1	1	1	1	2	1	1	2	0	0	2	3	2	2
E28	2	3	0	1	0	0	0	2	3	1	0	0	1	2	0	0	1	1	1	1	3	3	1	0	0	0	2	3	3
E29	2	3	0	0	0	0	0	2	3	0	0	0	0	2	0	0	0	0	2	0	2	2	1	0	0	0	2	3	3

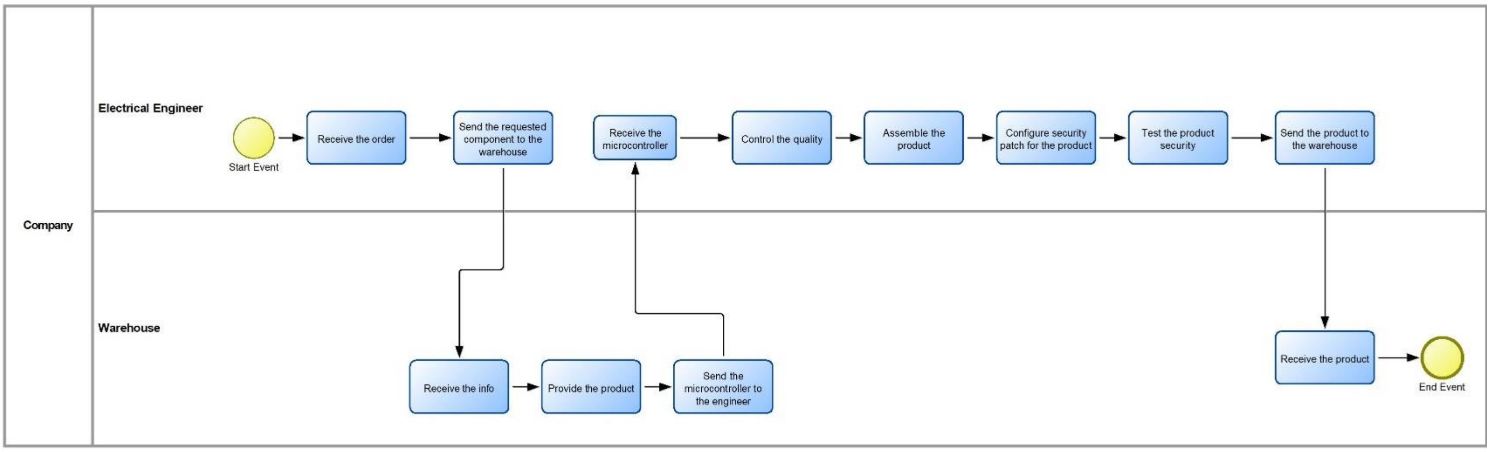
Appendix III. BPMN scenarios

Appendix III.1. Scenario 1

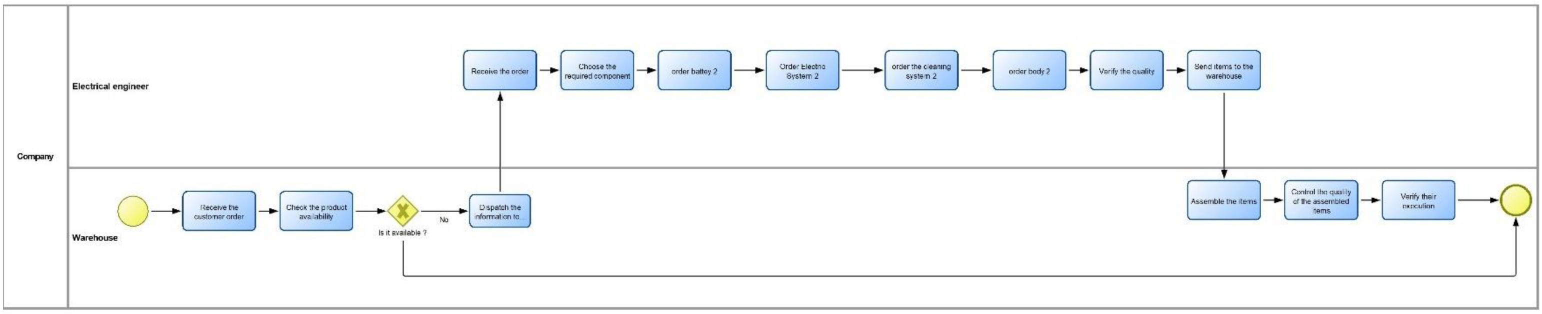
Cluster 1



Cluster 2

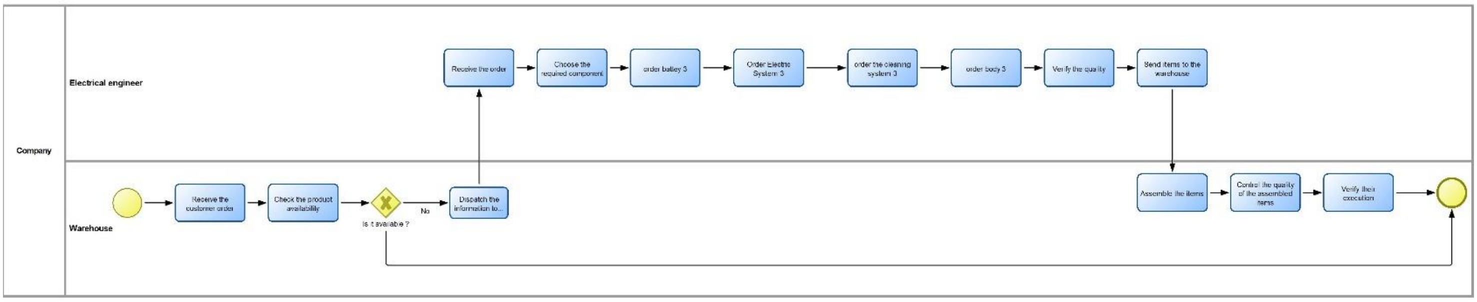


Cluster 3

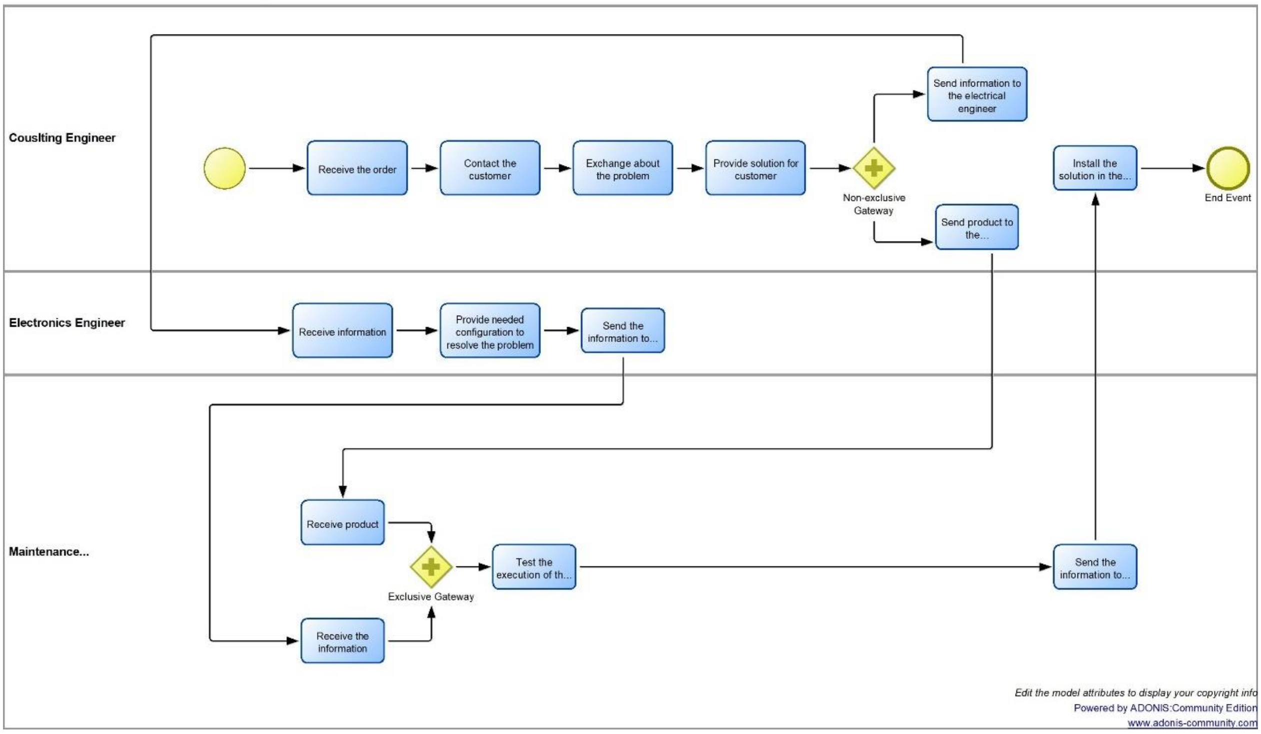


Appendix III.2. Scenario 2

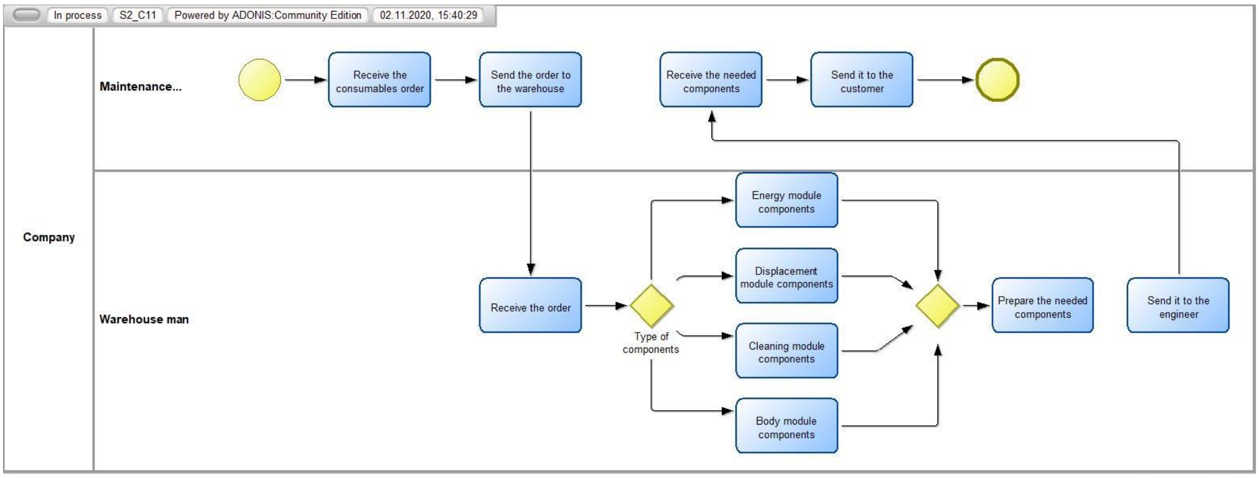
Cluster 4



Cluster 5

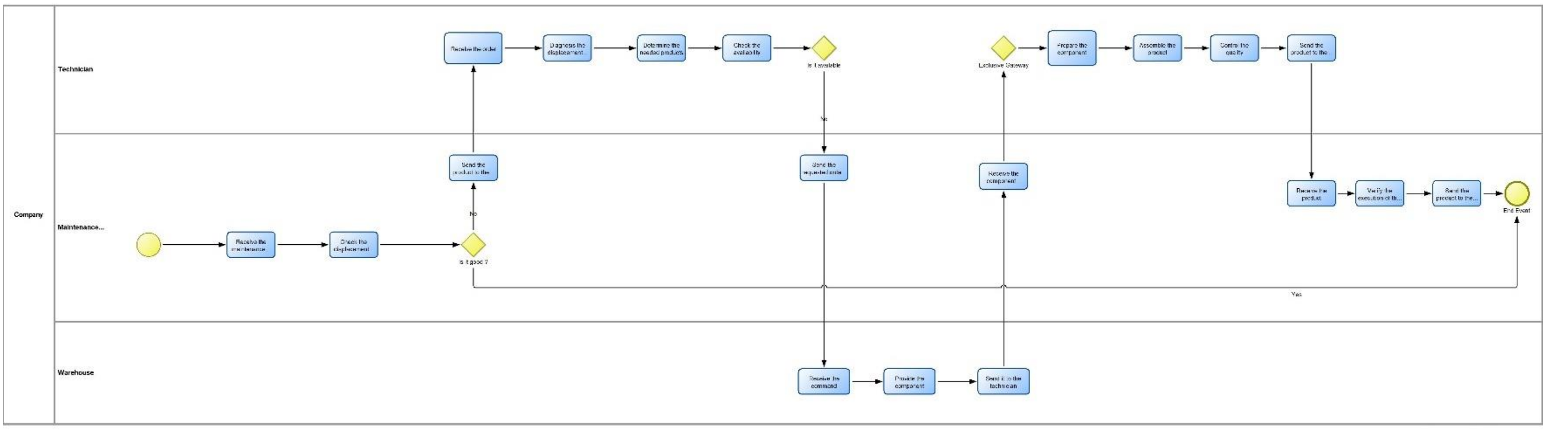


Cluster 11

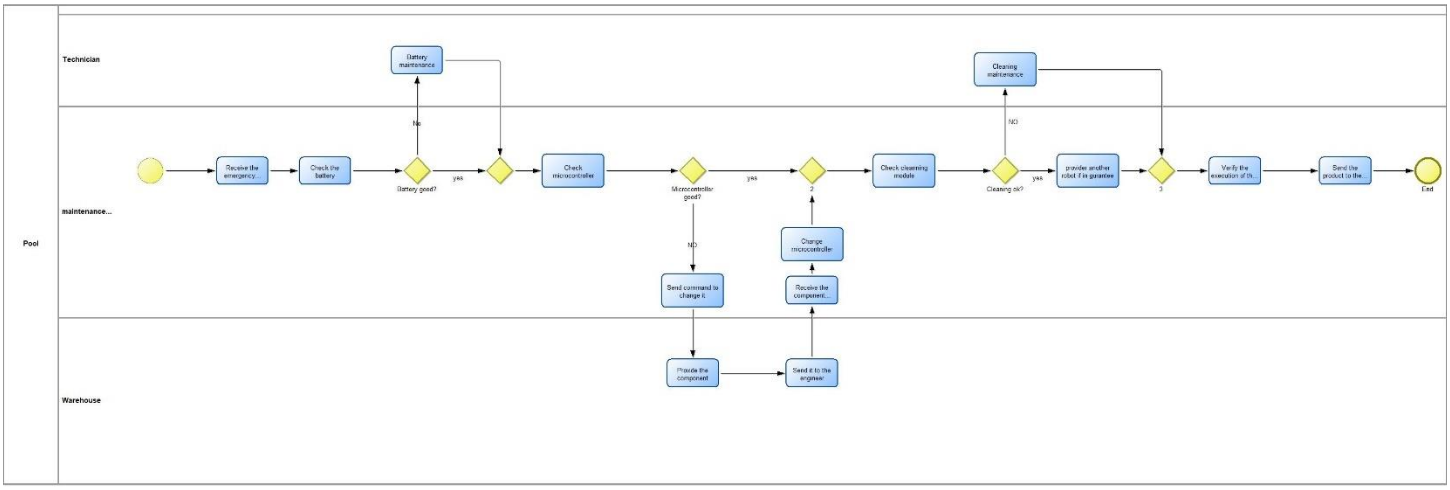


Appendix III.3. Scenario 3

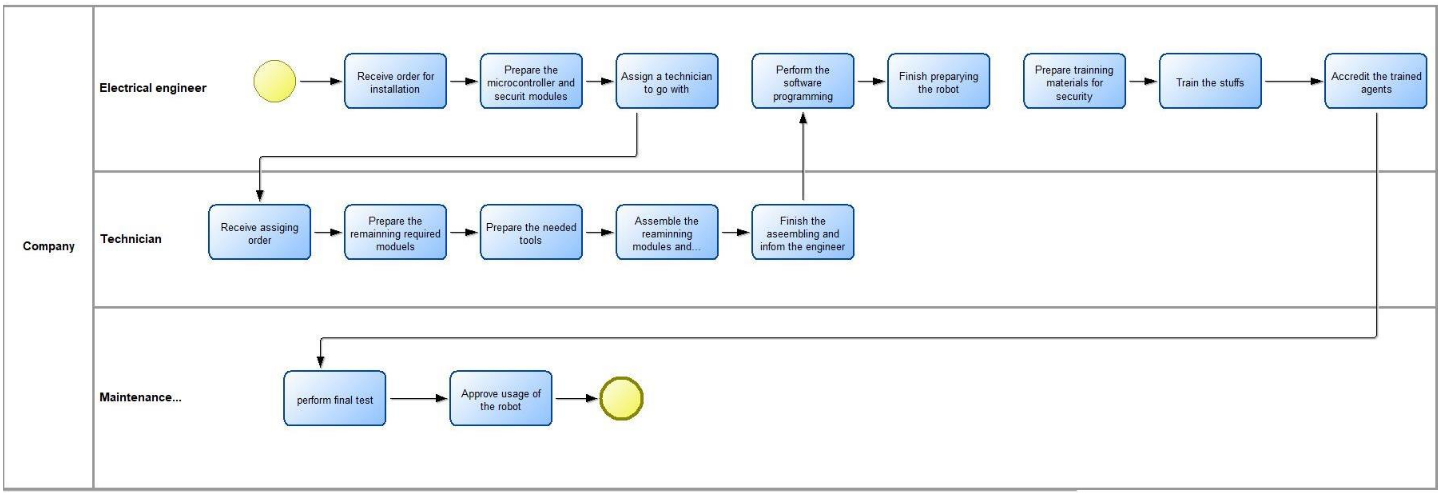
Cluster 8



Cluster 9

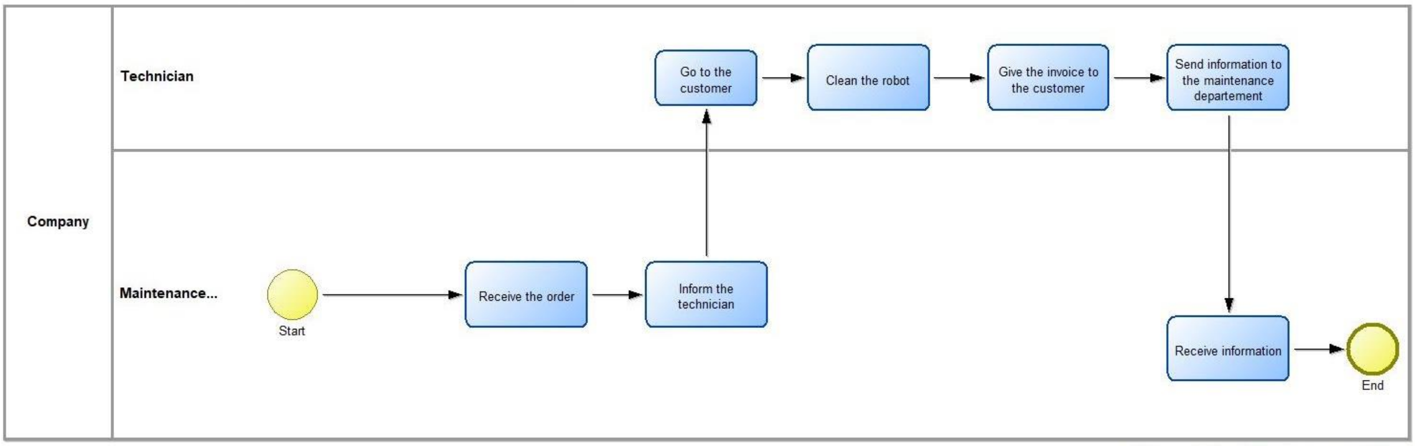


Cluster 11

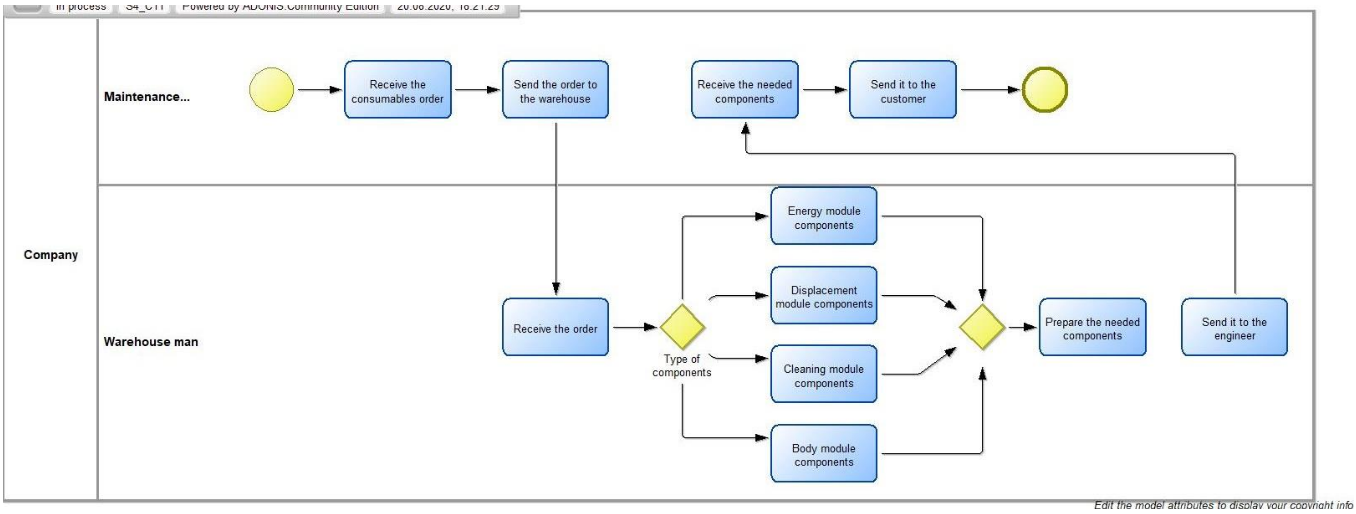


Appendix III.4. Scenario 4

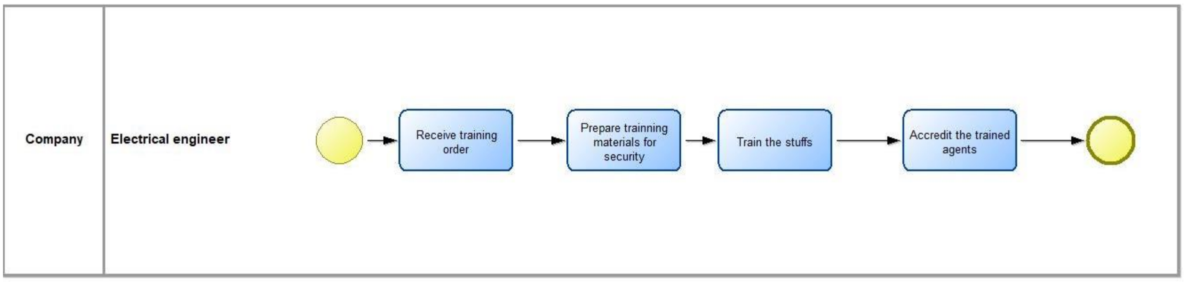
Cluster 9



Cluster 11

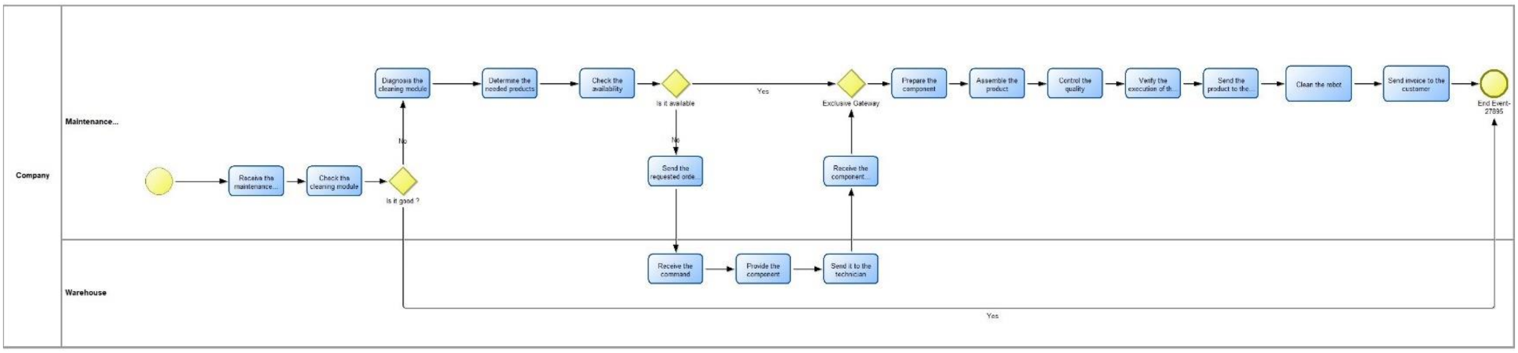


Cluster 12

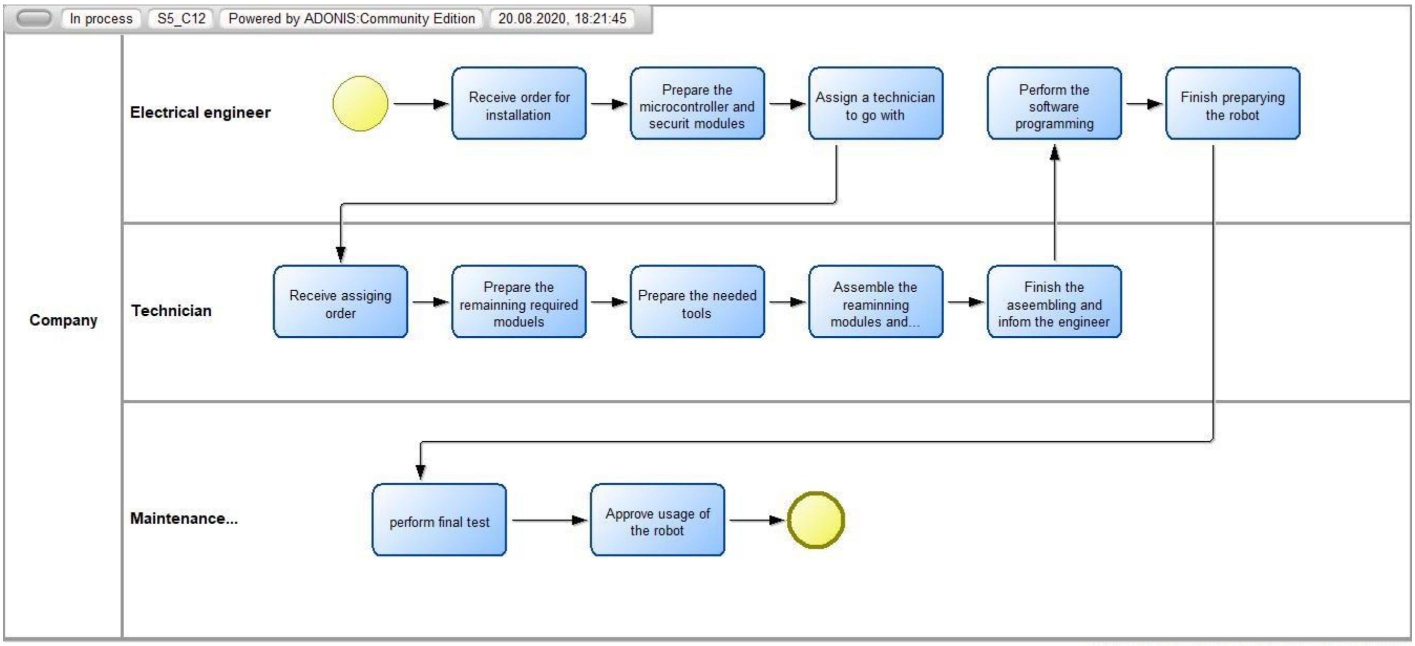


Appendix III.5. Scenario 5

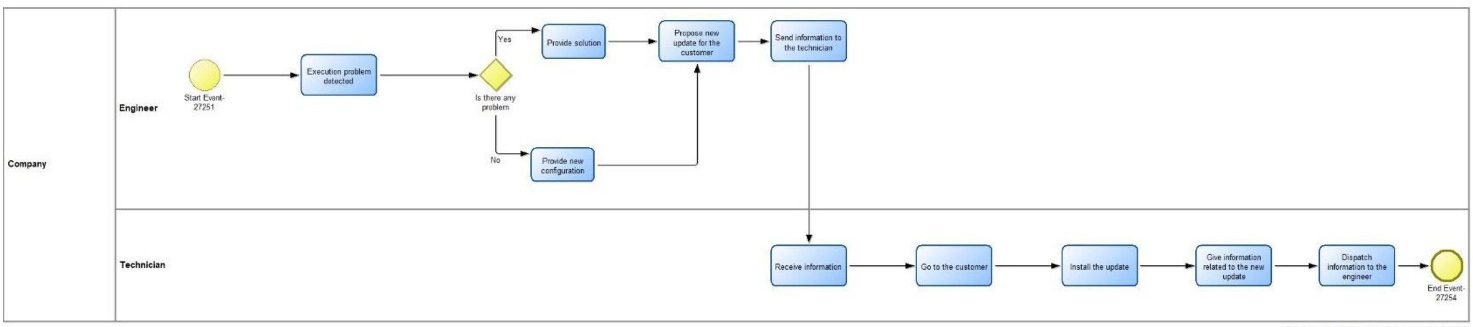
Cluster 7



Cluster 12

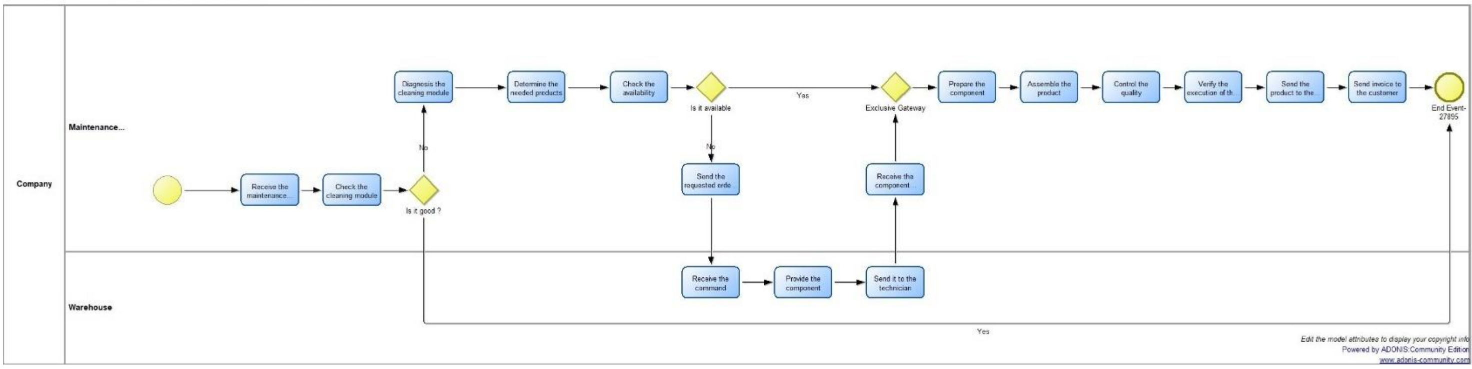


Cluster 13

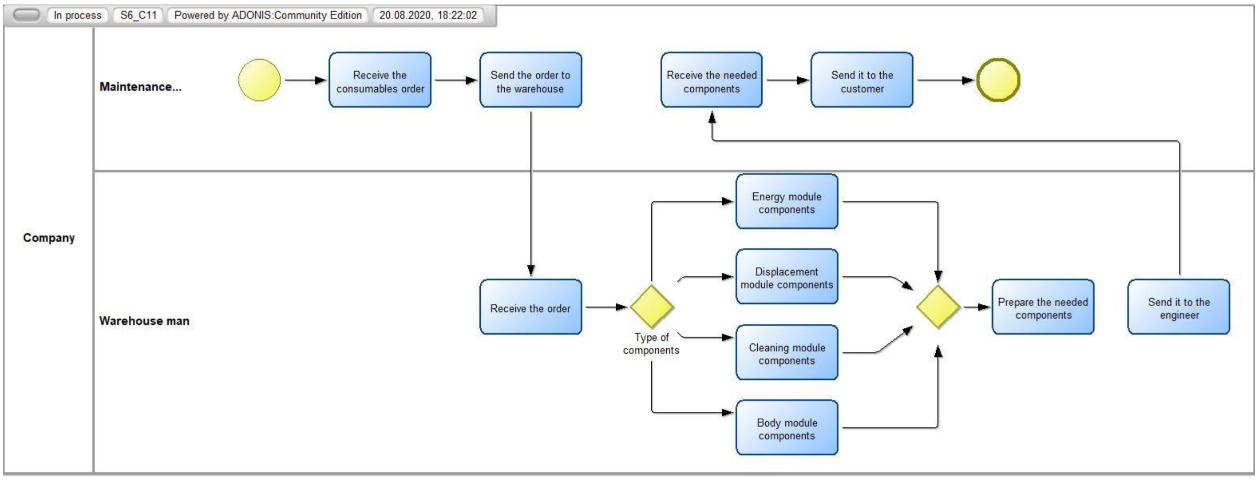


Appendix III.6. Scenario 6

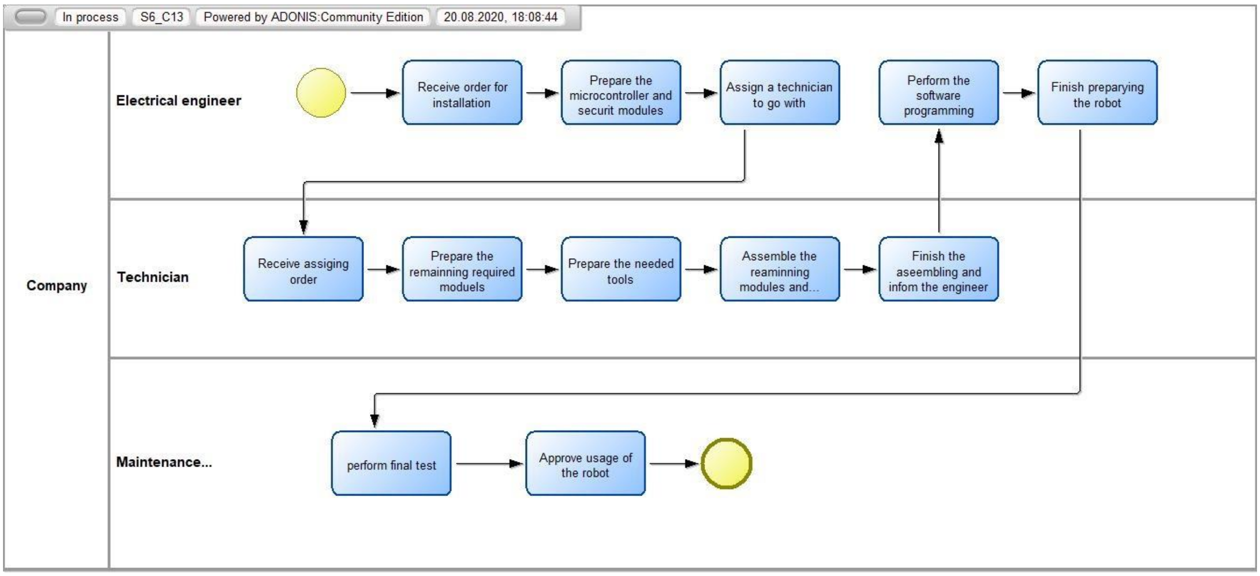
Cluster 7



Cluster 11

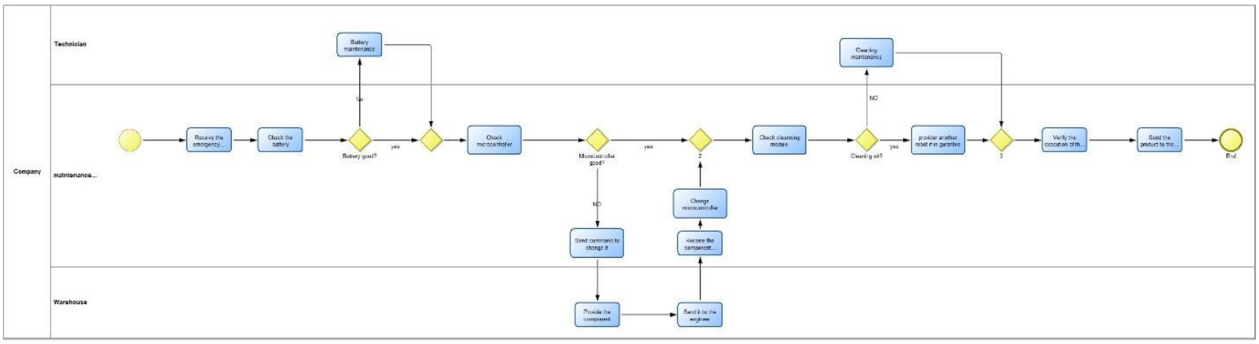


Cluster 13

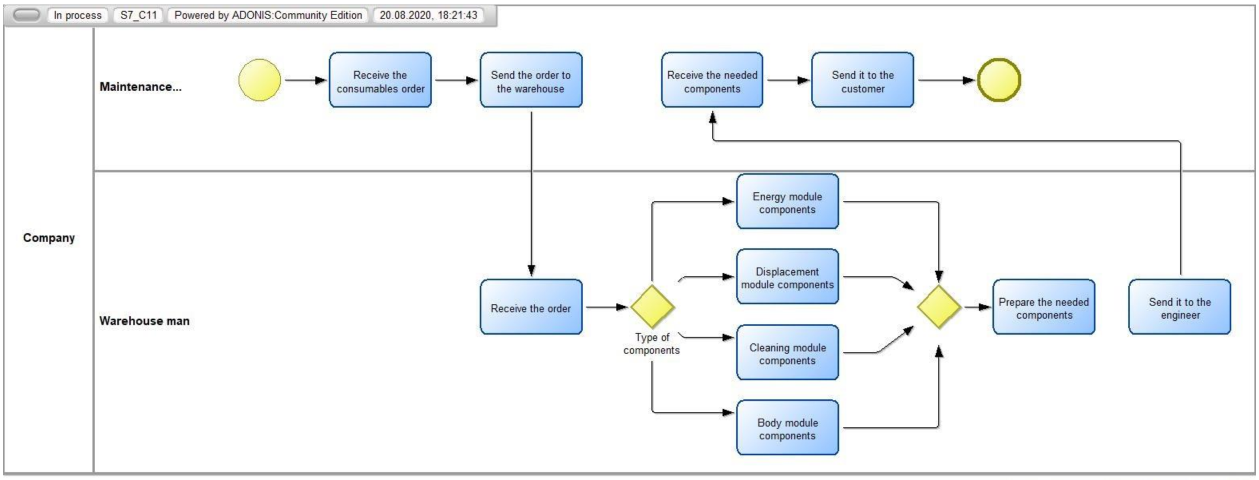


Appendix III.7. Scenario 7

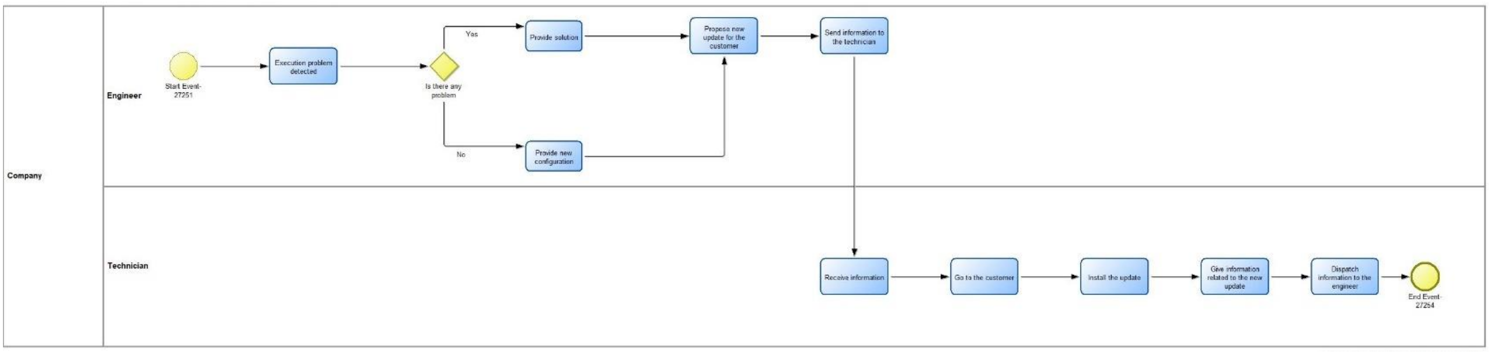
Cluster 10



Cluster 11

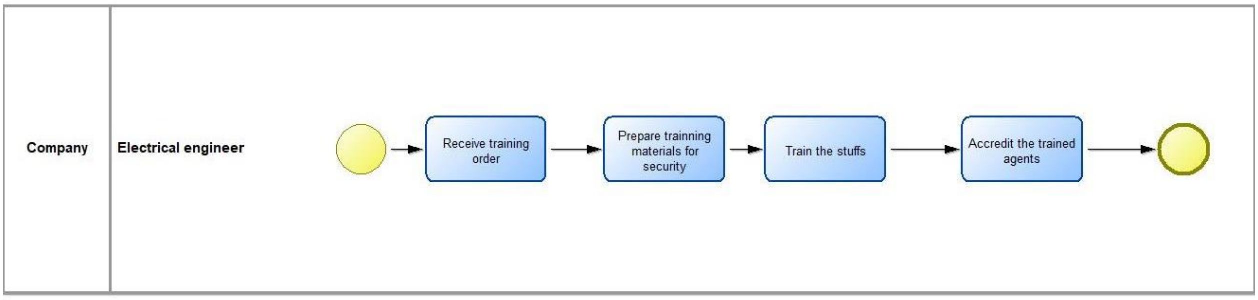


Cluster 14

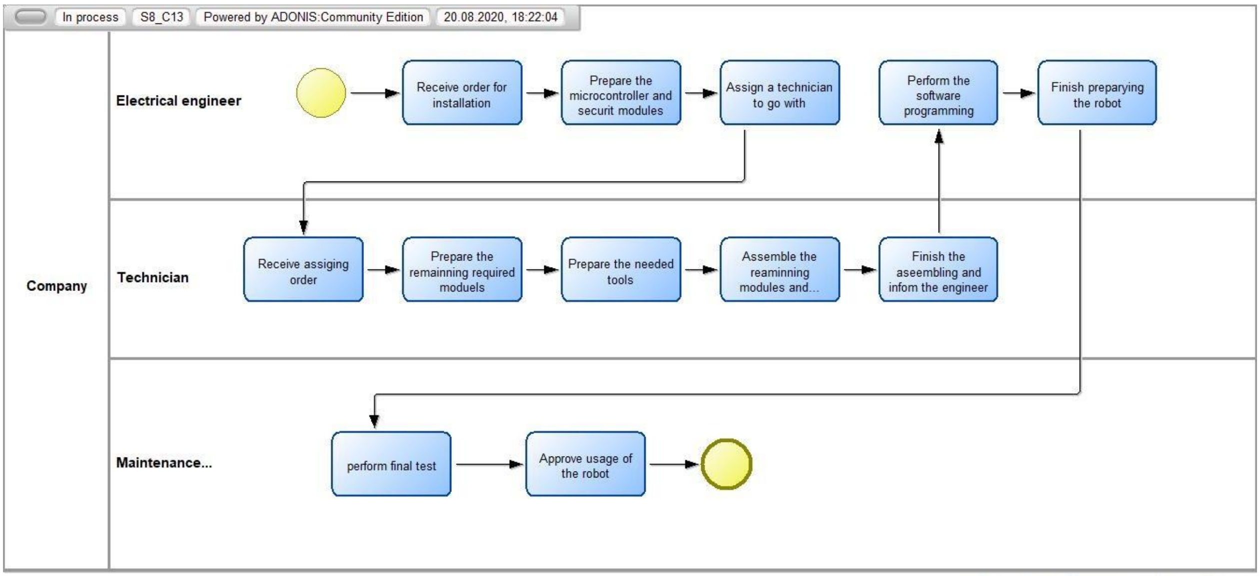


Appendix III.8. Scenario 8

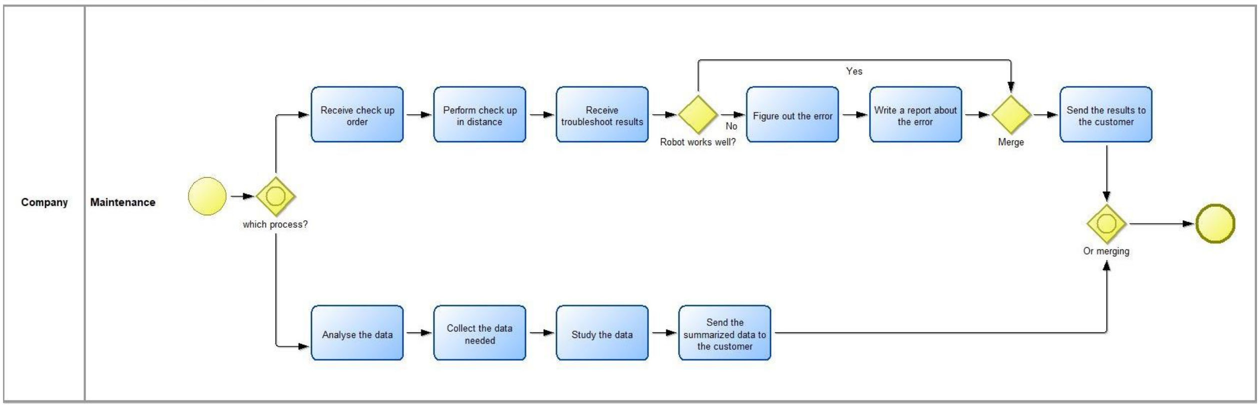
Cluster 12



Cluster 13



Cluster 14



Appendix IV. R Code

Appendix IV.1. Clustering code

```
"uploading the different numerical DSMs"
CleanRobot_Commonality1 <- read.csv(file.choose(), header = TRUE, sep = ";")
CleanRobot_Functional1 <- read.csv(file.choose(), header = TRUE, sep = ";")
CleanRobot_Resource1 <- read.csv(file.choose(), header = TRUE, sep = ";")
CleanRobot_Information1 <- read.csv(file.choose(), header = TRUE, sep = ";")
Cleanrobot_try1 <- read.csv(file.choose(), header = TRUE, sep = ";")
CleanRobot_Commonality <- CleanRobot_Commonality1[1:29, 2:30]
CleanRobot_Functional <- CleanRobot_Functional1[1:29, 2:30]
CleanRobot_Resource <- CleanRobot_Resource1[1:29, 2:30]
CleanRobot_Information <- CleanRobot_Information1[1:29, 2:30]
CleanRobot_try <- Cleanrobot_try1[1:29, 2:30]
"applying weight to each of the numerical DSM"
CleanRobot_Commonality_coeff = apply(CleanRobot_Commonality, 1:2, function(x) {x*0.3})
CleanRobot_Functional_coeff = apply(CleanRobot_Functional, 1:2, function(x){x*0.5})
CleanRobot_Resource_coeff = apply(CleanRobot_Resource, 1:2, function(x){x*0.1})
CleanRobot_Information_coeff = apply(CleanRobot_Information, 1:2 , function(x){x*0.1})
"Building the aggreated matrix"
CleanRobot_agg1 <- CleanRobot_Functional_coeff + CleanRobot_Commonality_coeff
+ CleanRobot_Resource_coeff + CleanRobot_Information_coeff
"Changing similarity matrix to dissimilarity matrix"
CleanRobot_agg1_diss <- apply(CleanRobot_agg1, 1:2,  function(x) {3-x})
"hierarchical clustering with ward.D method"
CleanRobot_agg1_dist <- dist(as.matrix(CleanRobot_agg1_diss))
CleanRobot_agg1_clust <- hclust(CleanRobot_agg1_dist, method = "ward.D")
CleanRobot_agg1_clust
plot(CleanRobot_agg1_clust,  labels = CleanRobot_Functional1[, 1])
"Optimum number of cluster for hierarchical and k-medoids"
fviz_nbclust(CleanRobot_agg1, FUN = hcut, method = "silhouette", k.max = 20)
fviz_nbclust(CleanRobot_agg1, FUN = pam, method = "silhouette", k.max = 20)

"visulaize hierarchcial and k-meodis  for total number of 12 clusters "
hc_silhouette <- hcut(CleanRobot_agg1, k = 12, hc_method = "ward.D")
fviz_dend(hc_silhouette, show_labels = TRUE, rect = TRUE)
k_silhouette <- eclust(CleanRobot_agg1, "pam", k=12)

"visulaize the silhouette inex for 12 clusters for both techniques"
fviz_silhouette(hc_silhouette, label = TRUE)
fviz_silhouette(k_silhouette, label = TRUE)
```

Appendix IV.2. ANP code

```
entries_20 <- c(1, 3, 9, 0.3333,1,7, 0.111, 0.143, 1)
Criterion20 <- matrix(entries_20, nrow=3, byrow=TRUE)
Criterion20
Criterion20_eigen <- eigen(Criterion20)
Criterion20_eigen
Criterion20_victor <- Criterion20_eigen$vectors[,1]/sum(Criterion20_eigen$vectors[,1])
Criterion20_victor

entries_21 <- c(1,7, 9, 0.143,1,5, 0.111, 0.2, 1)
Criterion21 <- matrix(entries_21, nrow=3, byrow=TRUE)
Criterion21
Criterion21_eigen <- eigen(Criterion21)
Criterion21_eigen
Criterion21_victor <- Criterion21_eigen$vectors[,1]/sum(Criterion21_eigen$vectors[,1])
Criterion21_victor

entries_22 <- c(1/1,    3/1,    1/5,    1/1,    3/1,    1/5,
                1/3,    1/1,    1/5,    1/1,    1/5,    1/3,
                5/1,    5/1,    1/1,    5/1,    5/1,    3/1,
                1/1,    1/1,    1/5,    1/1,    3/1,    1/3,
                1/3,    5/1,    1/5,    1/3,    1/1,    1/5,
                5/1,    3/1,    1/3,    3/1,    5/1,    1/1)
Criterion22 <- matrix(entries_22, nrow=6, byrow=TRUE)
Criterion22
Criterion22_eigen <- eigen(Criterion22)
Criterion22_eigen
Criterion22_victor <- Criterion22_eigen$vectors[,1]/sum(Criterion22_eigen$vectors[,1])
Criterion22_victor

entries_23 <- c(1/1,    1/3,    1/7,    1/3,
                5/1,    1/1,    1/1,    3/1,
                7/1,    1/1,    1/1,    1/3,
                3/1,    1/3,    1/5,    1/1)
Criterion23 <- matrix(entries_23, nrow=4, byrow=TRUE)
Criterion23
Criterion23_eigen <- eigen(Criterion23)
Criterion23_eigen
Criterion23_victor <- Criterion23_eigen$vectors[,1]/sum(Criterion23_eigen$vectors[,1])
Criterion23_victor

entries_24 <- c(1/1,    1/7,    3/1,
                7/1,    1/1,    9/1,
```

```
              1/3,          1/9,       1/1)
Criterion24 <- matrix(entries_24, nrow=3, byrow=TRUE)
Criterion24
Criterion24_eigen <- eigen(Criterion24)
Criterion24_eigen
Criterion24_victor <- Criterion24_eigen$vectors[,1]/sum(Criterion24_eigen$vectors[,1])
Criterion24_victor

entries_25 <- c(1/1,    1/3,       1/5,
              3/1,          1/1,       1/3,
              5/1,          3/1,       1/1)
Criterion25 <- matrix(entries_25, nrow=3, byrow=TRUE)
Criterion25
Criterion25_eigen <- eigen(Criterion25)
Criterion25_eigen
Criterion25_victor <- Criterion25_eigen$vectors[,1]/sum(Criterion25_eigen$vectors[,1])
Criterion25_victor

entries_26 <- c(1/1,    3, 1/3, 1)
Criterion26 <- matrix(entries_26, nrow=2, byrow=TRUE)
Criterion26
Criterion26_eigen <- eigen(Criterion26)
Criterion26_eigen
Criterion26_victor <- Criterion26_eigen$vectors[,1]/sum(Criterion26_eigen$vectors[,1])
Criterion26_victor


entries_27 <- c(0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,
  0,  0,  0,  0,  0,  0,  0,  0,  0,
        0,  0,  0,  0,
        0.66,  0  ,0,0,  0.385,  0.385,  0,  0,  0,  0,  0,  0,
  0,  0,  0,  0,  0,  0,
        0,  0,  0,  0,  0,  0,
        0.29,  0,  0,  0,  0.085,  0.085,  0.4375,  0.4375,  0,  0,  0,
  0,  0,  0,  0,
        0,  0,  0  ,0,  0,  0,  0,  0,  0,
        0.05,  0,  0,  0,  0.03,  0.03,  0.0625,  0.0625,  0.5,  0,  0,
  0,  0,  0,  0,
        0,  0,  0,  0,  0,  0,  0,  0,  0,
        0,  0.5,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,
  0,  0,  0,  0,  0,  0,  0,
        0,  0,  0,  0,  0,
        0,  0.5,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,
  0,  0,  0,  0,  0,  0,  0,
        0,  0,  0,  0,  0,
        0,  0,  0.25,  0  ,0,  0,  0,  0,  0,  0,  0,  0,
  0,  0,  0,  0  ,0,  0,  0,  0,
```

```
0, 0, 0, 0,
0, 0, 0.75, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0,
0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0,
0, 0, 0, 0, 0.05, 0.05, 0.04, 0.075, 0, 0, 0, 0,
0, 0, 0, 0, 0,
0, 0, 0 ,0 ,0, 0, 0,
0, 0, 0, 0, 0.025, 0.025, 0.21, 0, 0.05, 0, 0, 0,
0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0.205, 0.205, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0,0, 0, 0 ,0 ,0 ,0,
0, 0, 0 ,0, 0.05, 0.05, 0.175, 0.39, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0 ,0, 0, 0, 0,
0, 0 ,0, 0, 0.04, 0.04, 0.075, 0.035, 0.13, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0.13, 0.13, 0, 0, 0.315, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0 ,0, 0, 0, 0, 0, 0, 0.13, 0.14, 0.21,
0.18, 0.27, 0.2, 0.14, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0.13, 0.14, 0.13,
0.19, 0.27, 0.1, 0.14, 0, 0 ,0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0.13, 0.12, 0.1,
0.09, 0.12, 0.11, 0.13, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0.12, 0.12, 0.11,
0.17, 0.12, 0.16, 0.13, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0 ,0 ,0, 0, 0, 0.12, 0.12, 0.1,
0.09, 0.12, 0.11, 0.12, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0.12, 0.12, 0.11,
0.09, 0, 0.1, 0.12, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0 ,0 ,0, 0, 0, 0, 0.12, 0.12, 0.11,
0.09, 0.12, 0.12, 0.11, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0 ,0 ,0 ,0, 0, 0, 0 ,0 ,0.12, 0.12, 0.12,
0.09, 0, 0.1, 0.11, 0, 0, 0, 0, 0, 0, 0, 0
)
Criterion27 <- matrix(entries_27, nrow=24, byrow=TRUE)
Criterion27
install.packages("expm", repos="http://R-Forge.R-project.org")
Criterion28 <- Criterion27 %^% 4
```

École Nationale Supérieure des Mines
de Saint-Étienne

NNT : *Communiqué le jour de la soutenance*

Omar EZZAT

DISSERTATION TITLE: Product and service modularization for variety management in the context of mass customization

Specialty: Industrial Engineering

Keywords: Product Modularity, Service-oriented systems, Service modularity, Variety Management

Abstract: Many manufacturers are evolving from mass production to mass customization to cope with the increasing diversity of customer requirements. This leads to increasing complexity resulting from the great variety offered to customers. This problem is compounded by the integration of products and services within a single offering, as the importance of the service sector has increased over the years and companies have added services to their offering to meet the needs of customers. clients. To overcome this complexity, several methods have been proposed, such as modularity. Modularity has been seen as an effective method for meeting the challenges of variety management in the area of products and services. It has been discussed in the product area but rarely in the service area.

This thesis focuses on an approach to practically implement modularity on a service-oriented system that can be applied either to the product, or to the service, or to the integration of both. The approach can help reduce internal complexity resulting from the increased supply of products and services. Additionally, our approach focuses on the ability to have similarity measures between service and product elements. The assessment of the different outputs for the two techniques is used to identify the number and quality of aggregate outputs. Different measurement indicators are used to assess each exit scenario and to assess the clusters formed. Finally, a test case is carried out to validate our method.

École Nationale Supérieure des Mines
de Saint-Étienne

NNT : *Communiqué le jour de la soutenance*

Omar EZZAT

TITRE DE LA THÈSE : Modularisation des produits et services pour la gestion de la variété dans le cadre de la personnalisation de masse

Spécialité: Génie industriel

Mots clefs : Modularité du produit, Modularité des services, Systèmes orientés services, Gestion des variétés

Résumé: De nombreux fabricants sont en train d'évoluer de la production de masse à la personnalisation de masse pour faire face à la diversité croissante des exigences des clients. Cela induit une complexité croissante résultant de la grande variété proposée aux clients. Ce problème est aggravé par l'intégration de produits et de services au sein d'une même offre, car l'importance du secteur des services a augmenté au fil des ans et les entreprises ont ajouté des services à leur offre pour satisfaire les besoins des clients. Pour surmonter cette complexité, plusieurs méthodes ont été proposées, comme la modularité. La modularité a été considérée comme une méthode efficace pour relever les défis de la gestion des variétés dans le domaine des produits et services. Il a été abordé dans le domaine du produit mais rarement dans le domaine du service.

Cette thèse se concentre sur une approche pour mettre en œuvre pratiquement la modularité sur un système orienté service qui peut être appliqué soit au produit, soit au service, soit à l'intégration des deux. L'approche peut aider à réduire la complexité interne résultant de l'augmentation de l'offre de produits et de services. De plus, notre approche porte sur la capacité d'avoir des mesures de similitude entre les éléments de service et de produit. L'évaluation des différents extrants pour les deux techniques est utilisée pour identifier le nombre et la qualité des extrants de regroupement. Différents indicateurs de mesure sont utilisés pour évaluer chaque scénario de sortie et pour évaluer les grappes formées. Enfin, un cas de test est réalisé pour valider notre méthode.