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Developing a decision-support framework to advise companies in the planning of product configurators that can let the end user engineer-to-order the final product

Author
Marcos Saiz Montilla

Examination committee
Prof.dr. I. Gibson (Chairman)
Dr. M. V. Pereira Pessoa (Supervisor)
Dr.ir. P. K. Chemweno (External member)

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ABSTRACT

There is a general market trend focused on the demand for customized products based on the personal customer's needs. There are different business models that aim at achieving this customization to some degree. These mainly include assemble-to-order (ATO), make-to-order (MTO) and engineer-to-order (ETO). The business models of ATO and MTO generally utilize product configurators that allow the customer to select different elements of the product and obtain a customized item. In the ETO business model, that do not usually employ product configurators in its processes, the customization range is significantly higher than in the other two since the customer is not limited by a certain level of product variation. The literature points at the will of obtaining product configurators with more ETO possibilities to improve the potential level of customization the customer can achieve with a configurator. The identified research gap is the lack of efficient guidelines for companies to understand to which extent customization can be accomplished in product configurators by integrating them with ETO processes.

As a consequence, the objective of this research is "*To investigate, develop and evaluate a decision-support framework to advise companies in the planning of product configurators that can let the end user engineer-to-order the final product*". This objective is visualized with the creation of a framework that underlays the relation among the four main pillars identified in the literature that play a role in this scheme: the customer's needs and knowledge, the product configurator itself, the degree of customization the product can deliver and the capability of the company to achieve that customization. The decision-support framework helps companies to balance these different variables to deliver further customization as pulled by the customer with a product configurator.

The literature is reviewed to identify guidelines and best practices to fulfill the main objective. The framework includes different models and methods identified in the literature such as the Product Variant Master (PVM), activity diagrams, AS-IS and TO-BE process representations, use case diagrams and the Mamdani's Fuzzy inferences method. There are four phases in the framework and by going through them the companies obtain guidelines to plan the aforementioned configurator when possible based on the capabilities of the four main pillars.

The framework is then tested in the case of a real consumer good from the company Haverland. The findings from the literature and the case study are used to evaluate the framework with an application and a success evaluation. The application evaluation exhibits that the framework propitiously fulfills the research gap and can be considered beneficial for companies, but the main outcome from the success evaluation depicts that the achievable level of customization is still lower than the projected in ETO-only approaches.

The results from this thesis serve as a basis for future research in order to further investigate which factors and elements are relevant, and how their balance can be improved, to obtain a higher level of customization through product configurators when used in relation to the engineer-to-order business model.

LIST OF ACRONYMS

ATO: Assemble-to-Order

B2B: Business-to-Business

B2C: Business-to-Consumer

CAD: Computer-aided Design

CTO: Configure-to-Order

DRM: Design Research Methodology

DS-I: Descriptive Study I

DS-II: Descriptive Study II

ERP: Enterprise Resource Planning

ETO: Engineer-to-Order

FR: Functional Requirement

IDE: Industrial Design Engineering

IT: Information Technology

MoPD: Management of Product Development

MTO: Make-to-Order

MTS: Make-to-Stock

OPP: Order Penetration Point

PLM: Product Lifecycle Management

PS: Prescriptive Study

PVM: Product Variant Master

RC: Research Clarification

UML: Unified Modeling Language

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Note for the reader*

It is recommended to use Adobe Acrobat Reader or Adobe Acrobat Pro in order for the digital document to open automatically in a two-page view, which is the intended view to read this thesis.

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INTRODUCTION

1

The first chapter presents the introduction of the thesis. It includes the context and research problem (section 1.1), the objective, sub-objectives, and contribution of the thesis (section 1.2), the research approach (section 1.3) and the thesis structure (section 1.4).

This thesis describes a decision-support framework to advise companies in the balance of the capabilities of the product, the customer, the configurator and the own company in order to plan product configurators that can let the end user engineer-to-order the final product.

1.1 Context and research problem

There is a general market trend focused on the increasing demand for customized products based on the individual customer's needs (Forza & Salvador, 2006; Da Silveira et al., 2001; Heiskala et al., 2007). This personalization tendency is tackled through different perspectives and most of them are connected to mass customization. Mass customization relates to the ability to provide individually designed products and services to every customer through high process flexibility and integration (Da Silveira et al., 2001). There are, according to Da Silveira et al. (2001), four main methodologies that help to enable mass customization: Agile manufacturing, Lean manufacturing, Supply chain management, and Customer-driven design and manufacturing. This thesis targets at strategies that can be included in the last methodology.

As part of Customer-driven design and manufacturing, there are, for instance, different business models that manage these products processes and aim at achieving customization to some degree. These models include, mainly, make-to-order (MTO), assemble-to-order (ATO) and engineer-to-order (ETO) (Duchi et al., 2015; Olhager, 2003). Among these, ETO provides the highest degree of customization since it creates the product design and engineering from the ground up based on the customer order (Hicks & McGovern, 2009). Addo & Eyob (2012) describe ETO as a product development process, which starts with a product specification based on the customer order and finishes with an engineering design as its deliverable.

In the case of MTO or ATO business models, the final product consists of a combination of already available components or modules that the customer can choose from. These business models usually utilize product configurators that allow the customer to select the different elements of the product and obtain a customized item (Willner et al., 2014). A product configurator can be described as an information system that supports the creation and management of configuration based on the specifications given by the individual (Heiskala et al., 2007). Product configurators can also be considered strategies of the Customer-driven design and manufacturing methodology. Nevertheless, the customization in ATO or MTO is limited by the options that are offered by the company in terms of their internal variety (Blecker et al., 2004).

In all these models, the selection for the design is performed following the order from the customer, but in ETO the engineering, manufacturing and assembling of the product are also developed after the customer request is placed (Olhager, 2003). With the ETO model, the customization range is significantly higher than in the other two, since the customer is not limited by a certain amount of product variation (Hicks & McGovern, 2009), but has broader freedom when creating the order. All these business models need of an interaction with the customers in order to comprehend their requirements and this should take into account their expertise and translate their needs into features for the final product.

Product configurators, as used in MTO or ATO, comprise all activities contributing to create customized products from a set of predefined components, which can be parts or components, while taking into account a set of delimited constraints that restrain how items can be selected and combined (Zhang, 2014).

As described by Zhang (2014), there is naturally a wide range of restrictions that are imposed on the customer when using a product configurator, and this naturally leads to the failure for the user to customize to a bigger extent the final product (Blecker et al., 2004) when compared with ETO. Moreover, the customers aim at having a wider range of choices for their personalized product (Da Silveira et al., 2001). It can be stated that in this scheme, as described by Da Silveira et al. (2001), the configuration method itself, the product, the company and the customer are the main pillars that are interlinked and are influencing the creation of mass customization systems like product configurators.

While there is already some available literature regarding the will of extending product configurator capabilities to ETO approaches (Kristjansdottir et al., 2017; Kristianto et al., 2015; Shafiee et al., 2014), there is little research in terms of the relation between the consumer knowledge and the product configurator (Fürstner et al., 2012) in ETO environments. On the one hand, Fürstner et al. (2012) state the need to explore the limits for simplification and complexity in the development of product configurators in relation to customer knowledge and engagement. On the other hand, ETO can provide a high level of customization (Hicks & McGovern, 2009), but, as described by Pandit & Zhu (2007), the product development process in ETO is complex due to, among other factors, the translation of the customer requirements into the final product.

1.2 Thesis objective

The different approaches to tackle the growing demand for customized items can be confronted from various perspectives. In the case of the ETO business model or product configurators as used in ATO and MTO approaches, all the different areas of product development like manufacturing, product design, costs or prototype testing need to be considered in detail. In this thesis, the focus is on the prioritization process for companies to discern the most influential factors of the four main pillars defined by Da Silveira et al. (2001) that can be considered as the most important for the planning of mass customization systems like product configurators. Other aspects in the product development process, such as finance or marketing are not in the foreground of the thesis, since it would be out of the scope to cover all of them for the project. For business-to-consumer (B2C) products (consumer goods), the customers can have very different degrees of expertise in the product and in the configuration procedure compared to users in business-to-business (B2B) products (capital goods), nevertheless the customer perspective is usually neglected when creating product configurators in both B2C and B2B environments (Blecker et al., 2004). Moreover, the configuration process for B2B products is more challenging than in B2C products (Zhang, 2014). Therefore, the type of final product this thesis is focused on for its outcome is consumer goods.

Accordingly, with the context, problem and scope defined, the main objective of the thesis is:

To investigate, develop and evaluate a decision-support framework to advise companies in the planning of product configurators that can let the end user engineer-to-order the final product

This objective is visualized with the creation of a framework that underlays the relation among the four previously mentioned pillars that play a role in this scheme: the customer, with his/her needs and knowledge, the product configurator itself, the product with the degree of customization that it can deliver, and the capability of the company to achieve that customization. The decision-support framework helps companies to balance these different variables to deliver ETO possibilities (if possible) and, hence, further customization as pulled by the customer with a product configurator.

Accordingly, to achieve the main objective, a strategy is proposed. This strategy is achieved by following this list of sub-objectives for the thesis:

1. **Research the problem context and identify the research gap:**
   1.1 Product configurator classifications and challenges.
   1.2 ETO weaknesses, strengths and potential improvements.

2. **Identify guidelines, best practices and outcomes for the relation between product configurators and ETO.**

3. **Identify guidelines, best practices and outcomes for the relation between product configurators and the customer knowledge.**

4. **Select suitable models and methods from the literature to apply in the framework.**

5. **Create the framework:**
   5.1 Identify the elements of the framework.
   5.2 Develop and explain the framework.

6. **Evaluate the framework:**
   6.1 Test the framework in the case of a real consumer product.
   6.2 Check the applicability and usefulness of the framework with an application evaluation and a success evaluation.

Consequently, this thesis contributes to the practice by fulfilling the main objective of developing a framework that, by balancing the different pillars involved, helps companies to plan product configurators that can provide customers the customization possibilities to engineer-to-order the final product based on the potential customer's capabilities to do so.

1.3 Research approach

The Design Research Methodology (DRM), which is first introduced by Blessing & Chakrabarti (2009), is the approach that is adopted in this project as a supporting framework to fulfill each sub-objective, since its procedures are designated to establish rigorous research approaches by assisting to prepare and carry out design research.

The methodology framework in DRM (Blessing & Chakrabarti, 2009) consists of four main stages which are employed in this research as follows:

- **Research Clarification (RC)**
  This first stage helps to explain the current understanding of the problematic situation and the general research aim, developing a study plan and supplying a target for the later stages. It also develops the initial reference model and the initial impact model.

- **Descriptive Study I (DS-I)**
  Next, it is intended to broaden the comprehension of the design and the identified determinants that affect its success by exploring the phenomenon of design. The reference model is updated in this stage.

- **Prescriptive Study (PS)**
  The third stage aims at systematically developing support, reaching the defined research goal and considering the results of DS-I. The updated impact model is created based on the developed support.

- **Descriptive Study II (DS-II)**
  Finally, the applicability of the actual support, and its practicality and usefulness are evaluated through an application evaluation and a success evaluation.

The DRM proposes different approaches for the 4 stages that can be review-based, comprehensive and/or initial. The review-based approach is based on literature research and the comprehensive one is based on literature research and the results and conclusions achieved by the researcher. The third approach (initial study) is related to the evaluation of the outcome of the previous sections and the preparation for further future use. This project follows the review-based approach for the first 2 stages, the comprehensive one for the Prescriptive Study stage and it finishes with an initial Descriptive Study II.

All these stages are adapted to the particularities of this specific thesis as can be seen in figure 1. Each DRM stage is described with two columns: (1) the basic means procedure to fulfill the stage and (2) the main outcome of that stage, which connects with the different sub-objectives of the thesis.

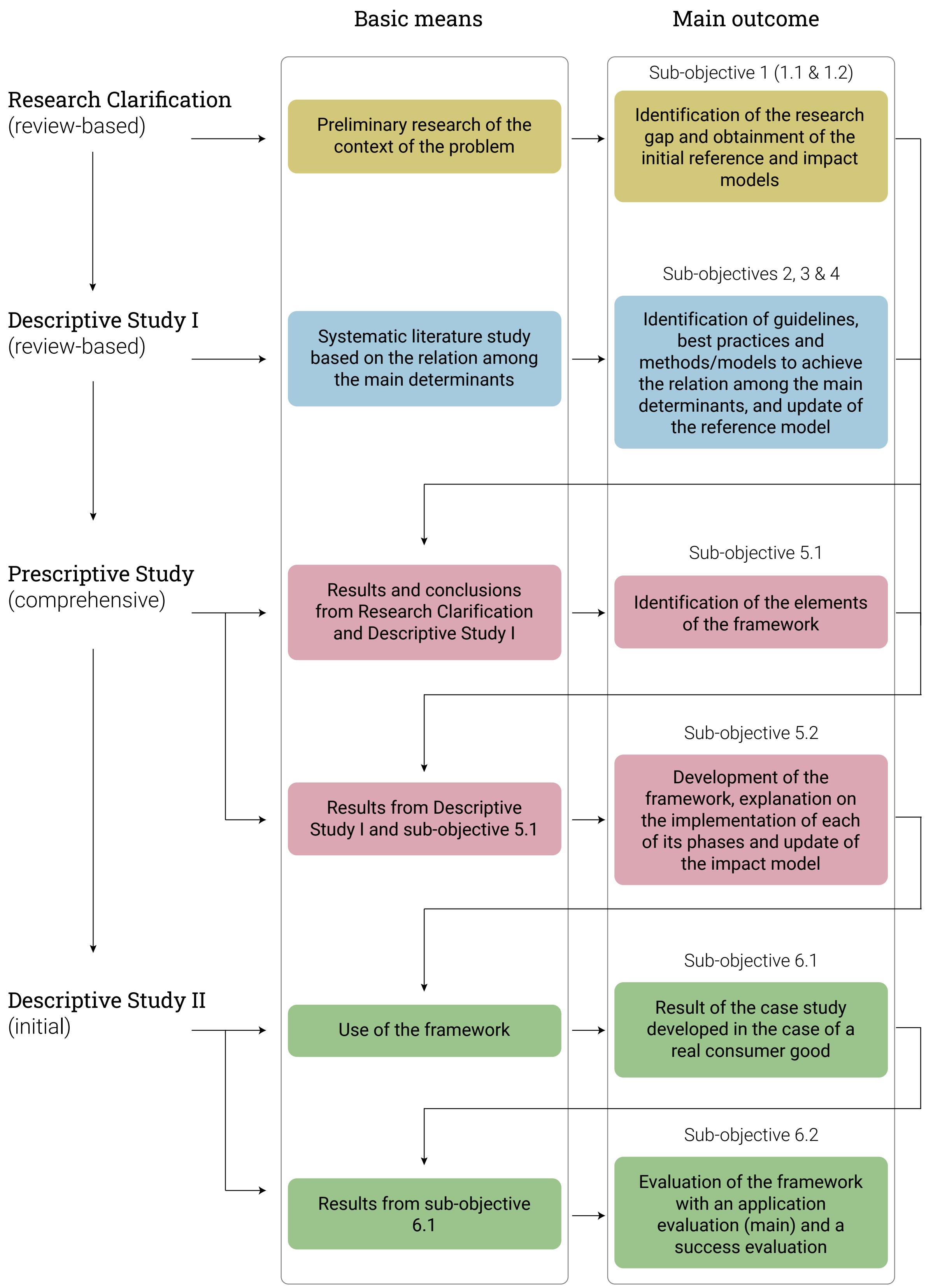


Figure 1: Research methodology applied in this thesis based on the DRM (Blessing & Chakrabarti, 2009)

1.4 Thesis structure

The thesis consists of a total of 6 chapters where the previously explained sub-objectives populate their content. The visual representation of the thesis structure is displayed in figure 2.

It starts with chapter 1 (Introduction), where first, the context and the research problem are described. Then, the objective, the sub-objectives, the research approach and the thesis structure are also explained.

In chapter 2, preliminary research is performed to investigate the context of the problem and to identify the research gap. This research is focused on the classifications and challenges of product configurators as well as on the weaknesses, strengths and potential

Figure 2: Visual representation of the thesis structure

improvements of ETO. This chapter also presents the initial reference and impact models.

Chapter 3 (Literature study) researches the relation between the main identified elements of this thesis: product configurators with ETO and product configurators with consumer knowledge. Afterwards, some theoretical background is presented with the selection of suitable methods and models found in the literature to be utilized for the creation of the framework. The chapter is finalized with concluding remarks from the literature study which set the basis for the framework creation. Based on the findings, the reference model is updated.

This is followed by chapter 4 (Framework), where first, based on the results and conclusions of chapter 3, the elements that are part of the framework, are identified, as well as the relations among them. Then, the framework is developed and each of its phases is explained. After this, the impact model is updated.

Afterwards, in chapter 5 (Case Study and Evaluation), the framework is tested in the case of a real consumer good. The second part of the chapter checks the applicability and usefulness of the framework with an application evaluation based on feedback gathered from the company where the framework was tested, and a success evaluation.

To conclude, in chapter 6 (Final remarks), the author reflects on the evaluations and the objectives of the research. Recommendations for future work are also presented based on limitations of this research.

PRELIMINARY RESEARCH

2

In this chapter, preliminary research on the context of the problem is performed. As described in the previous chapter, Customer-driven design and manufacturing is considered by Da Silveira et al. (2001) as an enabling methodology to achieve mass customization. This methodology actively considers the market trends focused on general and individual customer requirements in particular during the design, manufacturing and delivery of the products (Da Silveira et al., 2001; Jagdev & Brown, 1998). Da Silveira et al. (2001) state that some authors refer to the practices of this methodology as "one-of-a-kind production", similar to the approach of the ETO business model. Furthermore, the proper management of different product variants, like in product configurators, is also considered a consequence of implementing customer-driven ideas (Da Silveira et al., 2001). The concepts of product configurators and engineer-to-order are then investigated to understand the current situation in terms of classifications, challenges, strengths, weaknesses and/or potential improvements.

The goal of this chapter is to provide a comprehensive overview and basis of the research problem, which leads to the identification of the research gap. By doing this, the importance of the research on the relation of these topics, which is performed in the systematic literature study of chapter 3 is validated. Furthermore, the information presented in this chapter is put to use throughout the rest of the thesis. Several of the concepts presented are also utilized for the identification of the elements of the framework and its development (chapter 4). This investigation is broad, so it is understood how these concepts are tackled in the literature.

2.1 Product configurators

A product configurator is an information system used to manage products and their variants and create customer-specific adaptations of the product (Tiihonen & Soininen, 1997). The goal of a product configurator is to obtain a customized product according to the client's needs. Product configurators comprise all activities that contribute to the creation of customized products from a set of predefined components, while taking into account a set of delimited constraints that restrain how items can be selected and combined (Zhang, 2014). The use of product configurators can be traced back to the decade of 1970 when a company called Digital Equipment Corporation created a program called R1 that was used to configure computer systems to fulfill different customer specifications (McDermott, 1982). Ever since, the use of product configurators has been broadly adopted in different industries to translate the requirements of the customer into product documentation.

As stated by Da Silveira et al. (2001), product configurators are considered facilitators to achieve mass customization. The final product, the customer, the configuration method itself and the company are, according to Da Silveira et al. (2001), the main pillars influencing the creation of product configurators. The main aim of mass customization is to provide personalized products or services by the means of flexible processes in high volumes and at fairly low costs for the businesses (Da Silveira et al., 2001). Therefore, as the trend for customized products grew larger with time, companies found in product configurators a tool to accomplish this customization (Heiskala et al., 2007). Nevertheless, this customization is limited by the delimited configuration possibilities established by the company (Blecker et al., 2004). Furthermore, in B2C products, the consumer can have very different levels of expertise in both the product and the configurator process (Blecker et al., 2004), which also affects the customization possibilities. Moreover, this customer perspective is usually neglected when developing product configurators. In figure 3, Tiihonen & Soininen (1997) describe the sales-delivery process with the use of a product configurator: This general overview (figure 3), presents the steps of a sales delivery process in which the product configurator is used to translate the requirements from the customer into components orders and configuration descriptions that are needed to create the specific product instance for that customer. Nevertheless,

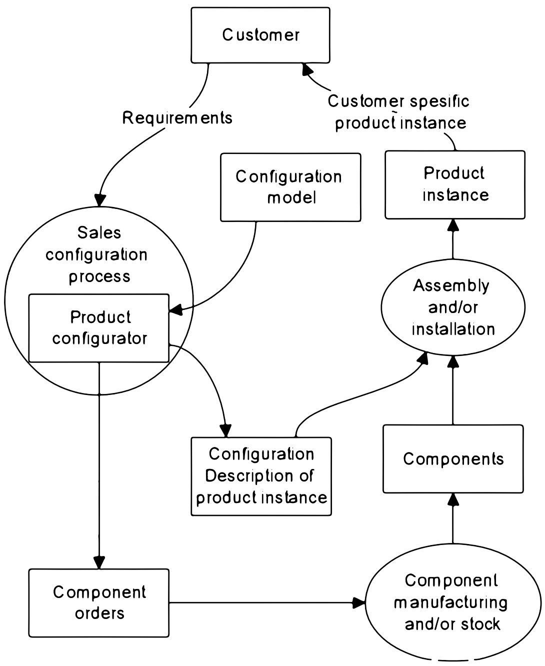


Figure 3: Sales delivery process with a product configurator (Tiihonen & Soininen, 1997)

there is not a universal and standard type of product configurator that fits all kinds of products and companies, they are applied in different areas of the product development process and through different procedures.

2.1.1 Product configurators classifications

Product configurators can be classified based on different approaches like configuration knowledge, business strategy or scope of use, among others. One thing that all product configurators have in common is the existence of restrictions on how the different components can be integrated into the final product (Zhang, 2014). This very broad concept sets the basis for the development and usage of product configurators. In studies developed by Blecker et al. (2004), Tiihonen & Soininen (1997) and Sabin et al. (1998), product configurators are conceptualized through different classifications. Next, the most relevant to understand and categorize them are described.

2.1.1.1 Configuration knowledge classification

This classification is based on various concepts needed for the representation of the configuration knowledge domain and the types of relations between the different components of the product (Sabin et al., 1998). This type of classification is divided into 3 sub-types (Blecker et al., 2004; Sabin et al., 1998):

- **Rule-based reasoning**
  A rule-based configurator works with the form of "if condition, then consequence". With this approach,

from every decision that is performed with the product configurator, the system examines the whole set of rules and only considers the ones that can be performed next (Sabin et al., 1998). These rules contain the basic compatibilities between the components and the expected actions to create the computational solution of the specific configuration problem (Blecker et al., 2004). The main problems that are faced with this approach are the separation between the direct relation among components and the possible actions of the user, as well as the procedure of gaining, maintaining and updating all the required knowledge to create the different rules of the configurator (Sabin et al., 1998).

- **Model-based reasoning**
  There are different model-based representations in configurators of which logic-based, resource-based and constraint-based approaches stand out (Blecker et al., 2004). In the logic-based approach, which is based on description logic, the objects in the domain, the different types of objects and their relations are described with constructors (like "AND", "AT LEAST", "OR", etc.) to allow the creation of complex iterations. In the resource-based approach each component is characterized by the number of resources it needs, uses and consumes (Blecker et al., 2004). In the constraint-based (or structure-based) approach, each component is described with a set of properties and the possibilities to connect with the other components. These constraints result in restrictions or requirements of specific combinations (Blecker et al., 2004). Product configurators usually combine some of these model-based approaches to obtain the required knowledge for the configuration (Tiihonen & Soininen, 1997).

- **Case-based reasoning**
  This approach is based on the statement that similar problems have similar solutions. Therefore, it relies on the information from previously used configurations in past customers which is used to adapt the new product configurator based on this knowledge (Blecker et al., 2004).

In consequence, rule-based reasoning is favorable for simple customizable products that contain little configuring information, and case-based reasoning is convenient when there are formerly solved instances or methods to customize the products. Within model-based reasoning, the resource-based approach is based on expert preliminary product knowledge from the customer in order to use the configurator. The constraint-based is usually used for predesigned components and can be difficult to maintain the configuring information. The logic-based approach can be utilized for complex customizable products due to consistency checking of the configuring information, and by users with little prior product knowledge.

2.1.1.2 Business strategy classification

There are different business models used in the mass customization paradigm. The three main ones are assemble-to-order (ATO), make-to-order (MTO) and engineer-to-order (ETO). Product configurators can be classified based on the main strategy the business is going for (Blecker et al., 2004). Product configurators are mostly used in ATO or MTO business models. In the case of these two, product configurators are easier to be applied since the consumer chooses from predefined components or designs based on the internal variety of the company (Blecker et al., 2004). For the ETO business model, the aim of using product configurators is rarer, since it is more complex and demanding due to the limited existence of predefined components.

2.1.1.3 Internal and external classification

Product configurators can also be classified into internal or external. Internal configurators are the ones that are used within the company and the end customer does not have direct access to them (Blecker et al., 2004). On the other hand, external configurators are those that are used to assist the end customer in the configuration of the product. External configurators are also described as commercial configurators (Tiihonen & Soininen, 1997), design configurators (Mäkipää et al., 2012) or sales/commercial configurator (communicates the product to the customer and provides real-time information) + technical configurator (checks the validity of the product variant and generates the bill of materials based on the customer's selection) (Forza & Salvador, 2002). External configurators can be divided as well between B2B (Business-to-business) and B2C (Business-to-consumer) configurators (cyLEDGE Media, 2018). B2B configurators are normally employed to support sales and B2C are often used as design tools to let the customer choose a specific configuration.

2.1.1.4 Scope of use classification

Product configurators can also be categorized as single-use and general-use systems. Single-use configurators are utilized in the technical and sales-delivery process of a specific product or family of products for a particular company, while general-use configurators are used to configure different product types for different companies (Tiihonen & Soininen, 1997).

2.1.1.5 Complexity classification

According to Tiihonen & Soininen (1997), product configurators can be classified according to their design complexity. There are in this case three types of configurators. The first type is the primitive configurator that just records the configuration actions performed by the user without checking its validity. The second type is the interactive configurator that can check whether a configuration decision is correct and guide the user to create these decisions. Finally, an automatic configurator has all the functionalities of the interactive one and can also generate parts or even entire configurations based on the customer requirements.

All these different classifications help to provide a better analysis of product configurators and understand the different types based on their categorization. The information provided in these classifications is utilized throughout the research to better comprehend the different configurators presented and to classify the type of product configurator that can be achieved with the framework to be developed. Blecker et al. (2004) determine that the conceptualization of different types of configurators helps in the organization and planning of a configuration system.

2.1.2 Product configurators challenges

Product configurators are utilized and applied in many different industries as it can be examined from the configurator database of Cyledge that covers a listing of 1200 product configurators used by companies in 17 different industries (cyLEDGE Media, 2018). Product configurators are used for simple products in terms of engineering like clothing, packaging or accessories, and also for more complex products like electronics, motor vehicles or industrial goods.

Product configurators provide companies numerous benefits like better product variety management (Forza & Salvador, 2002), a shorter sales-delivery process (Tiihonen & Soininen, 1997), better product customization and differentiation for the customer (Trentin et al., 2012; cyLEDGE Media, 2018) or simplifying the order acquisition activities (Salvador & Forza, 2004).

Nevertheless, as well as benefits, product configurators face abundant challenges. In the studies developed by Zhang (2014) and Heiskala et al. (2007), numerous issues and challenges regarding product configurators are investigated. Next, the most relevant challenges that contribute to the planning, development and design of product configurators are described, along with their relation to this research.

2.1.2.1 Configuration ontology

Ontologies are theories about types of objects, properties of these objects and their possible relation in a specific knowledge domain (Krebs, 2006). Ontologies provide the conceptualization that underlies effective knowledge representation and consist of several concepts and the relationship between them. It is a challenge for product configurators to provide proper configuration ontology for documenting configuration knowledge in an easy-to-understand form (Zhang, 2014). Therefore, the selection of concepts and elements that play a role in the development of product configurators is fundamental for the creation of the configurator. Zhang (2014) includes among these elements the product itself with its structure, or the capabilities of the company in terms of production. Da Silveira et al., (2001) also state, as previously mentioned, that the configuration method itself, the product, the company and the customer are the main pillars that are interlinked and influence the creation of product configurators. These four main pillars constitute the configuration ontology for this research and are deeply acknowledged for the framework development.

2.1.2.2 Configuration knowledge acquisition and representation

Product configuration involves the need for knowledge from different domains in product development. This knowledge is normally represented in product configurators with constraints and rules that determine the selection and combination of components in the final product (Zhang, 2014). It is a challenge to acquire this information and decide where to look for this knowledge. It is stated by Zhang (2014) that the arrangement of the configuration process for B2B products involves more challenges than for B2C products. As described in sub-section 2.1.1.1, commercial configurators usually combine different model-based approaches to represent the configuration knowledge (Tiihonen & Soininen, 1997). In this research, the knowledge acquisition process is tackled and described in the framework to be developed.

2.1.2.3 Customer needs

The identification of what the end user wants is of great importance to guarantee that the product configuration fulfills the customers' expectations during the configuration process (Zhang, 2014). This is a challenge especially when the customers do not know their real needs or can not express them appropriately (Blecker et al., 2004). Furthermore, a customer may not want to use the product configurator, may not know how to do so (Heiskala et al., 2007) or may feel overwhelmed by the number of configuration options presented. Thus, the customer-product configurator interaction and the related problems regarding this communication are key elements to take into consideration for the planning and development of configurators. Therefore, this is greatly considered for the framework development.

2.1.2.4 Configuration explanation

Explanations regarding the possible combinations in the configuration process are very important to avoid invalid decisions by the customer during the configuration process (Zhang, 2014). According to Haag et al. (2006), this explanation should be different when the user is the product configurator developer, the sales staff or the actual end user. For the latter, these explanations are presented as comprehensible guidelines to select the desired combinations for the final product. This thesis focuses on the configuration explanation challenge for end users. Furthermore, as it is stated later in chapter 3, Fürstner et al. (2012) consider that the customer's knowledge is also an important factor regarding the configuration explanation.

2.1.2.5 Configuration system design and development

There is a lot of research regarding solutions to design and develop product configurators. Most of them are focused on the development of single-use configurators (Zhang, 2014). According to Tiihonen & Soininen (1997), a product configurator should have an intuitive and visual interface, a structured and object-oriented method of modeling and the possibility to control the evolution of the products, the components and their connections. This challenge of designing the configuration system affects all types of configurators and the solution is usually exclusive for each of them. This thesis does not focus on the configurator design, but on the factors that influence its planning and development.

2.2 Engineer-to-order

In the engineer-to-order (ETO) business model, the product is designed, engineered and produced once the customer order has taken place (Iakymenko, 2018). The development of this type of product is often project-based since each item is specifically developed to fulfill the needs and requirements of the client. The usual ETO products are complex ones in terms of engineering like ships, offshore platforms or power generation plants (Iakymenko, 2018), but this model can be applied to any type of less complex consumer good. Design and project management are the main competencies for most companies that choose an ETO-only approach, while the fabrication process differs for every product and company (Hicks et al., 2000).

In ETO, the customer participates to some degree in the phases of design, engineering, configuration and production of the product to make sure that all his/her requirements are achieved (Olhager, 2003). The level of customization in ETO can vary significantly; from a mere customer-specific extension of a product parameter range to the complete development of a new product according to the customer requirements (Willner et al., 2014). ETO is characterized by its long lead time (Pandit & Zhu, 2007) which, in consequence, supplies project-based products in low volume (Vollmar & Gepp, 2015). This comes in contrast with other business models like make-to-stock (MTS), make-to-order (MTO) or assemble-to-order (ATO) which usually use product configurators and where products are less complex and are aimed to be produced in high volume (Vollmar & Gepp, 2015). In order to understand the context for ETO, these other business models are presented and briefly described.

In the MTS model, the product is created before the customer order is received and this is fulfilled with existing inventory stock which is later replenished through production orders based on a forecast (Alessandro, 2018). For MTO, the final product is made after the customer order and is, for the most part, a combination of standardized and personalized components that meet the client's specific needs (Alessandro, 2018). ATO

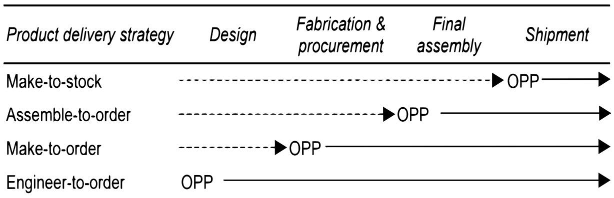


Figure 4: MTS, ATO, MTO and ETO business models characterized by their OPP (Olhager, 2003)

can be considered a type of MTO in which the components are already built and stocked and are only assembled after the customer order. In the study developed by Olhager (2003), these models are characterized by the order penetration point (OPP). As it can be seen in figure 4, the OPP separates the dotted lines that represent the activities that are forecast-driven in the product delivery strategy, and the straight lines that symbolize those activities that are customer-order-driven.

Accordingly, in the ETO model, the customers are more involved in the different phases of the product development process (Olhager, 2003) compared to MTO or ATO and especially with MTS. In MTO and ATO, the customers usually select, by the means of a product configurator, their preferred product variants within a predefined solution space (Willner et al., 2014).

2.2.1 ETO weaknesses and strengths

Companies that aim for the ETO model carry different challenges and benefits based on the weaknesses and strengths of ETO.

2.2.1.1 ETO weaknesses

The principal weakness of ETO is the long lead time associated with the products created with this model (Pandit

& Zhu, 2007; Addo & Eyob, 2012). This tendency is caused directly or indirectly by factors that are related to the design phase of the product (Addo & Eyob, 2012) where the customer plays a big part. These factors include poor organization between the participants in the project. This is particularly visualized in the early phases of the design when the customer requirements need to be accurately understood and interpreted, the different design alternatives have to be evaluated and the definitive design has to be selected (Pandit & Zhu, 2007).

The low volume achieved with ETO is also a weakness of this model. ETO produces products in very low volume (normally a volume of one) that have an extensive bill of materials (Hicks & McGovern, 2009). This is due to the complexity and high customization of the products created in ETO, which results in project-based approaches (Vollmar & Gepp, 2015) and supply chains that are ephemeral and only used once (Hicks & McGovern, 2009).

Other weaknesses of ETO are the engineering changes (Iakymenko, 2018) and high risks (Hicks & McGovern, 2009) associated with the whole process of this model. Engineering changes are modifications to the structure, behaviour or function of a product and they can be prompted by the customer, internal factors in the company or external factors like technology or regulations (Iakymenko, 2018). The participation of the customer in carrying out engineering changes is only sometimes required, not mandatory (Willner et al., 2014). In ETO, the engineering changes can happen throughout the whole product development process, while for example, in MTS these only happen before the production of each new product. The high risks mentioned by Hicks & McGovern (2009) are regarding the radical innovation surrounding each ETO product which prompts a potential technical and commercial failure to meet the customer requirements.

2.2.1.2 ETO strengths

The main strength of ETO is the high level of customization that products can achieve with this model, which is translated into a higher number of product variants (Hicks & McGovern, 2009; Pandit & Zhu, 2007). These products are required to be designed and engineered in detail based on the specifications and requirements of the customer order (Pandit & Zhu, 2007). As studied by Olhager (2003), the high level of customization achieved in ETO is due to the fact that all the design, manufacturing and assembly happens after the order penetration point. Therefore, all these processes are linked to the requirements of the individual customer who can trigger engineering changes throughout different phases of the process (Iakymenko, 2018), and results in a high and consistent level of customer service (Olhager, 2003).

Another of the strengths of ETO is the low inventory risk. This is due to the minimum inventory investment in the post-order penetration point activities (Olhager, 2003). Since most of the ETO products follow a project-based strategy (Vollmar & Gepp, 2015), there is no inventory of finished products (Matt, 2014) and the inventory stock is very low compared to other business models like MTO, ATO or MTS that stock already finished modules or whole products (Alessandro, 2018).

2.2.2 ETO potential improvements

The biggest challenge for companies that follow an ETO business model is the trade-off between customization and operational efficiency (Duchi et al., 2015; Forza & Salvador, 2002). In order to overcome this challenge, studies within various industries like the ones from Vollmar & Gepp (2015), Duchi et al. (2015) and Hicks & McGovern (2009) propose different potential improvements for ETO approaches.

2.2.2.1 Standardization programs

When developing a complex product, it is common to break down the design problem into smaller sub-problems to manage them more easily (Vollmar & Gepp, 2015). In the study developed by Vollmar & Gepp (2015) regarding industrial plants, it is stated that standardization is a common approach to handle complexity by modifications in the product structure in terms of decomposition and re-integration, especially for ETO products where no parts are standardized. Standardization is usually focused on the design and engineering phase of the product life cycle and can help to improve the overall project execution (Vollmar & Gepp, 2015). This has encouraged companies in ETO to adopt more standardized designs which have helped to reduce lead time (Hicks et al., 2000). The studies of Gepp et al. (2014) and Vollmar & Gepp (2015) describe 4 phases (figure 5) in standardization programs which are briefly described next:

- **Hierarchization**
  This first phase is also referred to as disassembly or decomposition. The product is decomposed into its elements and hierarchical levels are defined (Gepp et al., 2014) to select the one that could be standardized.

- **Modularization**
  During this phase, the elements are grouped by their functional, constructional or spatial relation (Gepp et al., 2014). By combining the functional and product breakdown structure, the product architecture is defined and the elaborated functions and products/components are grouped as modules taking into account the functional and physical connections between the elements (Vollmar & Gepp, 2015). The approach of product modularity is the strategy that characterizes the business models of ATO and MTO (Olhager, 2003).

- **Standardization**
  During this phase, the type of standardization for each module is defined and the technical design and development of the modules is initiated (Gepp et al., 2014).

- **Reuse**
  In order to ensure the applicability of the module, the reuse phase addresses measures and tools (Duchi et al., 2015) to ensure the repeated use of standardized modules in projects to achieve economic benefits (Vollmar & Gepp, 2015).

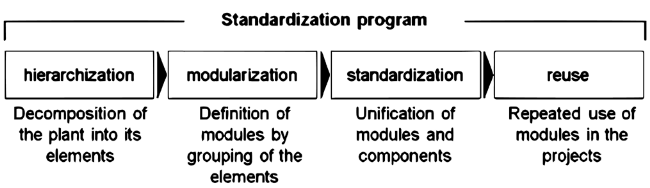


Figure 5: Phases of a standardization program for an industrial plant (Gepp et al., 2014)

The implementation of standardization programs can lead to a shift in ETO companies from a copy and modify design approach (from previous projects) to a combination of predefined modules to some extent, which can help to improve project execution (Vollmar & Gepp, 2015) and to reduce lead time (Hicks & McGovern, 2009).

2.2.2.2 Knowledge systems

Different authors like Pandit & Zhu (2007), or Duchi et al. (2015) propose different systems, tools or models to improve processes and standardization in ETO:

- **Information sharing**
  Pandit & Zhu (2007) propose an ontological framework that covers the major entities, their hierarchy and their relationships in an electrical transformer study that proves to be beneficial to facilitate efficient and effective information sharing between the different collaborating information systems in an ETO model. Duchi et al. (2015) investigate different best practices in three ETO companies like a documentation sharing platform or a task management system. These tools uphold a fluent information flow between the actors and stimulate a standardization of the information exchange (Duchi et al., 2015).

- **Configurators**
  Even though configurators are traditionally related to the business models of MTO/ATO with configured standard products, some ETO companies have utilized configurators in certain phases of the product development aiming for more efficient solutions (Duchi et al., 2015). Willner et al. (2014) state that configurators in ETO models work for the "standard" parts/products, while the "non-standards" are usually not included in the configurator and have to be managed within a separate ETO process. In this same study by Willner et al. (2014), the companies included in the case study, encountered difficulties when adding the "non-standard" parts that follow an ETO process into the product structure and the product configurator that manages the product variety. Duchi et al. (2015) describe in a case study that the use of an order execution configurator (internal configurator) in the sales phase helped to create reusable knowledge. It is established by Duchi et al. (2015) that product configurators can reduce the uncertainty and complexity in ETO approaches. The relation between the company and the ETO environment with its possible best practices like product configurators should be further explored as proposed by Duchi et al. (2015).

2.3 Preliminary research conclusion

In this chapter, an overview and basis of the research problem are presented. This is performed by investigating the broad terms of product configurators with their classifications and challenges, and engineer-to-order with its weaknesses, strengths and various potential improvements.

Different classifications for product configurators (Blecker et al., 2004;

Tiihonen & Soininen, 1997) are presented to be able to categorize the types of product configurators described in the thesis. It can be concluded that product configurators help to improve product variety management (Forza & Salvador, 2002), product differentiation (Trentin et al., 2012) and simplify the order acquisition activities (Salvador & Forza, 2004). Product configurators should provide an ontology to document configuration knowledge (Zhang, 2014) in the case of relevant elements affecting the configuration and the relationship between them. Da Silveira et al. (2001) identify the final product, the customer, the configuration method itself and the company as the main pillars influencing the creation of product configurators. It is also stated that product configurators should understand the needs and requirements of the customer (Zhang, 2014), explain the configuration process to the end user (Haag et al., 2006; Zhang, 2014) and create an intuitive configuration system interface (Tiihonen & Soininen, 1997). Product configurators are based on delimited constraints assumed from different factors like the capabilities of the company or the product structure that restrict the possible configuration possibilities (Zhang, 2014) and, therefore, limit the level of customization that can be achieved by the user (Blecker et al., 2004).

On the other hand, ETO can provide a high level of customization (Hicks & McGovern, 2009; Olhager, 2003) and high customer service while maintaining a low inventory stock (Olhager, 2003). Nevertheless, it is characterized by long lead times (Pandit & Zhu, 2007) and the low volume it can achieve (Hicks & McGovern, 2009) compared to the high volume and productivity of the MTO/ATO models (Vollmar & Gepp, 2015) that usually use product configurators to let the customer select their preferred product variants (Willner et al., 2014). According to Vollmar & Gepp (2015), the ETO model aims at achieving a better standardization, and also, as described by Pandit & Zhu (2007), at introducing knowledge systems to improve their processes among which Duchi et al. (2015) state that configurators can help to provide more efficient solutions.
Through the use of product configurators, Duchi et al. (2015) establish that the degrees of uncertainty and complexity in an ETO environment, which is characterized by the trade-off between high customization and operational efficiency, are reduced. For instance, the companies included in the case study developed by Willner et al. (2014) experience difficulties when adding the components that follow ETO processes into the product structure that should be included in the product configurator, leaving room for improvement in this area as described in the study. Duchi et al. (2015) propose the will to explore the relation between the companies' characteristics and the ETO environment with regards to potential best practices for ETO processes like product configurators.

Therefore, product configurators, as well as ETO, have certain capabilities and requirements as just described. The identified gap from this preliminary research is the lack of efficient guidelines for companies to understand to which extent customization can be achieved in product configurators by integrating them with ETO processes; considering in this process the capabilities of the customer, the product and the company, as well as the balance between these elements. To integrate the benefits and taking into account the challenges of these approaches, chapter 3 (Literature Study) focuses on researching the relation between product configurators and engineer-to-order as well as the relation between product configurators and the customer knowledge. This is performed to find the guidelines and requirements in order to let end users directly engineer-to-order the final product with the use of a product configurator. By doing this, the level of customization that can be achieved with ETO would be obtained through the use of product configurators that also consider the customer's competences, which is the main interest of filling the identified gap. The guidelines to be defined in the framework would act as the main supporters for the decisions regarding the customization possibilities in the planning of the product configurator. The learnings obtained in chapter 2 are also utilized to correctly guide the systematic literature study (chapter 3) and avoid possible impractical content when developing it. Furthermore, different concepts and terms presented in chapter 2 are utilized and referenced in further chapters of the thesis.

2.3.1 Initial reference and impact models

As described in section 1.3, the Research Clarification stage (associated with this chapter) from the DRM established by Blessing & Chakrabarti (2009), helps to understand the research problem and supply focus for later stages. It also provides the initial reference model and the initial impact model.

The reference model represents the level of understanding of the existing problematic situation at a certain stage of the research (Blessing & Chakrabarti, 2009). In the case of the initial reference model, it is associated with the end of the Research Clarification. The impact model represents the desired situation with the addition of support to improve the problematic situation (Blessing & Chakrabarti, 2009). Therefore, the impact model is generated based on the reference model. The initial impact model presents the preliminary support established at the end of the Research Clarification.

These models follow the graphical representation presented in figure 6. They describe statements between different factors in the situation. The factors are represented by attributes of an element, and the link between them indicates how the value of one attribute's factor affects the attribute of the other. The source for the effect between factors can be from a reference numbered [X] in the literature, from an assumption [A], from the experience of stakeholders [E], from own investigations [O], or unknown [?]. The transition from reference to impact model may require the introduction of new nodes/factors and links, (e.g., auxiliary effects of the use of the support), the removal of existing ones (e.g., those that are no longer relevant, once the support has been introduced) and/or the changes to the values of certain attributes (Blessing & Chakrabarti, 2009).

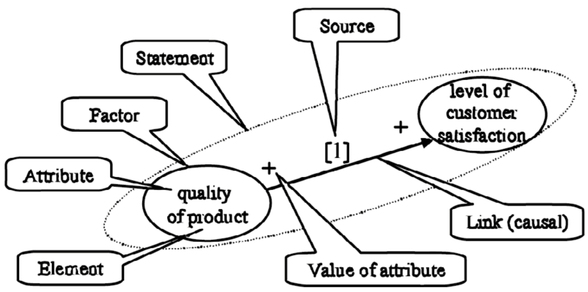


Figure 6: Graphical representation of a statement with associated terminology (Blessing & Chakrabarti, 2009)

According to the DRM by Blessing & Chakrabarti (2009), other elements in the reference model are the key factors and the success criteria. The key factors are those that seem to be the most useful factors to address in order to improve an existing situation. They are considered the core factors or the root causes. The success criteria relate to the goal or goals to which the research project intends to contribute. The success criteria are also associated with the success factors, which are those that provide the justification of the research. The desired values of the success factors are considered the success criteria which are then used in the evaluation (Blessing & Chakrabarti, 2009).

Since the Research Clarification stage presents the initial reference and impact models, the key factor(s) and the success factors are considered preliminary. The numbering of the references that appear in the reference and impact models can be inspected in Appendix B. This is performed to have a more visual understanding of the model and use the same format as Blessing & Chakrabarti (2009).

The initial reference model can be observed in figure 7. It is developed based on the conclusions detailed at the beginning of section 2.3. The use of product configurators (without ETO possibilities in this first stage) and the implementation of only the ETO business model by companies are established as the preliminary key factors, since they are the core factors to focus on in order to improve the current situation. The preliminary success factors that are established can be checked in the initial reference model. The desired values of these preliminary success factors would be: to obtain a (1) higher maximum level of customization that can be achieved by

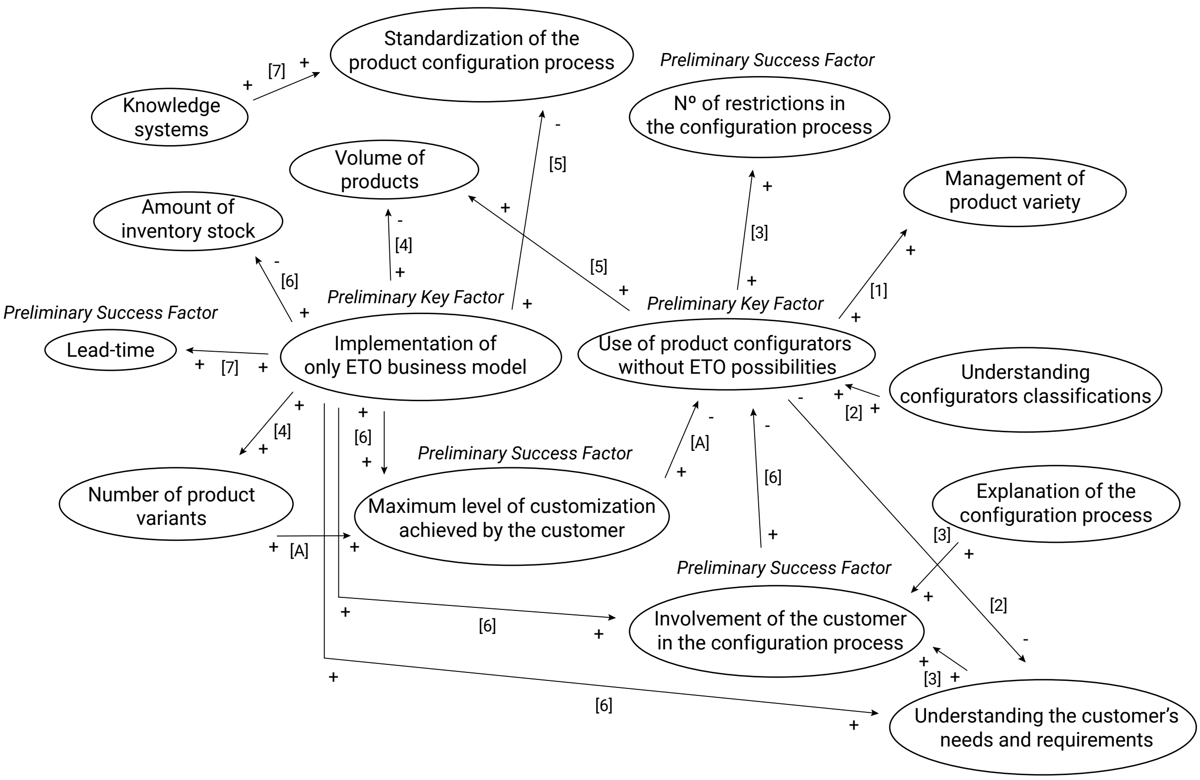


Figure 7: Initial reference model

the customer, (2) a better involvement of the customer in the configuration process, (3) a smaller number of restrictions in the configuration process and a (4) reduced lead time achieved by the company. These preliminary success criteria are established based on the preliminary key factors presented in the initial reference model, which are connected with companies that use product configurators without ETO possibilities involved (1 to 3) and companies focused on using only the ETO business model (4).

Accordingly, in the initial impact model (figure 8), in order to improve the current situation, two modifications in the case of preliminary support are established based on the initial reference model and the plans for the Descpritive Study I (chapter 3 in this thesis). These modifications are the adaptation of product configurators to be used in ETO approaches (ETO-only companies, typical ETO products, etc.), and a better engagement of the customer with the product configurator. These modifications are represented with a hexagon instead of the oval of the factors. The expected results of the introduction of the preliminary support can be observed in the initial impact model. They focus on the possibility of obtaining product configurators that can let users engineer-to-order the final product, as well as improving their involvement in the configuration process. Accordingly, the two preliminary key factors from the initial impact model are combined into only one preliminary key factor which is the use of product configurators, but with ETO possibilities this time. By adding the preliminary support and obtaining a new preliminary key factor, different nodes and links are discarded, and others are established like the adaptation of the product to be able to work in an ETO business model. These modifications aim to achieve the various preliminary success criteria previously established, with its biggest goal of investigating the

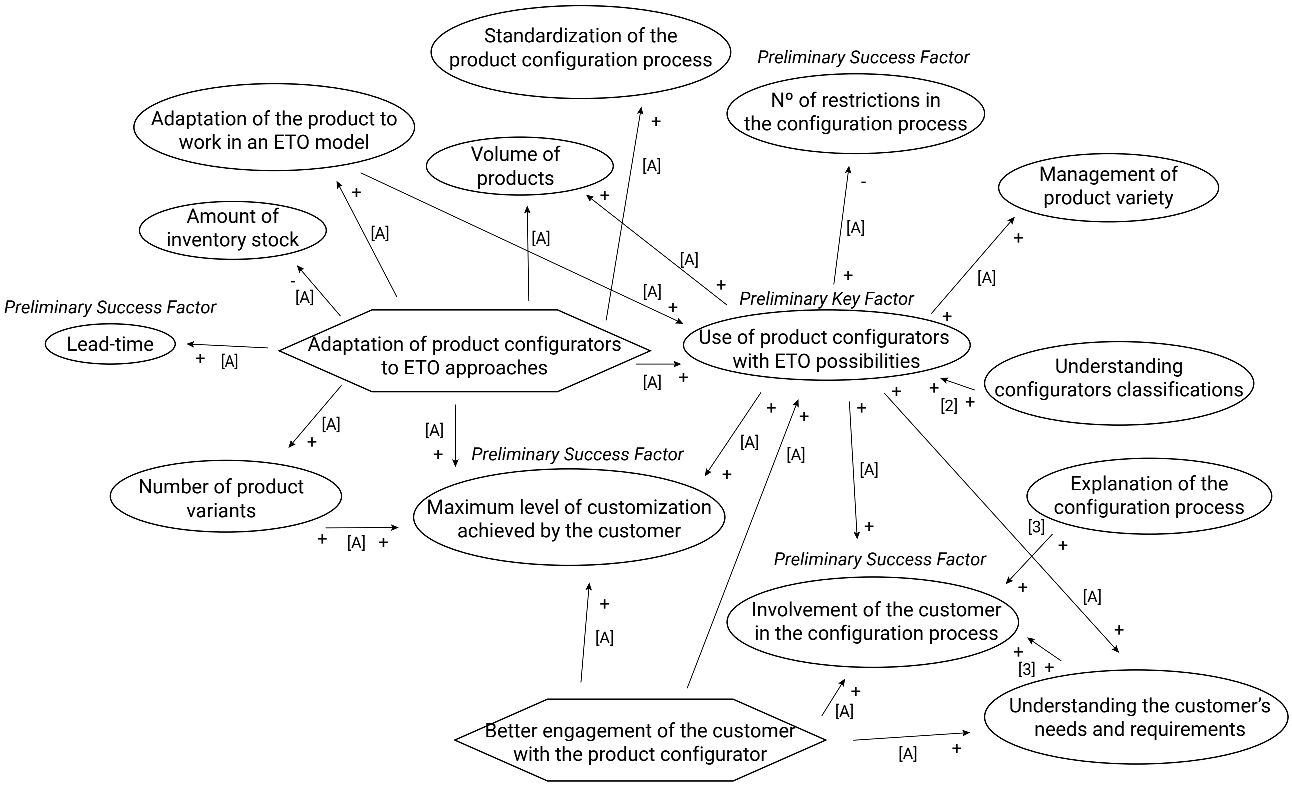


Figure 8: Initial impact model

maximum level of customization that can be achieved by the customer with a product configurator.

LITERATURE STUDY

3

The third chapter investigates, based on the findings from the preliminary research conclusion (section 2.3), and by means of a systematic literature study, the relation between product configurators and engineer-to-order, and the relation between product configurators and customer knowledge, while taking into account the 4 identified main pillars: the company, the product, the configurator and the customer. First, the research procedure (section 3.1) is presented with the strategy, objectives and search queries of the literature study. It is followed by the systematic literature review (section 3.2 and section 3.3) where the focus is on studies that investigated the adoption of product configurators in ETO environments and the implementation of the customer knowledge when developing product configurators. Afterwards, section 3.4 presents a theoretical background with the selection of methods and models from the literature study that are going to be used in the framework. The concluding remarks (section 3.5) regarding the systematic literature study are stated followed by an overview of basic guidelines, best practices and outcomes along with their references. The initial reference model is also updated in section 3.5.

3.1 Research procedure

In order to develop the framework, in which product configurators, engineer-to-order and customer knowledge are set to be key elements based on the preliminary research, an analysis needs be performed on the amount and type of research that has been performed on the relation of these topics. Since this thesis is an internal assignment, the literature study entails an important part of the project and it is the main element of the Descriptive Study I phase of the DRM by Blessing & Chakrabarti (2009). The strategy this literature study pursues is the following:

1. Investigate the **use** of product configurators in relation to engineer-to-order across the literature.
   1.1 Identify the most **recurrent procedures** and **guidelines** to achieve this relation as well as its **benefits**.

2. Investigate the **inclusion** of customer knowledge for the development of product configurators across the literature.
   2.1 Identify the **enablers**, **purpose** and **benefits** of this inclusion.

3. Provide a **theoretical background** on selected **methods and models** from the literature study to be used in the framework.

The strategy of the literature study is based on the conclusions from the preliminary research (section 2.3) and aims at obtaining guidelines from the literature for companies to determine which factors of the 4 main pillars and which procedures should be available to plan a product configurator that can let the end user engineer-to-order the final product based on his/her knowledge capabilities. Suitable methods and models identified in the research are also described and explained in order to utilize them for the framework. The outcome of this systematic literature study sets the foundation for the identification of the elements of the framework and its development. The database of Scopus (Elsevier, 2021) is used to create the two search queries performed. The specific inclusion criteria, analysis of the papers and research questions are presented next for each of the searches.

For the first search query, the keywords used are based on the preliminary support of "Adaptation of product configurators to ETO approaches" created in the initial impact model. Furthermore, based on the thesis objective and the research gap, the capabilities of the product, the company, the configurator and the customer are checked and taken into account when reading the papers. Table 1 presents an overview of the first search query in which "product configurator" and "product configuration system" are considered synonyms. "Engineer-to-order" is also searched as "ETO" representing the acronym of this business model. These terms form the keywords for this search query and are searched in the titles, abstracts or keywords of the papers. The boolean operators "OR" and "AND" are also utilized to obtain the results. The papers are sorted on the highest amount of citations. The justification and main goal of the first search query are related to points 1 and 1.1 of the literature study strategy previously mentioned. This first search query has the objective of obtaining information about the extent of customization that can be achieved with the use of a product configurator with ETO possibilities (due to the high levels in the ETO model), and the requirements to accomplish it. The research question for this first search query would be: "what are the best practices to adopt ETO processes in product configurators in order to increase the potential level of customization the customer can achieve?". As described by the DRM guidelines from Blessing & Chakrabarti (2009), this is a relational research

Table 1: First search query on Scopus database (performed in April 2021)

Keywords	(TITLE-ABS-KEY ("product configurator" OR "product configuration system") AND TITLE-ABS-KEY ("engineer-to-order" OR "ETO"))
Sort on	Cited by (highest)
Justification	Relation between the use of product configurators with the business model of engineer-to-order. (Points 1 and 1.1 of literature study strategy)

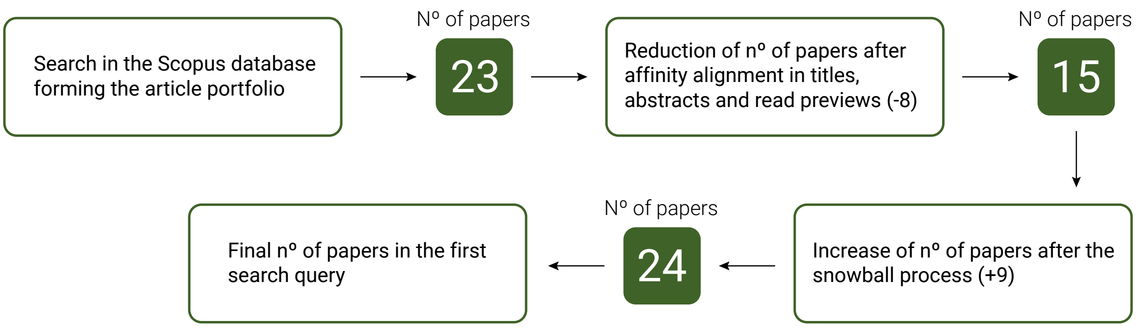


Figure 9: First search query paper selection process (performed in April 2021)

question, since it looks at the relationship between two variables.

The first search query is performed on the Scopus database in April 2021 and a total of 23 hits are obtained. After checking the titles, abstracts and a preliminary read, 8 documents are discarded. During the snowball process, 9 new papers are included in the query based on interesting citations. Finally, a total of 24 papers are included for the first search query. This can be seen graphically in figure 9.

For the second search query, the keywords are based on the other preliminary support of the initial impact model: "Better engagement of the customer with the product configurator". Moreover, the results from the first search query do not provide an extensive insight into the customer capabilities when using product configurators, which ratifies the creation of this second search query. As well as with the first one, the capabilities of the product, the company, the configurator itself and the customer are taken into account when reading the papers. In table 2, an overview of the second search query is displayed. The first two keywords are the same as the ones from the first search query, and the new terms are "customer knowledge" and "customer-oriented", which is also included to expand the search. The papers from the second search query are also sorted on the highest amount of citations. The justification and main goal of the second search query are related to points 2 and 2.1 of the literature study strategy and aims at understanding how the customer knowledge is relevant for the level of customization that can be achieved with the use of a product configurator. The research question for the second search query would be: "how does the customer knowledge affect the potential level of customization that can

Table 2: Second search query on Scopus database (performed in May 2021)

Keywords	(TITLE-ABS-KEY ("product configurator" OR "product configuration system") AND TITLE-ABS-KEY ("customer knowledge" OR "customer-oriented"))
Sort on	Cited by (highest)
Justification	Relation between product configurators and the customer knowledge about the final product and the configuration process. (Points 2 and 2.1 of literature study strategy)

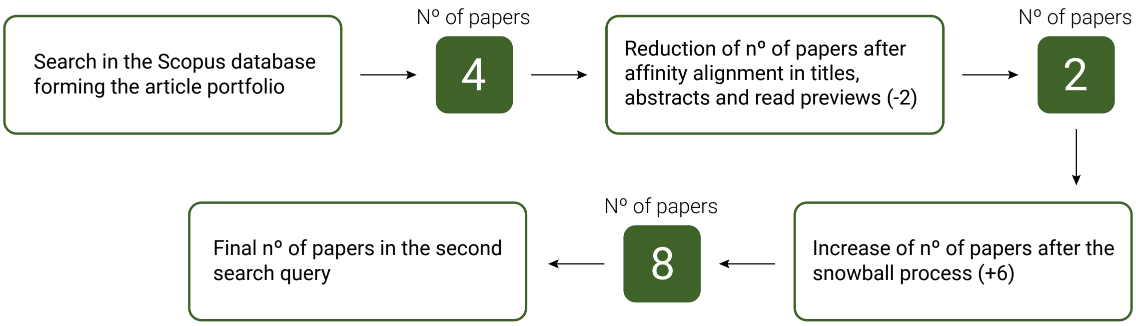


Figure 10: Second search query paper selection process (performed in May 2021)

be obtained through the use of a product configurator?". As well as in the first search query, this research question is also relational.

The second search query is also performed on the Scopus database, but in May 2021 with a total of 4 hits. Two papers are discarded after checking, titles, abstracts and preliminary reads and 6 new papers are added after the snowball process, leaving a total of 8 papers for the second search query (figure 10). Therefore, including both search queries the literature study consists of a total of 32 papers. Naturally, some of the papers referenced in the preliminary research also appear in the literature study due to the commonality of the topic areas and the continuous use of the concepts and terms presented.

3.2 Relation of product configurators with ETO

The research starts with the investigation of the use of product configurators in ETO environments and the relation between the two. Product configurators are applied to mass producers that aim at increasing variety, and also tried to be applied to ETO companies that aim to increase standardization of their product offerings without limiting their customers in terms of customization (Kristjansdottir et al., 2017). As described by Zheng et al. (2017a) and Zheng et al. (2017b), the use of product configurators in an ETO model is based on the fact that customers prefer to develop new designs from the existing products in a tangible or visualized way instead of designing them from scratch.

This investigation is performed by means of the first search query indicated in table 1 and figure 9, which resulted in papers that covered this topic to some extent and in different industries. Among these papers, the work from authors Zheng, Kristjansdottir, Shafiee, Haug and Hvam is extensively described and discussed.

The section is divided into different sub-sections. These sub-sections cover points 1 and 1.1 of the literature study strategy and are structured to answer the research question from the first search query. Sub-sections 3.2.1, 3.2.2, 3.2.3 and 3.2.4 describe the most recurrent procedures found in the literature regarding the relation between product configurators and the ETO business model to let the end user engineer-to-order the final product by means of product configurators. As previously described, the 4 main pillars and their capabilities are taken into account when reading the papers and developing the literature study. More in detail, sub-section 3.2.1 and sub-section 3.2.3 focus especially on the capabilities of the company and the configurator, and sub-section 3.2.2 and sub-section 3.2.4 aim on the capabilities of the product and the company. Next, sub-section 3.2.5 focuses on the capabilities of the 4 main pillars, and describes the different organization schemes reported in the literature regarding the adoption of product configurators within ETO environments. To conclude, sub-section 3.2.6 outlines the benefits and challenges of this relation. The main capabilities relationship between the four main pillars and their corresponding sub-sections can be seen graphically in figure 11.

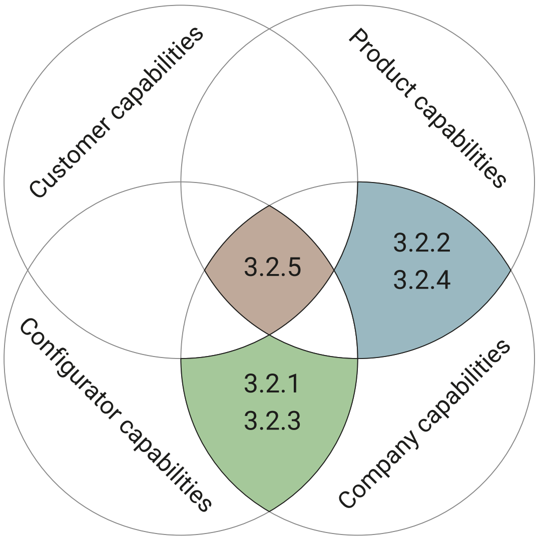


Figure 11: Graphical distribution in terms of main pillar capabilities of sub-sections in section 3.2

3.2.1 Combination of business models

Product configurators, commonly used in mass customization processes like ATO and MTO, have to be adjusted according to ETO's product and process requirements for their successful application in an ETO environment (Willner et al., 2013). Product configurators that operate in an ATO/MTO model utilize customers' specifications as input, and the system derives the recommended or target product fulfilling customer needs as output (Zheng et al., 2017b).

The configuration process is simpler in MTO and ATO companies compared to ETO ones due to the existence of a defined solution space in the first two models (Blecker et al., 2004). This defined solution space refers to the modules and components that are combined according to pre-defined constraints (Kristjansdottir et al., 2017). The solution space is undefined in ETO companies and thus the number of possible configurations can be close to infinite (Blecker et al., 2004). Therefore, most product configurators in ETO companies are created with a high level of abstraction, since it can be too time-consuming to define the solution space in a more detailed way (Haug et al., 2011).

As a result of the complex products and processes in ETO companies, product configurators are generally gradually implemented where only subsets of the product are included to support specific processes (Kristjansdottir et al., 2015). Product configurators are then used in ETO companies to increase the sales of more standardized products (following an approach more similar to the one of ATO and MTO) and help companies have more control of the product variety offered to the market (Forza & Salvador, 2002). For ETO companies that want to utilize a product configurator to support the sales and engineering processes, there is a need for a more structured approach to break down the overall processes so the most critical ones can be identified and analyzed (Kristjansdottir et al., 2015).

Therefore, to increase variety and customization, and adapt product configurators to ETO environments, a combination of the models ATO, MTO and ETO is usually performed within the configurator. In such a way, the customers can select from options in an ATO/MTO model and then could also choose to define their requirements in an ETO model (Levandowski et al., 2015) when the existing product family and variety may not satisfy their requirements (Zheng et al., 2017b). This combination approach permits customers to undergo a personalized configuration process in ETO environments in a more efficient way especially when doing so in a virtual environment (Zheng et al., 2017b).

Shamsuzzoha et al. (2011) also aim at a transition from ETO to configure-to-order (CTO; another business model that can be considered a variant of ATO), to make the component commonality higher and the manufacturing of the customized final product more cost-efficient.

There are already companies that use this type of hybrid product strategy within the configurator offering customers standard products, mass-customized products, and individually designed products (Mäkipää et al., 2012). The MTO/ATO approach can be merged with the ETO scenario when there are options for the customer to tailor his/her choice of product. This combined approach supports business organizations in adjusting their production processes according to the level of customization offered by them (Shamsuzzoha et al., 2011). An ETO company does not necessarily fall under a single engineering dimension but can provide products with elements from ATO, MTO and ETO at the same time (Bredahl et al., 2021). The move from an ETO company to become mass customizers (like full ATO/MTO companies) is supported by the use of configurators, enabling the company to produce quotes much faster than without them (Haug et al., 2019a). Nevertheless, the full transition of exclusively ETO companies to mass customization is usually neglected in the literature (Haug et al., 2009), which can be a reason why this hybrid approach of business models within product configurators is followed by companies that want to increase both customization and standardization in the product configuration process.

3.2.2 Proper identification of product parts and modules

It is stated in the literature that, in order to accomplish to some extent the combination of business models within the product configurator, it is endorsed to determine which parts or modules of the product should follow which of the models.

The product configurator developed by the company needs to check if the customer requirements can be fulfilled by the common attribute modules (MTS model) or the customized attribute modules (ATO/MTO models). Otherwise, it should record the new design information of the personalized attribute module and undertake an ETO design process to fulfill it (Zheng et al., 2017b). This new personalized design should be captured and recorded into the knowledge base (Zheng et al., 2017b), so they can be developed much easier in future processes by adding or upgrading new customized modules in an ETO process without affecting other product structures (Zheng et al., 2017b). A similar approach is described by Shamsuzzoha et al. (2011) where the possibility of the individual customer need for a variant is checked out among the configuration options and if it is not found, the individualized product is achieved following the ETO operational steps but within the ATO/MTO scenario of the product configurator. This operating environment develops the possibility to define new modules or components (known as white spots) according to the customer needs with the use of product configurators (Shamsuzzoha et al., 2011).

There is often a settlement regarding the level of detail and completeness, which is the number of parts/modules included in the configuration system (Kristjansdottir et al., 2015; Kristjansdottir et al., 2016), since not all components need to be visible to the end customer in the product configurator and the ones who do can have different levels of customization. This is related to the product part level and the product detail level introduced by Haug et al. (2019b) that refers to which parts should be included in the product configurator for the customer to see and better understand the configuration process, the details about the parts/modules and their relationship.

Shafiee et al. (2017) propose the use of the Product Variant Master (PVM) by Hvam et al. (2008) to identify the most important product variants needed for the product configurator. The PVM is used to break down the components of the product into a tree structure and identify the main product variants and possible constraints for the product (Hvam et al., 2008). The PVM is successfully implemented by Hvam et al. (2008) in a case-study project to determine the most interesting variants for a mechatronic product of a company that had up to 500 possible variants. To identify the different components in a product, Sylla et al. (2018) differentiate between a non-standard component in a group, a non-standard group of components in a product and a non-standard integration of components in a product. This differentiation in Sylla et al. (2018) is based on B2B companies that use product configurators and the possible configuration solutions do not fulfill all the customer requirements. Following this study, Sylla et al. (2019), propose a four-level configuration model to identify the ETO level of any non-standard solution. This is performed by identifying the generic items of the product (based on the differentiation of Sylla et al. (2018), their cost and their relative importance in the overall product (Sylla et al., 2019).

In another study developed by Wang & Tseng (2014), a Naive Bayes method is proposed to identify the probability of an emerging need that cannot be fulfilled by the existing product family. The Bayes factor quantifies the occurrence possibility of a certain event (Wang & Tseng, 2014). It would work as a diagnosis method to check if the variant could be achievable within the possible product configuration space or if it should capture the customer requirements in an ETO manner as described in Zheng et al. (2017a). The configuration system can either undertake an ATO/MTO approach by retrieving the most suitable product variant within the bandwidth, or an ETO way by creating new designs in a co-creation model that depends on the customers, the identified vendors/suppliers and the company (Zheng et al., 2017a).

The identification and standardization of the parts in ETO means, from an engineering point of view, to increase the predefined part of the engineering work and from a production perspective, to a greater degree, to be able to assemble-to-order instead of manufacturing new components for each order (Haug et al., 2009). This is performed by predefining all possible component choices as well as the constraints that determine how they may be combined (Haug et al., 2019a). The identification of the manufacturing techniques and their possible improvement is also identified by Haug et al. (2009) as an important factor to achieve standardization of parts and modules in ETO environments.

As described in section 2.1 by Zhang et al. (2014), product configurators are based on the establishment of product constraints and this has to be taken into account when identifying the parts. According to Haug et al. (2019a), there are ETO companies where only some of the product solution space is pre-defined (which would refer to the MTS/ATO/MTO parts), while the detailed design decisions do not take place within the predefined solution space (which would be the ETO parts). Following the different presented procedures, it can be stated that it is relevant to identify the parts/modules that aim and suffice for a higher customization and should follow an ETO approach, and the ones for which the customization level can be satisfied with an ATO or MTO approach; all with the use of a product configurator.

3.2.3 Integration of product configurators with other IT systems

It is commonly expressed in the literature that the integration of product configurators with other IT (information technology) systems is beneficial for its implementation in ETO companies and the overall efficiency of the configurator (Willner et al., 2013; Bredahl et al., 2021; Kristjansdottir et al., 2017).

Applying configurators as stand-alone solutions does not provide a considerable added value. An integration of configurator solutions into the existing IT landscape is crucial to enable automation of processes, a close collaboration between departments and a proficient exchange of data (Willner et al., 2013).

In order to adapt product configurators to ETO environments, they have to be fully integrated with the present IT infrastructure (Willner et al., 2013). Kristjansdottir et al. (2017) state that the configuration process is highly dependent on retrieving information from both internal and external IT systems. Internal integrations include IT systems used within the company. These can include CAD (Computer-aided design), to generate 3D models, ERP (Enterprise resource planning), to retrieve information related to customers or costs, and PLM (Product lifecycle management) (Hvam et al., 2008; Blecker et al., 2004; Kristjansdottir et al., 2016). External IT systems integrations can retrieve information like prices or sizing parameters needed during the configuration process from a supplier's database or even another product configurator (Zheng et al., 2017a; Kristjansdottir et al., 2017).

A rule-based and consistent preparation of product and process data with the aid of the product configurator contributes to a generation of bills of materials and operational routings more easily processable by ERP systems (Willner et al., 2013). Felfernig et al. (2014) assert that in ETO companies the integration of existing configuration technologies with recommended approaches is crucial to support end users in the configuration processes. This would also be beneficial for engineers creating the product that can sometimes waste time repeating the same processes without realizing that another similar project was completed earlier, and they could simply reuse the data (Shafiee et al., 2017). Comparing the new project with previous ones could also result in developing a recommendation system in the companies (Felfernig et al., 2014).

Another related aspect to the integration of IT systems is the use of product configurators in different stages of the product development process. As described in subsection 2.1.1, external configurators can be divided into sales configurators + technical configurators (Forza & Salvador, 2002). Product configurators are normally used to only support a specific part of the sales and/or engineering processes or a subset of the product family (Kristjansdottir et al., 2015).

Nevertheless, sales and technical configurators are not mutually exclusive, they may be used in conjunction with one another and the output of the sales configurator can be used as input for the technical configurator (Kristjansdottir et al., 2016). The alignment of the sales and technical model also stresses the need for the arrangement of various IT systems (Bredahl et al., 2021). Using both sales and technical product configurators enables the engineers to base their work on the results from the sales product configurator and to further work with the data inside the technical configurator (Kristjansdottir et al., 2017). This optimization and standardization of the workflow means that the relevant data for configuration is stored in a single system: a setup that allows both salespersons and engineers to work more optimally from the end user inputs (Kristjansdottir et al., 2017). The combination of sales and technical configurators is successfully achieved in a case study by Kristjansdottir et al. (2017) for a company focused on catalyst and surface science to identify new applications for various configurators in their company.

In relation to this, Mäkipää et al. (2012) propose the use of design configurators, which would be an external configurator that also covers the sales and technical configuration functionalities. With this design configurator, there is an integration of CAD and PLM systems, and the transfer of an order from sales to manufacturing can be hastened (Mäkipää et al., 2012). The case studies developed by Mäkipää et al. (2012) focus on maritime transportation and composite beams respectively. In these case studies, unique drawings for components and products were created based on the customer requirements with the use of design configurators. The integration of product configurators and CAD systems can enable the possibility of generating 3D models based on the output generated from the technical product configurator (Kristjansdottir et al., 2016).

In the study by Bredahl et al. (2021), the term "multistage configurator" is presented to describe a strategy where the product configurator supports several stages of the order-fulfillment process, such as the sales/quotation phase or the initial design. The repeatability of products and projects, relatively low product complexity and similar product specifications are considered enablers in ETO companies for gaining benefits from the multistage configuration strategy (Bredahl et al., 2021). This type of ETO company is referred to by Willner et al. (2016) as a repeatable ETO, which is the main candidate to adapt product configurators to ETO processes and create a configurator with ETO possibilities.

Combining different IT systems within the product configurator and using it in different stages of the product development process also streamlines the communications across different departments, where the product configurator is used as a platform to exchange data and to give input (Kristjansdottir et al., 2017).

3.2.4 Modularity, scalability and reuse strategies

For product configuration in an engineer-to-order environment, an important task is to translate customer requirements into technical parameters and further to physical building blocks (Kristianto et al., 2015). Modularity, scalability and reuse are described in the literature as strategies to develop this translation. Some of these approaches are similar to the potential improvements related to ETO described in sub-section 2.2.2.

3.2.4.1 Modularity

Modularization strategy is started by firstly identifying functional, technical, and physical interdependency by considering liaison among these functions, specifications and parts (Kristianto et al., 2015). Within product configurators, modular design is a collection of modules that can be interchangeable among different products in the product family to achieve different functions. It is conducted by the mapping process between the product function domain and the physical domain (Zheng et al., 2017a). There are, according to Zheng et al. (2017a), 3 different types of functional requirements (FRs) that are related to the identification of parts described in sub-section 3.2.2: The essential FRs, which are the ones connected with the common physical modules, and stand for the compulsory functions that should be fulfilled by all the products. The customized FRs, connected with the customized physical modules, are the optional functions that already exist in the configuration solution scope (Zheng et al., 2017a). Customers can either choose to select them or not. And the personalized FRs, associated with the personalized physical modules, represent the functions that are unknown to the configuration system, which should be defined or added by customers in an ETO way (Zheng et al., 2017a).

Kristjansdottir et al. (2016) suggest that to implement product configurators within ETO, the modules should be decoupled from each other and thereby make it possible to configure product variants in a structure that has not been previously defined but fulfills all requirements of the customer. This is similar to the proposed component-based development by Tiihonen et al. (1996) that consists of building quality systems that satisfy business needs preferably by using parts rather than handcrafting every individual element.

3.2.4.2 Scalability

The scalable design in a product configurator stands for the ‘stretch’ or ‘shrink’ of the design specifications in the platform to satisfy different customer requirements, which is fulfilled through parametric design optimization (Zheng et al., 2017a; Zheng et al., 2017b).
The design configurator introduced by Mäkipää et al. (2012) also proposes a shift in the product design approach from modular-based to parametric-based design connected to the CAD systems to automatically generate parametric models. Unlike modular design, which achieves customer satisfaction by changing different modules among the product at a higher level, the scalable design is capable of setting optimized performance parameters regarding customers' preferences without violating the design constraints (Zheng et al., 2017a).

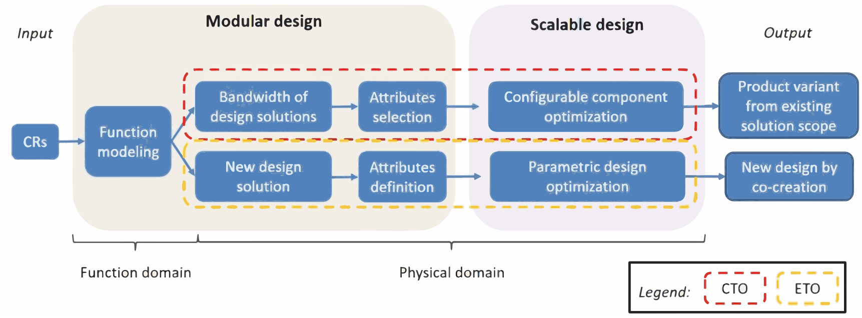


Figure 12: Modularity and scalability stages (Zheng et al., 2017a)

A concise specification of parameterized product structures and, possibly, modular component families is obligatory for the set-up of a fast and efficient product configuration process suitable for ETO products (Willner et al., 2013).
Zheng et al. (2017a) describe the modular and scalable strategies as two stages in the product configurator process in which modularity would go first followed by scalability. Figure 12 describes graphically these 2 stages comparing their use in a CTO and an ETO environment.

3.2.4.3 Reuse

Design reusability is important to shorten delivery lead times and to minimize development costs (Kristianto et al., 2015). Design reusability in ETO considers not only the bill of materials (BOM), but also the product structure that reflects inter-dependency among the parts that compose the product (Brière-Côté et al., 2010). The development of a product family logic in a product configurator, based on modularity and hierarchy principles, contributes to an increased reuse of parts (Brière-Côté et al., 2010). The definition of a stringent product family logic provides the backbone for leveraging the full benefit of a configurator solution.(Willner et al., 2013). If an existing product has standardized and decoupled interfaces, the design of the next product can borrow heavily from the modules of the previous product (Shafiee et al., 2017). If the newly developed module or part attracts an increasing level of interest from potential customers it can be merged into the platform for future use (Shamsuzzoha et al., 2011).

3.2.5 Organization of the product configurator development process

The literature describes different organizational strategies for the development process of product configurators within ETO environments (Zheng et al. 2017a; Shafiee et al., 2014; Kristjansdottir et al., 2015).

The framework proposed by Zheng et al. (2017a) and Zheng et al. (2017b) presents a product configurator process from the first contact of the customer with the product configurator to the order confirmation. This framework is applied for the successful creation of a configurator that can obtain highly customizable bicycles. The main factors/stakeholders in this framework are the company, the suppliers/vendors for the personalized attribute modules described in sub-sections 3.2.2 and 3.2.4, and the customer. First, the system asks for the customer preference of the vendors/suppliers based on their performance from different perspectives. This is used to filter the qualified vendors/suppliers. Then, the customer selects or defines the optional FRs. The essential FRs are already defined by the company since they are compulsory for all the products. Then, the customers can select the design attributes from the customized physical modules when they are within the product family scope of the product configurator or can define their own which would result in a personalized physical module. This last option is performed through an ETO process in which the vendors would have to provide this new module. The creation of the personalized physical module requires communication between the customer and the vendor that can be performed by direct contact with the customer or through co-design toolkits of the company's product configurator. To satisfy these individual customer requirements in terms of different modules/parts in the product, the companies have to take into account their manufacturing capabilities and what manufacturing technologies there are available, like adaptable design, reconfigurable production systems or additive manufacturing (Zheng et al., 2017a). As also described by Zheng et al. (2017a) and Zheng et al. (2017b) the identified suppliers also play a role in the organization of the different modules or parts, especially the personalized modules, since the suppliers are directly connected with the company's manufacturing capabilities.

A personalized recommendation mechanism to adapt to customer preference, and a user-friendly interface for co-creation (e.g. visualized design toolkits) are considered as well by Zheng et al. (2017a) as key aspects to achieve a better configuration process in an ETO environment. Bredahl et al. (2021) also state that a well-structured and comprehensive product configurator for the customer is needed as well as the possibility for the product configurator to handle the off-standard components by allowing an ETO approach when needed.

In the study by Shafiee et al. (2014), the presented framework covers different topics to take into account when creating the product configurator workflow. It is tested with a case study to improve the configurator of a company focused on the design of process plants. AS-IS and TO-BE process representations are used to show the current situation of the company and the possible scenarios for the future process. These representations are usually executed to have a standard definition of business processes (in this case the configuration process) and to execute improvements (Shafiee et al., 2014). Their utilization, in this case, can be performed from different perspectives, such as MTO, ATO, ETO or a combination of them (Tiihonen et al., 1996). Next, it is required to identify the stakeholders that are part of the product configurator (e.g. customers, product developers, sales staff, etc.). For that, Shafiee et al. (2014) propose the implementation of use case diagrams (which are usually performed to create new software systems), along with the use of the TO-BE process representation. Kristianto et al. (2015) state that in the sales and technical stage, the process is typically a joint work between the customer, the sales team and the engineers of the company, which would be the stakeholders for the product configurator process, that need to be identified. Next, the integration of the product configurator with other IT systems of the company such as ERP or CAD has to be specified (Shafiee et al., 2014). This is followed by the selection of the product function, properties and features that need to be included in the

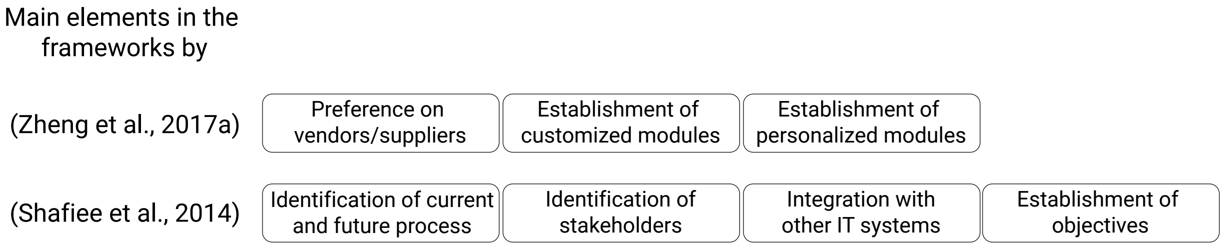


Figure 13: Main elements of the frameworks by Zheng et al. (2017a) and Shafiee et al. (2014)

product configurator for the customer to be able to create the final product. According to Shafiee et al. (2014), the objectives for the creation of the product configurator in an ETO environment also need to be specified.

The framework presented in Kristjansdottir et al. (2015) shares some steps with the previous ones. This framework was utilized to develop a product configurator for a construction company. The operational objectives for the product configurator need to be identified as well as the engineering processes where the product configurator would be beneficial. Then, these processes are evaluated regarding the current process (created from flowcharts with Business Processes Modeling Notation) and the future scenario generation. As well as Shafiee et al. (2014), Kristjansdottir et al. (2015) also propose utilizing use case diagrams for the identification of the stakeholders involved in the configuration process. In another step of this framework, the engineering processes, which could be parts or components of the product, that are to be supported with the product configurator, are selected based on cost-benefit and risk analysis for each scenario (Kristjansdottir et al., 2015).

In figure 13, the main elements (described in this sub-section) of the frameworks by Zheng et al. (2017a) and Shafiee et al. (2014) are highlighted graphically.

3.2.6 Benefits and challenges

This section describes the main explicit benefits and challenges found in the literature regarding the use of product configurators in relation to ETO environments.

Many engineering-oriented companies have gained significant benefits from the use of product configurators. Haug et al. (2019b), Kristjansdottir et al. (2015) and Kristianto et al. (2015) describe that a time reduction in terms of man-hours and lead time can be expected through this utilization. It is described in the literature that the movement from ETO towards mass customization supported by a product configurator, enables the company to significantly reduce time making sales quotations and offer them to a higher number of customers (Shafiee et al., 2017; Haug et al., 2009; Heiskala et al., 2007). A product quality improvement can be expected, which can lead to cost reductions and sales increase (Haug et al., 2019b), due to a reduction in errors, an increase in the accuracy of the proposals and a decrease in complexity (Willner et al., 2013; Haug et al., 2019b; Shafiee et al., 2017). Kristjansdottir et al. (2015) also describe an improved ability to analyze opportunities due to an enhanced dialogue with the customers and increased efficiency of the business processes.

Haug et al. (2019b) and Willner et al. (2013) state that some of these benefits may be attributed to more standardized processes and exact calculation methods or, according to Brière et al. (2010), due to systematic reuse of standard and predefined components. The configurator needs to support a certain amount of variety for it to be useful, and the benefits of adding variety would be low to a point where it increases as the configurator begins to support adequate variety for it to be useful. Next, at some point, the benefit of extra variety decreases, as this variety concerns increasingly rare uses (Haug et al., 2019b).

The main potential challenges regarding the use of product configurators with ETO approaches are, according to Kristianto et al. (2015), caused by demand uncertainty and product customization such that production control becomes more difficult. In addition to these, Kristjansdottir et al. (2015) describe that there is a great challenge for full ETO companies when using a product configurator in order to determine which processes and product parts should be supported by the configurator. The high level of customer involvement during product design is also considered a challenge (Kristjansdottir et al., 2015; Kristianto et al., 2015), as well as the possible inaccessible product knowledge based on project scope (Haug et al., 2019a).

3.3 Relation of product configurators with customer knowledge

This research continues with the investigation of the planning and development of product configurators while taking into account the customer knowledge and the relation between these two determinants. Product configurators involve the customer in the configuration process and this active customer participation is crucial for the successful incorporation of customer needs into the product, which directly influences the final product offering (Du et al., 2006). This changes the role of the customer from being the consumer of a product to being an active partner in a process of adding value (Fuerstner et al., 2012), especially if ETO possibilities are available to the user. Most of the practices and procedures described in the previous search query take into account the customers, but do not consider their knowledge of the product or the configuration process when using a product configurator.

This second investigation is performed by the means of the second search query indicated in table 2 and figure 10 from section 3.1. The sub-sections in this second investigation cover points 2 and 2.1 from the literature study strategy and are structured to answer the research question from the second search query. As in the previous section, this one also aims at finding out relevant knowledge for the identification of the elements of the framework and its development. This is achieved with the objective of investigating how the customization level that can be obtained with the product configurator is affected by the customer knowledge. This topic is not heavily researched in the literature, and this section is only divided into sub-sections 3.3.1 and 3.3.2, which describe the procedures found in the literature that arise from this relation. Both of these sub-sections focus mainly on the capabilities of the configurator and the customer. As well as in section 3.2, the relation between the different capabilities involved in this scheme can be seen in figure 14.

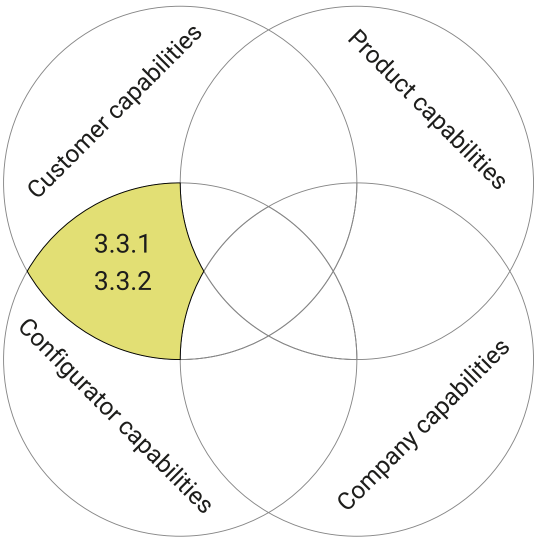


Figure 14: Graphical distribution in terms of main pillar capabilities of sub-sections in section 3.3

3.3.1 Different customer profiles

During the customization of a product with the support of a product configurator, there is a risk that customers will abort the configuration process if the configuration dialogue does not suit the customer well (Forza & Salvador, 2006; Fuerstner et al., 2012). In order to reduce this risk, Forza & Salvador (2006) state that some authors in the literature propose the use of different configuration approaches based on the type of customer. Nevertheless, the assignment of the approach type mentioned by Forza & Salvador (2006) is usually defined directly by the system, not by the customer (Fuerstner et al., 2012), and it is mainly based only on different recommendations for the user.

Even though customers are considered knowledgeable in general, they are still far from being experts that can co-create all products or services (Fuerstner et al., 2012). Customer profiles can be defined based on different aspects, such as purchase history, similarities to other customers or their approach when using the configuration process (Weng & Liu, 2004; Fuerstner et al., 2012). This research focuses on the last of those aspects. To be able to develop a product configurator for different ranges of customers and to avoid the abortion of the configuration process, Fuerstner et al. (2012) identify three customer profiles with different levels of knowledge of the configured product and their own real individual needs: beginner, intermediate and professional. Zheng et al. (2017a) classify the customer regarding their different capabilities of design specification knowledge into normal users and expert users. Forza & Salvador (2006) differentiate between non-expert customers and those who are highly interested and experienced customers (in the product to be configured). Before differentiating the type of customers, it is stated by Du et al. (2006), that the target group or market must be established to deliver the right product variety, and also to understand the customization possibilities of the target market (Forza & Salvador, 2006).

In the product configurator process developed by Fuerstner et al. (2012), for each customer profile a different configuration dialogue is defined so that the amount and complexity of input information decrease in lower customer profiles. This is successfully tested with the creation of a product configurator for a thermal insulation company. These customer profiles group individual customers based on some crucial characteristics such as knowledge about the product or the configuration process. Based on the defined customer profiles, different descriptions of the same product can and should be provided (Fuerstner et al., 2012). For Fuerstner et al. (2012), the "beginner customer" is a customer without proper technical knowledge about the product to be configured, a customer with no need for highly accurate results, or a customer with a need of a fast enough result. The "intermediate customer" is a customer with average technical knowledge about the product, but it can also be a customer without proper technical knowledge about the product but with more time for completing the configuration process or with a need for more accurate results. Lastly, the "professional customer" is a customer with great knowledge about the problem of the product configuration, or it could also be a customer with general technical knowledge about the product, but with more time for completing the configuration process or with a need for very accurate results. In the simpler classification of Zheng et al. (2017a), the "normal users" are those with little design knowledge and the "expert users" are knowledgeable customers regarding the product configuration process.

To classify the customers into each customer profile, Fuerstner et al. (2012) utilize the Mamdani's fuzzy inferences method (Torres & Krishnankutty., 2008), which is one of the most commonly seen fuzzy methodologies. These are used in multiple areas such as engineering and has applications in decision-making problems, planning and production (Coroiu, 2015). For the use of the method in Fuerstner et al. (2012), questions related to (1) the knowledge about the product, (2) the needed accuracy of the configuration results and (3) the amount of time to complete the configuration process are asked to the customer prior to the start of the use of the product configurator. Based on the answers and different variables, the Mamdani's fuzzy inference method helps to classify the user into beginner, intermediate or professional customer (Fuerstner et al., 2012).

Afterwards, performance-oriented language can be used for non-expert customers while components-oriented language can be used for highly interested and experienced customers (Forza & Salvador., 2006), as well as combinations from the guidelines described in sub-section 3.2.5. In these guidelines described by Zheng et al. (2017a), it is presented a series of steps that the customer can follow during the configuration process, but do not explain how that process may be affected by the classification of the customer into different profiles. Therefore, based on the customer profile selected by interacting with the user, the product configurator should provide different results and satisfy different objectives regarding the complexity of the dialogue, the time required by the configuration process and the accuracy of the obtained results (Fuerstner et al., 2012). It is stated by Fuerstner et al. (2012) that this approach can be applied to capital goods and consumer goods and if the possible structure is known, regardless of its complexity, the product solution will meet the exact requirements of customers to a greater or lesser extent in correspondence to the level of input and customer knowledge.

3.3.2 Knowledge and motivation

It is stated in the literature that the knowledge/expertise of the customer is an important factor for the preference of configurators (Randall et al., 2007; Fuerstner et al., 2012; Zheng et al., 2017a), but, according to Weinmann et al. (2011b), the motivation to process information about the product is also another influencing factor.

As well as Fuerstner et al. (2012), Weinmann et al. (2011a) state that it makes sense to provide user-adaptive systems based on the customer profile. Weinmann et al. (2011a) and Randall et al. (2007) describe that users with high knowledge and motivation are keener to use parameter-based configurators that allow the user to specify design specifications (this would be an interactive configurator as described in sub-section 2.1.1), while those with low expertise and motivation, it is better advised to use needs-based configurators that automatically calculate the parameters based on the users weighted needs (this would be an automatic configurator as described in sub-section 2.1.1). This would be similar to the performance-oriented language (low knowledge) and the components-oriented language (high knowledge) approach described by Forza & Salvador (2006), or the selection of customer requirements described by the framework of Zheng et al. (2017a) in sub-section 3.2.5. These different levels of knowledge can then be connected with the different business models that can be combined within the product configurator as stated in sub-section 3.2.1.

Weinmann et al. (2011b) describe that the impact of motivation is an even stronger factor than the knowledge for the selection of the preferred configuration. Weinmann et al. (2011a), as well as Fuerstner et al. (2012), state that the use of questions before the configuration process is the most ideal way to understand the level of knowledge and motivation. Weng & Liu (2004) also classify the customer profile based, among other factors, on the level of interest or motivation for the product, but they use a two-stage clustering technique to recommend a certain product to the customer, instead of adapting the configuration process to the customer as in the other approaches that were described. Addressing the procedure by Fuerstner et al. (2012) to differentiate customer profiles described in sub-section 3.3.1, and including the motivation level from Weinmann et al. (2011b), question (1) would be related to the knowledge of the customer, while questions (2) and (3) to the motivation.

3.4 Selected models and methods

The previous sections (3.2 and 3.3) describe the different basic guidelines and best practices found in the literature study to help companies balance the capabilities of the 4 main pillars in order to plan a product configurator that can let end users engineer-to-order the final product based on the customer profile. In the final remarks section of this chapter (section 3.5), the guidelines and the best practices are synthesized and described. Nevertheless, before diving into section 5 and, afterwards, chapter 4 which is focused on the development and implementation of the framework, several models or methods mentioned in the literature (that will be employed within the framework) need further learning in order to be able to properly use them.

Section 3.4 covers the third point of the literature study strategy and describes, with a theoretical background, the selected models or methods, the criteria as to why they are selected based on the literature, and how they are planned to be used in the framework. There are a total of 5 models/methods: AS-IS and TO-BE process representations, the Product Variant Master, Mamdani's fuzzy inferences method, Use case diagrams and Activity diagrams. The two last ones are explained in the same sub-section of UML (Unified Modeling Language).

3.4.1 AS-IS and TO-BE process representations

As described by Shafiee et al. (2014), an AS-IS process representation shows exactly the current situation of a company and the complications of the process. The TO-BE process representation is drawn according to the number of scenarios for the future process established by the company. The framework described by Kristjansdottir et al. (2015) also presents a similar approach where the current scenario is created with flowcharts based on Business Processes Modeling Notation, but it is not specified if the future process is created through the same process. Furthermore, by being mostly focused on the benefits and risks of the possible outcomes, it offers a more restricted and less open solution compared to the AS-IS and TO-BE process representations presented by Shafiee et al. (2014).

The AS-IS process representation presents a visual diagram of the current process with its associated text and metrics to determine the possible areas of improvement (Monteleone, 2010). In this thesis, the AS-IS process

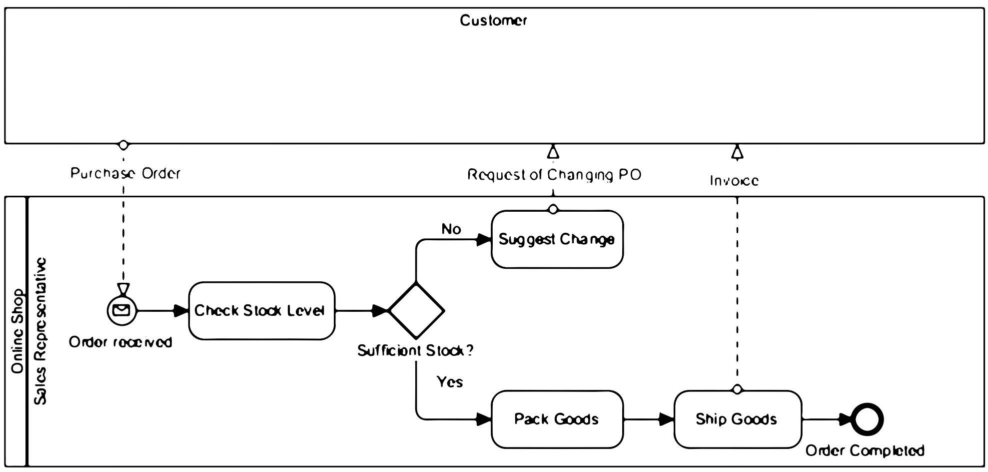


Figure 15: AS-IS process representation example (Visual Paradigm, 2016)

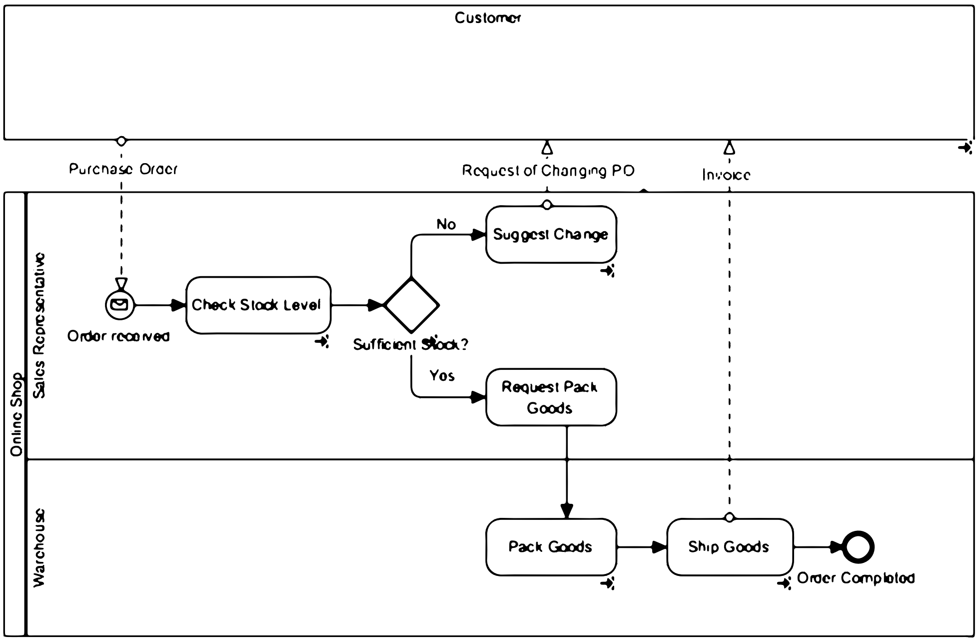


Figure 16: TO-BE process representation example (Visual Paradigm, 2016)

representation is used to show the current configuration process that the user goes through. The different steps can sometimes be associated with their corresponding stakeholder stage and also various types of flowcharts are employed to illustrate the processes. Figure 15 shows a simple process example of an AS-IS process representation.

Then, based on the identified improvements, the modified diagram (TO-BE) is created with the new enhancements incorporated and an analysis is performed on how to transition to the new process (Monteleone, 2010). Figure 16 shows the corresponding TO-BE process representation from the previous example in figure 15.

In this thesis, in order to create the TO-BE process representation, the company has to take into account the level of customization that wants to be achieved with the product configurator, the organization of the modules/parts based on the business model and the customer profile (outcomes obtained from the use of the framework to be created). Furthermore, the stakeholder requirements for the achievement of this customization (process supported by the use case diagrams to be explained) also need to be considered to develop a proper overview of the future process.

3.4.2 Product Variant Master (PVM)

The Product Variant Master (PVM) is used to break down the components of the product into a tree structure and identify the main product variants and possible constraints for the product (Hvam et al., 2008). In this thesis, the PVM is used to classify the modules and/or parts of the product to help in the identification of which business model works best for each product module/part. Alternatively, Wang & Tseng (2014) propose the use of a Naive Bayes method to identify the probability of a customer requirement that is not possible to be fulfilled with a part within the configuration system. Sylla et al. (2019) also introduce a model to identify the ETO-level of non-standard parts. Nevertheless, these two last methods are based on already existent knowledge about the differentiation of parts. With PVM, this distinction is performed while also covering the possible customization level that the components can aim to based on the requirements of the company.

In general, the left-hand side of the PVM (also known as the "part-of"-structure) shows the components included in the product, while the right-hand side (known as the "kind-of" structure) shows the versions or variables (Hvam et al., 2008). The structures are divided into classes, which can be defined as a group of objects with the same structure or function.
In the part-of structure, a class can also contain one or more sub-classes. Each class can also contain attributes that describe the class and constraints that define the rules for how classes and their attributes can be combined (Hvam et al., 2008). Each sub-class has cardinality describing how many sub-classes a class has.

Then, the kind-of structure describes the range of variation for a given class. Figure 17 shows a simplified and generic overview of the Product Variant Master. Therefore, in this thesis the part-of structure describes the product modules/parts by breaking them down into classes and the kind-of structure is used to define which modules/parts can and should aim for the different business models by identifying their potential versions. If a module or part is identified as a possible personalized module, it does not mean that it should always follow an ETO approach. In this case, depending on the customer profile (identification method to be explained in this section), the module/part to be customized could follow an ATO, MTO or ETO strategy.

To describe the constraints among the different modules and parts, combination tables can be used to identify the possible relations between them. Alternatively, verbal, logical and calculation constraints can also be utilized. The Product Variant Master can be created from a customer point of view, an engineering point of view or a production point of view (Hvam

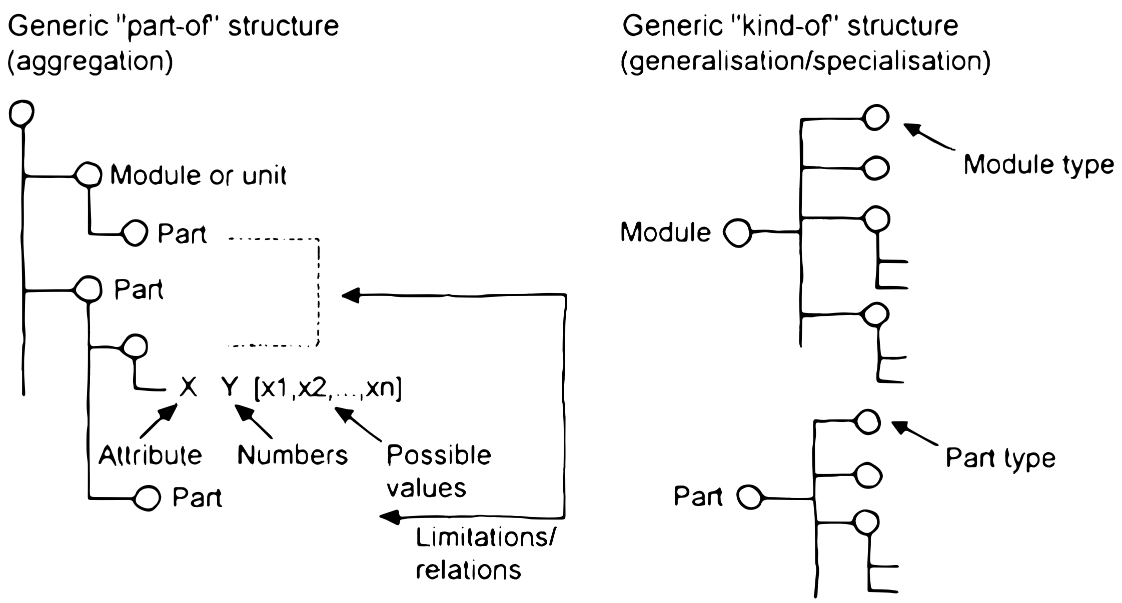


Figure 17: Generic principles of the Product Variant Master (Hvam et al., 2008)

et al., 2008). This thesis focuses on the customer view which contains both functional and structural aspects of the product range (Hvam et al., 2008). As stated in the systematic literature study, a product configurator with ETO possibilities work best with not highly complex products with a well-defined structure (Bredahl et al., 2021). The quantity of modules and parts included in the Product Variant Master is defined by the own company. It is advised to only include in the PVM modules and parts with customization potential if there are a big number of components in the product. Through this procedure, it is avoided an unnecessarily lengthy process with modules/parts that are known to not provide any further possible product variety.

3.4.3 Mamdani's fuzzy inferences method

A fuzzy analysis is used to solve problems that do not have a specific and certain base and are related to uncertainty and vagueness (Coroiu, 2015). It is used to transform an input space into an output space by means of fuzzy logic (Torres & Krishnankutty, 2008). The Mamdani's fuzzy inferences method described in Fuerstner et al. (2012) and Torres & Krishnankutty (2008) is used in this thesis to determine the customer profile based on the level of knowledge and motivation of the product configurator user. Weinmann et al. (2011a), as well as Fuerstner et al. (2012), assert that product configurators should be adapted based on the customer profile, but before doing so it is crucial to classify the users with their corresponding profile. The Mamdani's fuzzy inferences method is selected for this thesis as it is one of the easiest (to apply), oldest and most popular fuzzy inference methodologies (Torres & Krishnankutty, 2008) proving this way its effectiveness.

The Mamdani's method has a simple structure of minimum and maximum operations. The fuzzy inference process is comprised of four consequent steps:

1. Evaluating the antecedents.
   First, given the provided input (always a numerical value), the membership degree, which is the degree to which an input belongs to a specific fuzzy set, is determined. The membership degree must always belong to a $0 \leq x \leq 1$ interval.

2. Obtaining conclusions.
   Then, for each rule resulting from the membership degree of the previous step, an implication operator is applied to obtain a new fuzzy set which is the conclusion of the rule. The operator used in this work is the product, which scales the result.

3. Aggregating all conclusions.
   Afterwards, the output of the rules obtained in step two is combined into a single fuzzy set by using an aggregation operator. In this thesis, a sum is used.

4. Defuzzifying.
   Finally, a unique numerical value is obtained as the output of the inference process. In this case, the final output can be three customer profiles defined by the author based on the literature: "beginner", "intermediate" or "advanced". These are obtained after the defuzzification.

The provided input for the first step is obtained by asking a set of questions to the customer before the configuration

process. In this thesis, these questions are based on the level of knowledge and motivation of the customer.
The questions, their corresponding membership degree, and the logistic variables are similar to the ones proposed by Fuerstner et al. (2012) with the corresponding adaptation to this work created by the author. Furthermore, as it is later described in chapter 4, this use of the Mamdani's fuzzy inferences method is the one proposed by the thesis, but the companies can also adapt it to their situation.

Regarding the level of knowledge, two questions are presented, one about the customer knowledge in the final product to be designed, and the other one about the configuration capabilities:
(1) What is your estimated knowledge about the product to be configured?
The membership degree can go from a minimum of "I have no knowledge at all about the product to be configured" (0) to a maximum of "I consider myself an expert in the field of the product" (1). This numerical answer is presented later with the letter "*x*".
(2) How would you describe your parametric or graphic design capabilities?
The minimum would be "I have no experience with parametric or graphic design" (0) to a maximum of "I can develop parametric models or graphic designs without any guidance" (1).

Regarding the level of motivation to perform the configuration process, two more questions are asked to the customer:
(3) How important is it for you the customization level of the product to be configured?
In this case, the membership degree can shift from "Customization is not a priority for me " (0) to "I want to customize the product as much as possible" (1).
(4) How much time do you have for the configuration process?
The minimum would be "I have limited time for completing the configuration process" (0) to "I have enough time to complete the configuration process" (1).

Based on these answers, four logistic variables are obtained. Each variable has three resulting values that are associated with a number [*μ(x)*].
(1) Knowledge about the final product (k), with resulting values of "poor", "average" and "good".
(2) Parametric or graphic design capabilities (l), whose possible values are "low", "medium" and "high".
(3) Customer customization preference (m), with values of "irrelevant", "important" and "very important".
(4) Time for the configuration process (n), for which the values are "not enough", "average" and "enough".

The first fuzzy set is then calculated with the membership functions for the variables. The percentages are defined by the author and are established based on the work from Torres & Krishnankutty (2008), Weimann et al. (2011b), and especially from Fuerstner et al. (2012). These functions are presented in equations 1 to 4:

Equation 1: Initial fuzzy set (k)

$$\mu_k(x_k) = \begin{cases} Poor\ (0,3) & 0 \le x_k < 0,3 \\ Average\ (0,6) & 0,3 \le x_k < 0,6 \\ Good\ (0,8) & 0,6 \le x_k \le 1 \end{cases}$$

Equation 2: Initial fuzzy set (l)

$$\mu_l(x_l) = \begin{cases} Low\ (0,2) & 0 \le x_l < 0,2 \\ Medium\ (0,6) & 0,2 \le x_l < 0,7 \\ High\ (1) & 0,7 \le x_l \le 1 \end{cases}$$

Equation 3: Initial fuzzy set (m)

$$\mu_m(x_m) = \begin{cases} Irrelevant\ (0) & 0 \le x_m < 0{,}1 \\ Important\ (0{,}7) & 0{,}1 \le x_m < 0{,}5 \\ Very\ important\ (0{,}9) & 0{,}5 \le x_m \le 1 \end{cases}$$

Equation 4: Initial fuzzy set (n)

$$\mu_n(x_n) = \begin{cases} Not\ enough\ (0) & 0 \le x_n < 0{,}2 \\ Average\ (0{,}5) & 0{,}2 \le x_n < 0{,}7 \\ Enough\ (0{,}9) & 0{,}7 \le x_n \le 1 \end{cases}$$

Then, for each of the rules created by the initial fuzzy sets, an implication operator (in this case a product/scale) is applied obtaining new fuzzy sets. The scale operator (β) used for each of the variables is described in equation 5.

Equation 5: Second fuzzy sets

$$\beta(y) = \begin{cases} 20\% & y = k \\ 25\% & y = l \\ 35\% & y = m \\ 20\% & y = n \end{cases}$$

Naturally, the sum of the scale operators must equal 100%. These percentages are also defined by the author and based on the statement from Weinmann et al. (2011b) that establish the level of motivation as a more important factor than the level of knowledge for the customer profile determination.

The third step is the combination of all the previous fuzzy sets into a single third fuzzy set by the means of an aggregation operator, which in this case is a sum. Equation 6 represents this step:

Equation 6: Third fuzzy set

$$\mu_k(x_k)[\beta(k)] + \mu_l(x_l)[\beta(l)] + \mu_m(x_m)[\beta(m)] + \mu_n(x_n)[\beta(n)] = z$$

Lastly, a numerical value is obtained and based on this number, the defuzzification (equation 7) is performed obtaining the customer profile (δ) which, as previously described can be "beginner", "intermediate" or "advanced". These percentages are also defined by the author and based on the examples from the literature.

Equation 7: Defuzzification

$$\delta(z) = \begin{cases} Beginner & 0 \le z < 0{,}3 \\ Intermediate & 0{,}3 \le z < 0{,}7 \\ Advanced & 0{,}7 \le z \le 1 \end{cases}$$

3.4.4 UML diagrams

Shafiee et al. (2014) and Kristjansdottir et al. (2015) propose the implementation of use case diagrams for the identification of stakeholders in the configuration process to be developed. Kristianto et al. (2015) also establish the typical stakeholders in this process, but do not specify how to identify them.

Use case diagrams are part of the Unified Modeling Language (UML). The UML is a general-purpose, graphically based modeling language that has its origin in the field of object-oriented programming and is usually intended to describe and create software systems (Kleidermacher & Kleidermacher, 2012). The use case diagram is considered part of the behavioral diagrams included in the UML, which are those that capture the varieties of interaction and instantaneous states within a model as it executes over time, tracking how the system will act in a real-world environment, and observing the effects of an operation or event, including its results (Kleidermacher & Kleidermacher, 2012). In this thesis, two types of behavioral diagrams from the Unified Modeling Language are used within the framework to be developed: use case diagrams and activity diagrams.

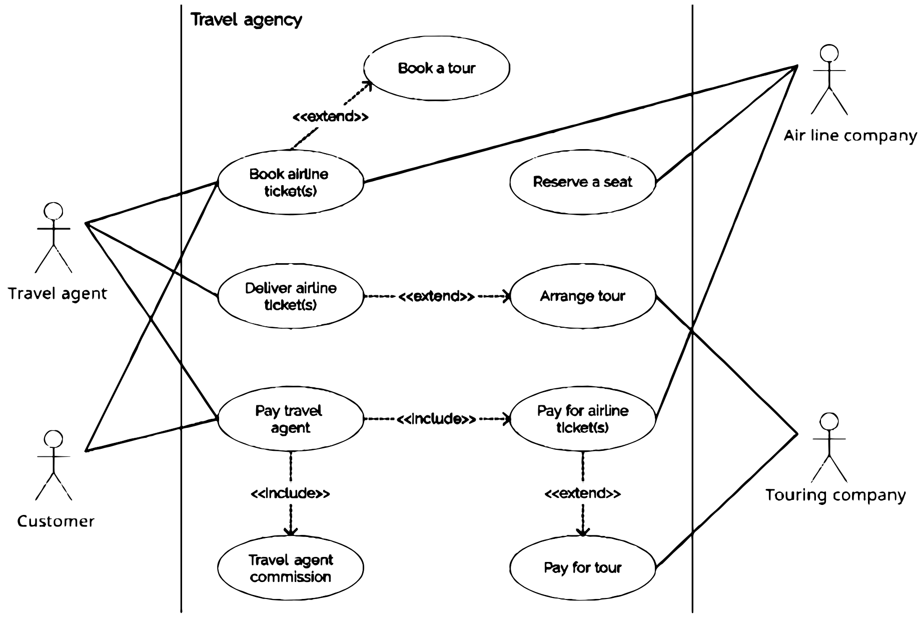


Figure 18: Example of a use case diagram (Creately, 2021)

3.4.4.1 Use case diagrams

The use case diagrams are used to model user/system interactions (Kleidermacher & Kleidermacher, 2012). They give a graphic overview of the actors involved in a system, the different functions needed by those actors, and how these different functions interact (Creately, 2021). The main relationship type in the use case diagram is the association between an actor and a use case. Nevertheless, there are also others like the "extend" or the "include" between two use cases (Creately, 2021). In the case of "include", one of the use cases is conditioned by another one to be performed, it denotes a full dependency to another use case. In the case of "extend", the association is an addition to a use case, not always dependent on the other every time the first use case is performed.

In this thesis, as proposed by Shafiee et al.(2014) and Kristjansdottir et al. (2015) in the literature study, the use case diagram is utilized to identify the relevant stakeholders in the configuration process that the user goes through when using the product configurator. Figure 18 shows an example of a use case diagram for a travel agency.

3.4.4.2 Activity diagrams

The activity diagrams are used to represent interactions between processes. These diagrams show how the system entities, usually components, run in parallel with each other and the synchronization points between them (Kleidermacher & Kleidermacher, 2012). Basically, activity diagrams graphically represent workflows. They can be used to describe the business workflow or the operational workflow of any component in a system (Creately, 2021). Figure 19 shows an example of a simple activity diagram for the SIM process menu in a phone.

This type of behavioral diagram from the Unified Modeling Language is chosen to organize the different phases of the framework, since it offers a visual and standard method to visualize the framework's workflow, and helps to provide an intuitive way to understand

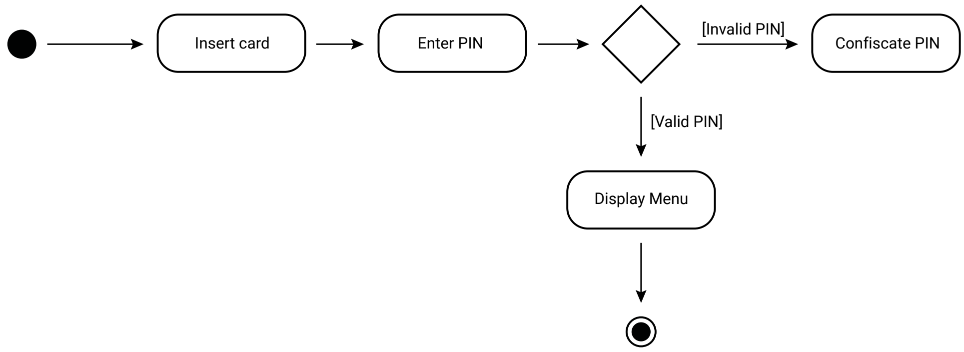


Figure 19: Example of an activity diagram (Creately, 2021)

the decision-support process. It is also utilized to represent the information of the AS-IS and TO-BE process representations previously described, in order to use similar approaches in terms of workflows.

The main elements to develop an activity diagram are the following (Lucidchart, n.d; Creately, 2021) (described graphically in figure 20):

1. Start symbol. It represents the beginning of a process or workflow in an activity diagram. It can be used by itself or with a note symbol that explains the starting point. When a letter is included, it represents the continuation of the diagram.

2. Activity symbol. It indicates the activities that make up a modeled process.

3. Connector symbol. It shows the directional flow, or control flow, of the activity.

4. Decision symbol. It represents a decision and always has at least two paths branching out with condition text to allow users to view options.

5. Note symbol. It allows for the communication of additional messages that do not fit within the diagram itself.

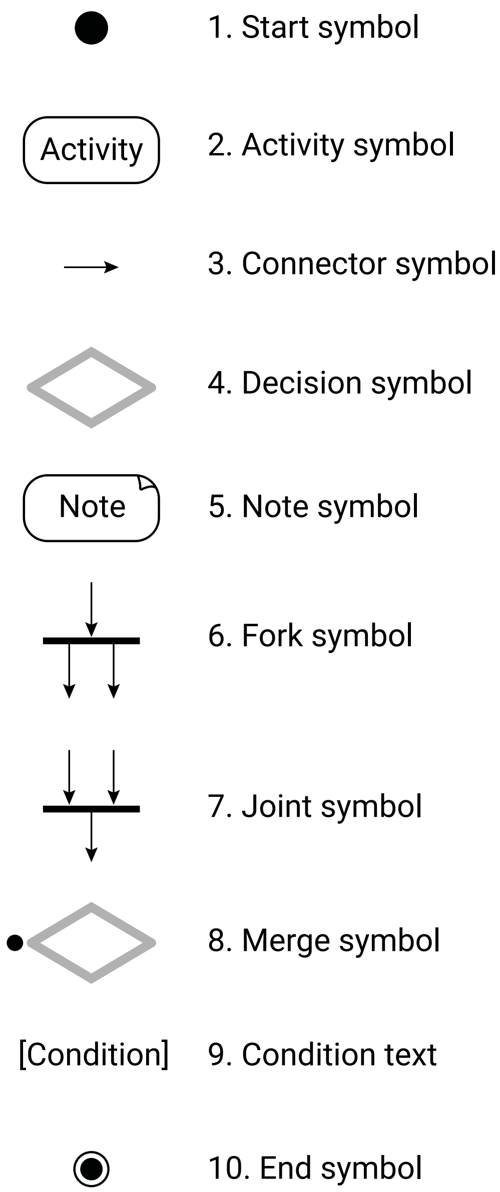


Figure 20: Main activity diagram elements

6. Fork symbol. It splits a single activity flow into two or more concurrent activities.

7. Joint symbol. Combines two or more concurrent activities and re-introduces them to a flow where only one activity occurs at a time. The process can not continue until both concurrent activities are performed.

8. Merge symbol. It brings together multiple flows that are not concurrent. It has several inputs, but one output.

9. Condition text. It is placed next to a decision marker to let know under what condition an activity flow should split off in that direction.

10. End symbol. It marks the end state of an activity and represents the completion of all flows of a process. It can also be used with a note symbol explaining the ending point.

3.5 Principal remarks from the literature study

The goal of the literature study is to identify guidelines from the literature, based on the 4 pillars, to enable end users the possibility to engineer-to-order the final product based on their customer profile and by the means of a product configurator. For that, based on the results from the preliminary research (chapter 2), this systematic literature study has been focused on researching the literature regarding the relation between product configurators and the business model of engineer-to-order, as well as the relation between product configurators and the customer knowledge. The capabilities of the company, the product, the configurator and the customer are checked and taken into account when reading the papers and developing the literature study.

The review describes the most recurrent procedures, guidelines and outcomes regarding the aforementioned relations across the literature. The combined findings from the investigation of the two search queries serve as a basis for the identification of the elements and the development of the framework (chapter 4). Section 3.5 provides the principal remarks from the systematic literature study which comprises a synthesis of points 1, 1.1, 2 and 2.1 from the literature study strategy, while point 3, although also detailed in this section, has already been covered separately in section 3.4. This section, 3.5, is also divided into two sub-sections: 3.5.1 presents the key elements from the review in the shape of 3 tables and 3.5.2 provides the updated reference model.

It can be concluded, answering the first research question, that in order to adapt product configurators for the engineer-to-order model, different business models (ATO, MTO and ETO) should be combined within the product configurator (Haug et al., 2019a; Levandowski et al., 2015), since it is stated that it can not cover an exclusive ETO approach (Bredahl et al., 2021). For this task, the different parts/modules of the product should be categorized into the business model that they have to follow (MTS, ATO, MTO and/or ETO) (Zheng et al., 2017a; Shamsuzzoha et al., 2011) based on the levels of customization required by the customer or the capabilities of the product and the company. Regarding the second research question, it is stated that the amount of customization that can be achieved within a product configurator is restricted by the level of knowledge and motivation from the customer (Weinmann et al., 2011a; Randall et al., 2017), for whom the product configuration process should be adapted based on the customer profile (Fuerstner et al., 2012). For the product configurator to be successful in an ETO environment, the level of detail and completeness of the product parts and modules that are shown to the customer in the product configurator should be stated beforehand (Kristjansdottir et al., 2015; Haug et al., 2019b). The use of the configurator for both the sales and the technical stage of the product development process is also described as an important remark in the literature to use product configurators with ETO possibilities (Kristjansdottir et al., 2017; Mäkipää et al., 2012), as well as the use of modularity (Kristianto et al., 2015) and scalability strategies in sequential order (Zheng et al., 2017a).

Other guidelines found across the literature are the integration of the product configurator with other IT systems in the company (Willner et al., 2013; Bredahl et al., 2021), the identification of the current and future configuration process (Shafiee et al., 2014), the increased possibility to use product configurators in ETO environments when products have low product complexity and/or similar specifications in the product family (Bredahl et al., 2021), the identification of objectives (Shafiee et al., 2014) and stakeholders (Kristianto et al., 2015) in the product configurator process or the reuse of parts and previous designs within the configurator (Brière-Côté et al., 2010).

3.5.1 Key elements

This subsection presents a summary of the essential elements that have been discussed throughout the literature study along with their respective references. It provides a synopsis of points 1, 1.1, 2 and 2.1 of the literature study strategy described in section 3.1, and also connects it to point 3.

Table 3 presents the basic guidelines and table 4 the main best practices found in the literature regarding the potential planning of a product configurator that permits end users engineer-to-order the final product taking into account the customer knowledge. Table 5 shows the main positive outcomes from the relation of product configurators with engineer-to-order and with customer knowledge, as described in the literature.

The elements presented in the tables are displayed as short and concise phrases. They are further explained next to understand them properly and use them as a basis for the identification of the elements in the framework and its implementation. First, the basic guidelines are described. The references associated to these guidelines can be found in table 3.

G1. The configurator has to be integrated with the necessary IT systems to achieve the desired level of customization by the company. The literature identifies mainly ERP, CAD and/or PLM systems.

G2. The company has to establish the objectives that are aimed to be fulfilled with the creation of the future configuration process to evaluate its effectiveness.

Table 3: Basic guidelines found across literature

BASIC GUIDELINES	References
G1. Integration of product configurators with other IT systems in the company	Willner et al., 2013; Bredahl et al., 2021; Kristjansdottir et al., 2017; Zheng et al., 2017a; Shafiee etal., 2014; Mäkipää et al., 2012
G2. Identification of the objectives that the product configurator should achieve	Shafiee et al., 2014; Tiihonen et al., 1996; Kristjansdottir et al., 2015
G3. Identification of the target group for the product to be configured	Du et al., 2006; Forza & Salvador, 2006
G4. Identification of different levels of customer knowledge and motivation for the customer profile differentiation	Fuerstner et al., 2012; Weinmann et al., 2011a; Zheng et al., 2017a;
G5. Visual user friendly interface for all the range of customers	Zheng et al., 2017a; Bredahl et al., 2021
G6. Establishment of product constraints	Hvam et al., 2008; Haug et al., 2019a; Zhang et al., 2014
G7. Identification of the current and future configuration process	Shafiee et al., 2014; Kristjansdottir et al., 2015
G8. Identification of manufacturing techniques and possible improvements	Haug et al., 2009; Zheng et al., 2017a

G3. The target group for the product that is going to be configured has to be established to understand the customization level that is expected from the configurator, as well as checking if it is worth increasing the customization possibilities for the customer.

G4. In order to classify the different customers that are going to use the configurator, an identification based on the customer level of knowledge and motivation should be performed. The Mamdani's fuzzy inferences method can be used to identify the different customer profiles that are going to use the configurator.

G5. The configurator should provide a visual and easily understandable user interface, no matter the customer profile.

G6. The physical and regulation constraints for the product where the configurator is going to be applied, need to be established for the company to understand the level of customization that can be achieved for that product with the configurator. The part-of structure of the PVM can be used for this activity.

G7. The current and the future configuration process should be described by the company to plan the product configurator. The AS-IS and TO-BE process representations can be used for this task.

G8. The company needs to identify its current manufacturing capabilities and, if possible, improve them or find other manufacturing technologies to be able to provide ETO possibilities to their product offering.

Next, the best practices from table 4 for the product configurator planning are explained more in detail:

P1. The product configurator needs to be able to support different business models (MTS, ATO, MTO, ETO) within the same configuration system in order to be able to adapt to different customization levels based on the capabilities of the company, the product and the customer.

P2. The company must decide, based on the product constraints, customization expectations and available technology potential, whether the different product modules/parts should follow one or another of the aforementioned business models within the product configurator. The kind-of structure of the PVM can be utilized for this activity.

P3. According to the customer profile (mainly defined by the level of knowledge in the product and configuration system, and the motivation to go through the configuration process), the configurator is adapted based on the different business models to deliver a proper and suitable configuration process for the customer.

P4. Based on the business model and the level of configuration, each module/part should provide more or less detail regarding the digital representation of the product in the product configurator.

P5. In order to create a product configurator that can let customers engineer-to-order the final product, this configurator needs to cover the sales and the technical stage of the product development process. Otherwise the configurator would not be able to provide the expected results.

P6. To adapt to the different business models within the configurator, the company has to be able to offer modular design to some extent in the product. The identification of the different product modules and parts is needed to establish this. The part-of structure of the PVM can be used for this activity.

P7. The company also needs to be able to provide scalable design to some extent in the product to fulfill the same objectives as with the previous best practice. It is stated that both modularity and scalability strategies should be employed to use product configurators in ETO approaches.

P8. The company should aim for a reuse of parts and previous designs if the customer has not chosen an ETO approach. This is performed to increase standardization in the product and in the configurator whenever possible, and to save costs.

P9. To be able to correctly plan the product configurator, the most relevant stakeholders surrounding the configurator development have to be identified. The use case diagram can be adopted for this task.

P10. Among these stakeholders, the suppliers for the product have to specially be identified to help in the differentiation of the modules/parts based on the business models (P2).

P11. It is stated that a configurator that can support ETO possibilities

Table 4: Best practices found across literature

BEST PRACTICES	References
P1. Combination of different business models (ATO, MTO, ETO) within the product configurator	Levandowski et al., 2015; Zheng et al., 2017b; Shamsuzzoha et al., 2011; Mäkipää et al., 2012; Bredahl et al., 2011; Haug et al., 2019a; Zheng et al., 2017a; Haug et al., 2019b
P2. Proper identification of which product modules/parts should follow a specific business model approach (MTS, ATO, MTO, ETO)	Zheng et al., 2017a; Shamsuzzoha et al., 2011; Kristjansdottir et al., 2015; Haug et al., 2019b; Shafiee et al., 2017; Sylla et al., 2018; Wang & Tseng, 2014; Zheng et al., 2017b; Haug et al., 2009
P3. Adaptation of the product configurator based on the customer profile (level of knowledge+motivation)	Fuerstner et al., 2012; Weinmann et al., 2011a; Zheng et al., 2017a; Randall et al., 2017
P4. Selection of level of detail and completeness of parts/modules that should be included in the product configurator	Kristjansdottir et al., 2015; Kristjansdottir et al., 2016; Haug et al 2019b; Shamsuzzoha et al., 2011
P5. Use of product configurators for sales + technical stage of the product development process	Kristjansdottir et al., 2016; Bredahl et al., 2021; Mäkipää et al., 2012; Kristjansdottir et al., 2017
P6. Use of modularity in the product in order to apply product configurators in ETO environments	Kristianto et al., 2015; Zheng et al., 2017a; Kristjansdottir et al., 2016; Zheng et al., 2017b; Willner et al., 2013
P7. Use of scalability in the product in order to apply product configurators in ETO environments	Zheng et al., 2017a; Zheng et al., 2017b; Mäkipää et al., 2012; Willner et al., 2013
P8. Reuse of parts/modules and previous designs	Brière-Côté et al., 2010; Kristianto et al., 2015; Willner et al., 2013; Shafiee et al., 2017
P9. Identification of stakeholders in the product configurator development process	Shafiee et al., 2014; Kristjansdottir et al., 2015; Kristianto et al., 2015
P10. Identification of suppliers (included as stakeholders) for the product modules/parts	Zheng et al., 2017a; Zheng et al., 2017b
P11. Products with low product complexity and/or similar product specifications considered best candidates	Bredahl et al., 2021; Willner et al., 2016;

Table 5: Outcomes found across literature

OUTCOMES	References
O1. More standardized products and processes	Forza & Salvador, 2002; Kristjansdottir et al., 2017; Bredahl et al., 2021; Haug et al., 2019b; Willner et al., 2013
O2. Creation of faster sales quotes	Haug et al., 2019a; Shafiee et al., 2017; Heiskala et al., 2007; Haug et al., 2009
O3. Increased sales	Forza & Salvador, 2002; Haug et al., 2019b
O4. Higher level of customization	Zheng et al., 2017b; Kristjansdottir et al., 2017
O5. More collaboration and communication between departments and stakeholders	Willner et al., 2013; Kristjansdottir et al., 2017; Kristjansdottir et al., 2015
O6. Lead time reduction	Haug et al., 2019b; Kristjansdottir et al., 2015; Kristianto et al., 2015
O7. Better customer involvement by adapting the configuration process to the customer profile	Fuerstner et al., 2012; Weinmann et al., 2011a
O8. More efficient configuration process in ETO companies through the use of product configurators	Zheng et al., 2017b; Shamsuzzoha et al., 2011; Willner et al., 2013; Bredahl et al., 2021
O9. Accuracy increase and complexity decrease in the configuration process	Willner et al., 2013; Haug et al., 2019b; Shafiee et al., 2017

works best for products that are not very complex or otherwise it would suppose a tedious process for the company to create the product configurator and with possible unsuccessful outcomes.

As mentioned in section 3.4, the framework to be developed utilizes activity diagrams to describe the workflows that include the different guidelines and best practices.

To finish this sub-section, table 5 describes the main benefits and positive outcomes from the investigation developed in the literature study. The objectives that want to be obtained with the TO-BE process representation can be selected from this table.

O1. By using product configurators in ETO companies, processes and products can be standardized to some extent simplifying the product life-cycle management.

O2. The use of a configurator for typical ETO products streamlines the creation of sales quotes and their transfer to the customer.

O3. It is stated in the literature that the use of a product configurator with ETO possibilities means an increase in sales for the company.

O4. Implementing ETO processes to product configurators is translated into a bigger product variety and a higher level of customization.

O5. The use of this type of product configurator improves the collaboration and communication between different departments of a company since it requires different areas to work together to plan and develop the configurator.

O6. For ETO-only companies, creating a configurator for their products is translated into a lead time reduction by reducing significantly the time required to translate customers' requirements.

O7. By adapting the configuration dialogue for different customer profiles, there is a lower risk for users to abort the configuration process and, therefore, improve the customer involvement with the configurator.

O8. Connecting to (O1), when ETO companies use product configurators, the configuration process becomes more efficient and less time is lost in the first product development stages.

O9. The use of product configurators by ETO companies increases the accuracy of the configuration outcomes created by the customers, which decreases the complexity of the process.

3.5.2 Updated reference model

As described in section 1.3, the Descriptive Study I stage from the DRM by Blessing & Chakrabarti (2009) is aimed to broaden the understanding of the design and the determinants that influence its success by means of a systematic literature study. Furthermore, the reference model is updated based on the initial impact model and the findings from the literature study.

Updating the reference model means that assumptions may be confirmed or rejected, new influencing factors can be identified and links may have to be added, removed or modified, Furthermore, the key factors and success criteria may have to be changed or reconsidered (Blessing & Chakrabarti, 2009).

The updated reference model can be observed in figure 21. The new factors and their statements are all established based on the key elements from the literature study described in sub-section 3.5.1. When more than one reference is coincident on a specific statement, only one of the references is mentioned in the updated reference model to avoid possible confusion. As with the initial reference and impact model, the reference correspondence is included in appendix B.

The final key factor is maintained from the initial impact model and new factors and statements are included in the updated reference model based on the findings of this section. Some others are also changed or removed. The relation between the new and old factors is graphically displayed in the updated reference model, which works as a

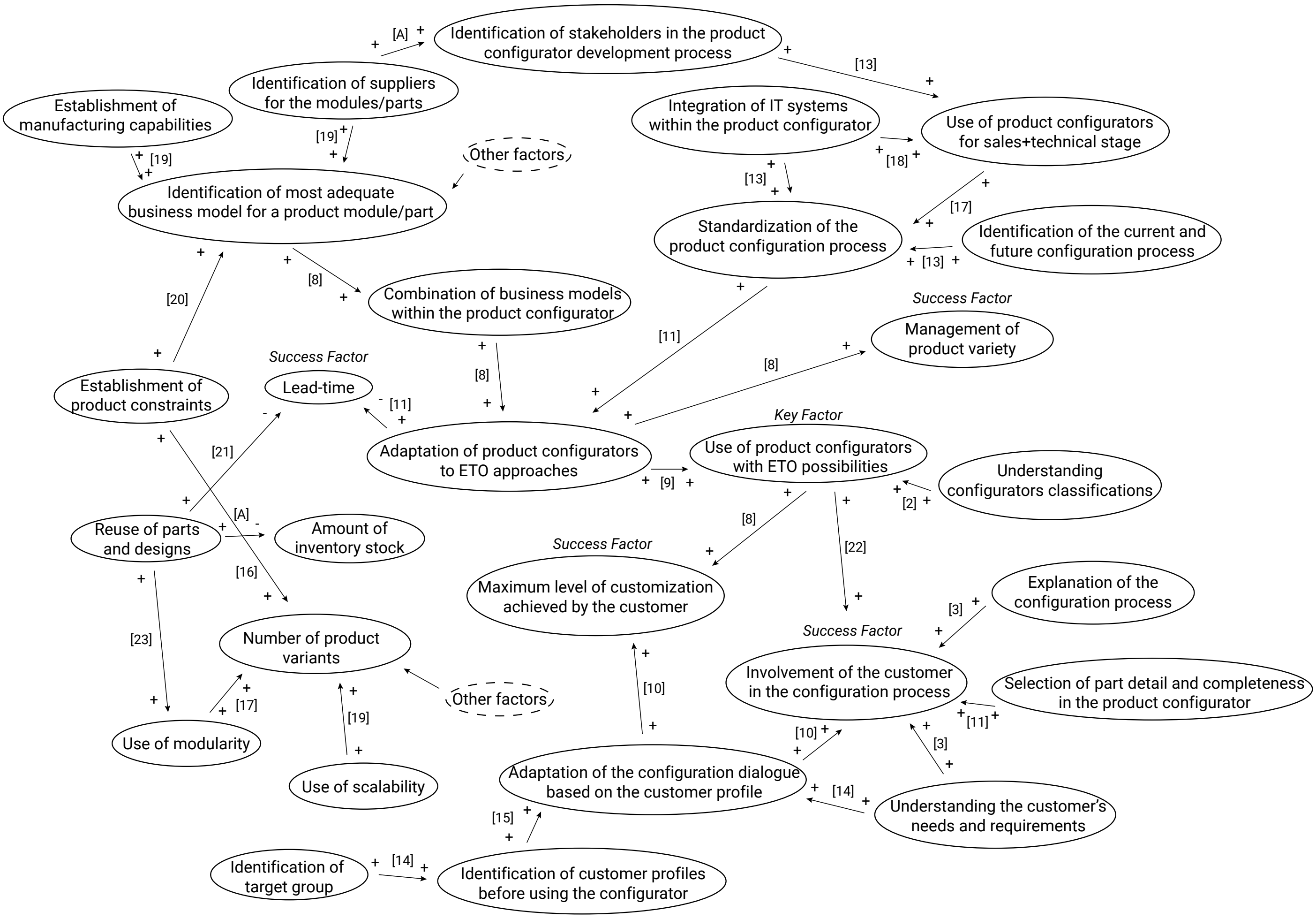


Figure 21: Updated reference model

summary of the results of the two search queries compared to the situation in the initial reference model. The preliminary success factors and the success criteria are all maintained except for the number of restrictions in the configuration process, which is removed due to not finding a proper relevance of this factor in the systematic literature study. A new success factor is added, which is the management of product variety. The desired value for this new success factor is obtaining better management of product variety. To develop the evaluation in further chapters, the success criteria of the final success factors have to be compared with the statements from the preliminary key and success factors of the initial reference model.

FRAMEWORK

4

Chapter 4 describes the framework that underlays the relation and balance between the capabilities of the company, the configurator, the product and the customer in order to be able to plan product configurators that can let end users engineer-to-order the final product based on the customer profile. Chapter 4 comprises the Prescriptive Study stage from the DRM by Blessing & Chakrabarti (2009). It follows a comprehensive approach since it results in a support that is realized to such an extent that its core functionality can be evaluated to some degree for its potential to fulfill the purpose for which it was developed (Blessing & Chakrabarti, 2009). Once the support is developed, chapter 5, (Case study & Evaluation) provides the aforementioned evaluation.

The framework is based on the findings from chapter 2 (section 2.3), and chapter 3 (section 3.4 and section 3.5). First, section 4.1 describes the main elements surrounding the framework, and section 4.2 displays its development and implementation. The update of the initial impact model is also performed in section 4.2 based on the support created.

4.1 Elements

The identification of the elements of the framework is based on the basic guidelines and best practices found in the systematic literature study (sub-section 3.5.1). To organize this information, the elements are decoupled from the four main pillars that have been described throughout the project: (1) the customer, (2) the product configurator, (3) the final product and (4) the company. These pillars serve to explain the organization and division of all the elements. The mind map in figure 22 and figure 23 presents graphically the 4 pillars (customer and product configurator in figure 22, and product and company in figure 23) with all the elements. In order to connect with the findings from the literature study, table 6 presents the relation of the main elements (E) in the mind map with the basic guidelines (G) and best practices (P) from sub-section 3.5.1 along with the pillar that the main element is associated with. This mind map presents practically the same information as the updated reference model from sub-section 3.5.2 since this is also created based on the findings from the systematic literature study. Nevertheless, the mind map divides the different elements according to the pillar they are associated with and displays the knowledge in a graphically easier to understand approach. To create a strong link between the mind map (foundation of the framework development) and the updated reference model, figure 24 presents the new factors from the systematic literature study added to the updated reference model color-coded based on the 4 main pillars. Therefore, with table 6 and figure 24, the continuity of the research is ratified. Next, to better comprehend the mind map, the different elements of the four pillars are briefly described. These elements are the ones used for the development and implementation of the framework (section 4.2).

1. **Customer**
   The main elements decoupled from the customer are the target group for the product, the level of customer knowledge, the level of motivation and the type of customer profile. The current target group is first identified to determine the customization needs of the customers. The level of knowledge takes into account

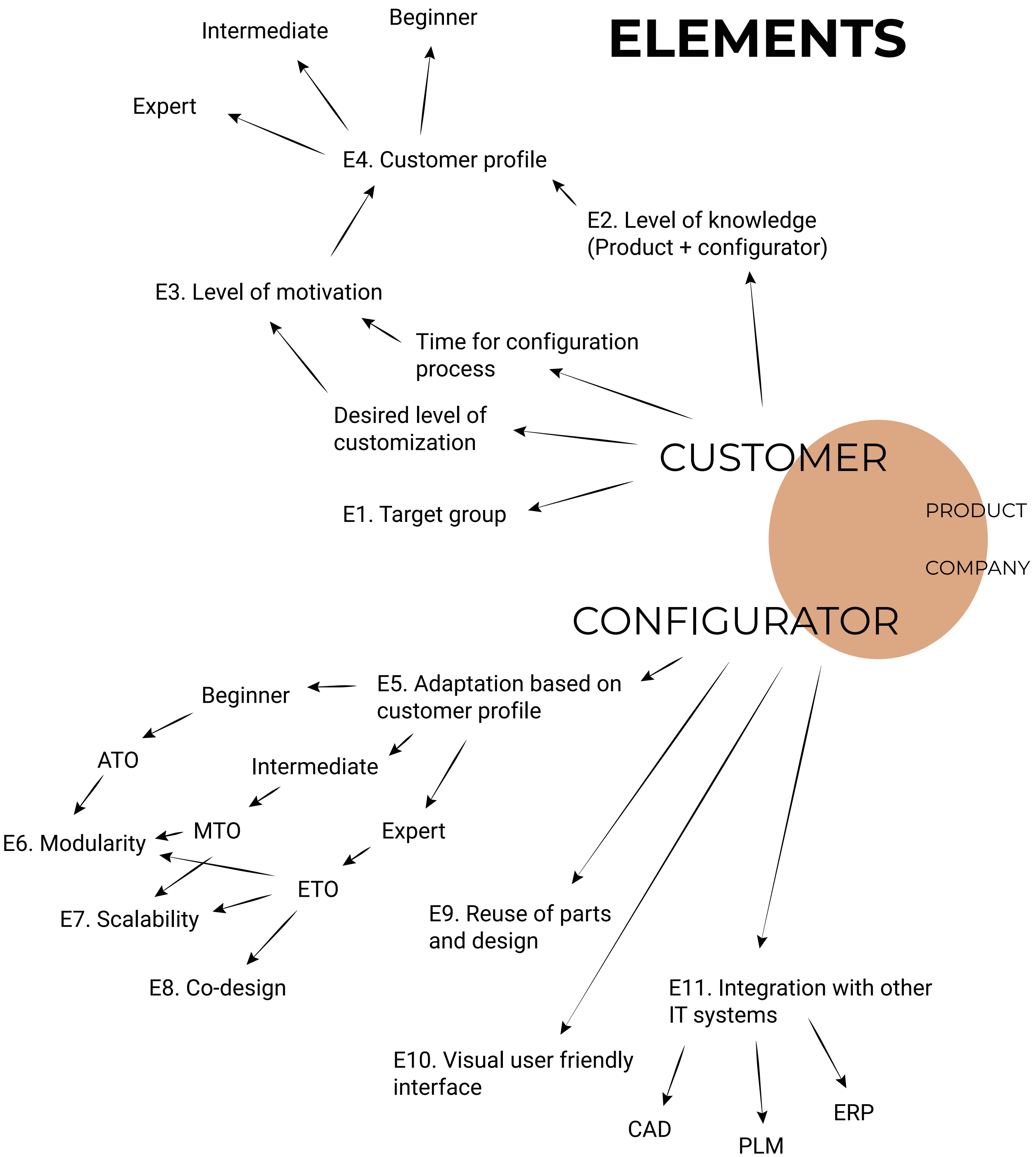


Figure 22: Elements surrounding the framework (Customer and configurator pillars)

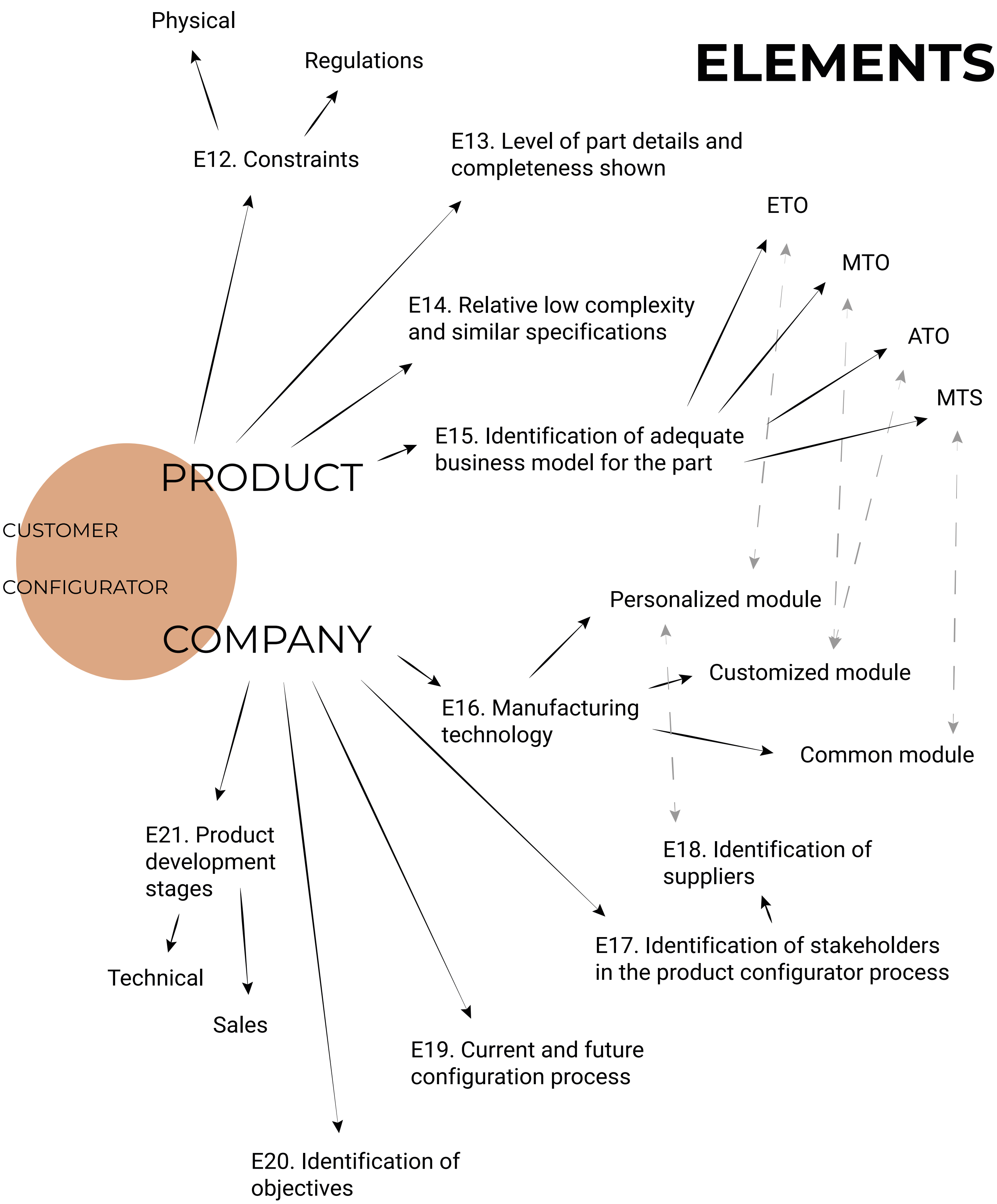


Figure 23: Elements surrounding the framework (Product and company pillars)

Table 6: Relation of main elements with basic guidelines and best practices found in the systematic literature study (table 3 and table 4 from sub-section 3.5.1)

Basic guidelines (G) and best practices (P)	MAIN ELEMENTS	Pillar
G3	E1	Customer
G4, P3	E2, E3, E4	
P1, P2, P3	E5	Product configurator
G6, P6	E6	
G6, P7	E7	
G6, P1, P2	E8	
P2, P8	E9	
G1, G5	E10, E11	
G6	E12	Final product
P1, P2, P4	E13	
P11	E14	
G6, P1, P2	E15	
G8, P1	E16	Company
P9, P10	E17, E18	
G2, G7	E19, E20	
G7, P5	E21	

the product and the configuration process. The level of motivation focuses on the capability of the customer to process information about the product. Based on the level of knowledge and motivation, and through the use of the Mamdani's fuzzy inferences method (Torres & Krishnankutty., 2008), the customer profile is defined, which, in this research, divides the customers into three categories: "beginner", "intermediate" and "advanced".

2. **Product configurator**
   One of the main elements regarding the product configurator is its adaptation to the user based on the customer profile just described. The combination of different business models (ATO, MTO, ETO) within the product configurator accomplishes the fact that each type of customer is satisfied with the configuration process in terms of complexity, customization and time spent.
   If the customer is considered a "beginner", the product configurator follows an ATO approach in which a modularity strategy (meaning that the customer can choose between different module options) is followed. If the customer profile is "intermediate", then an MTO approach is followed where the customer can choose modularity and scalability (in which parametric or design changes can be performed to the modules/parts versions), in that order. And if the customer profile obtained is "advanced", an ETO approach is followed in which the customer can choose to go through a modularity or scalability strategy, or can opt to co-design that module/part based on his/her requirements within some limits established by the company.
   The combination of models within the

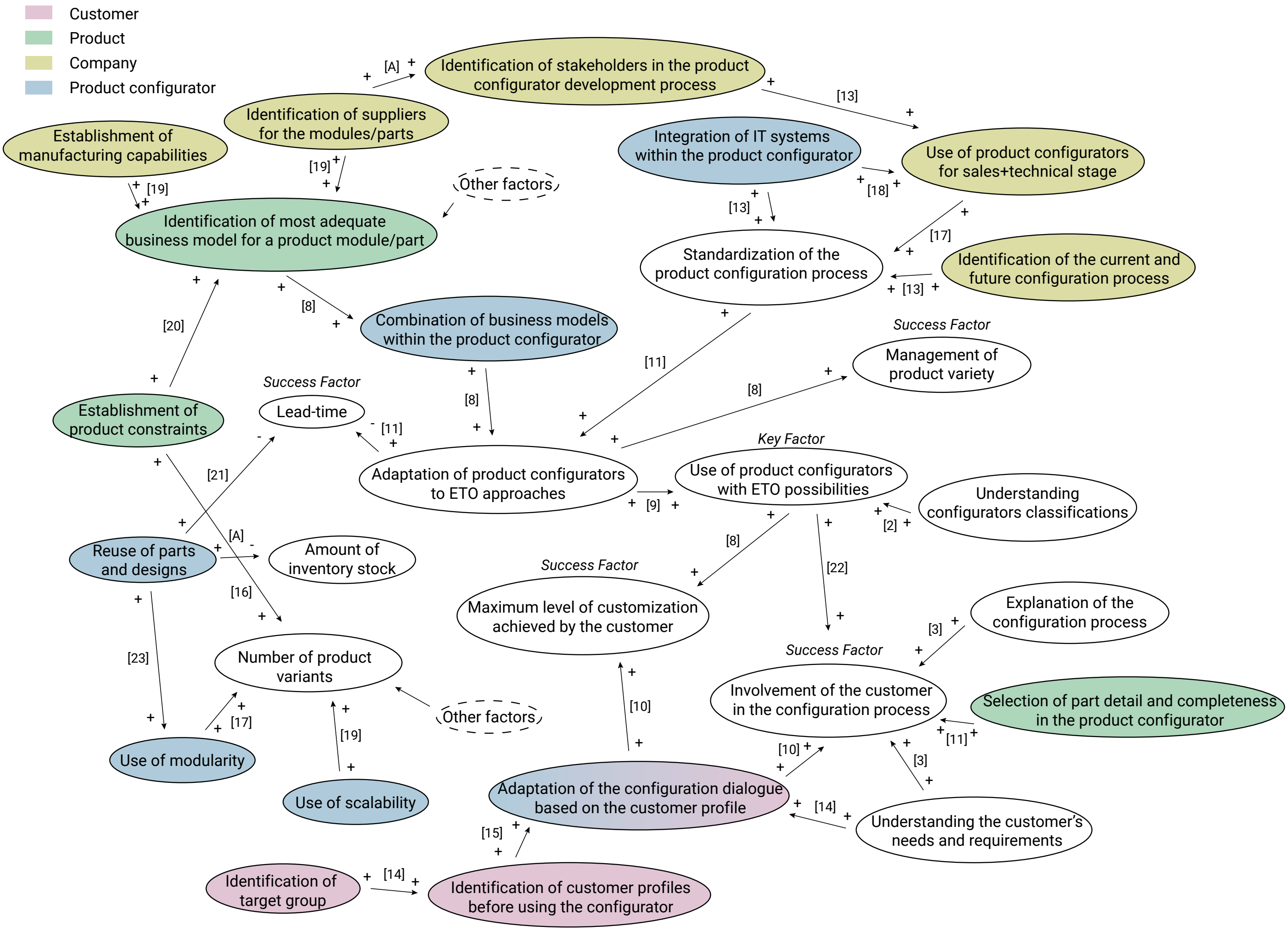


Figure 24: Updated reference model with new factors color-coded based on the four main pillars

configurator also takes into account the capabilities of the product and the company.

To achieve these procedures, the product configurator has to be integrated with other IT systems (another main element) like CAD, to obtain 3D models from the configuration process, PLM to track the configured product throughout its life cycle, or ERP for the communication between departments.

The reuse of parts and designs (that for example have been created through an ETO approach) is another factor beneficial for obtaining more ATO or MTO configurations, which are translated into more standardization and economic profitability for the company. All these features have to be packed in a visual user-friendly interface, not only for the beginner customer profile, but for the other two as well, in which 3D models of the possible variants of the final product are presented.

3. **Final product**

   A critical element for the final product is the identification of which business model works best for the different modules and/or parts of the product. For that, the Product Variant Master introduced by Hvam et al. (2008) is used to break down the modules/parts of the product, identify the

most important product variants and establish the business model (these can be MTS, ATO, MTO or ETO) that the module/part should be associated with.
This is also utilized to decide on the level of detail and completeness from the part/module that is showed to the customer in the product configurator. The modularity, scalability and ETO design strategies are restricted based on the physical constraints of the final product or possible regulations and have to be taken into account throughout the whole process. All these procedures regarding the product work best for final products with not a relatively high complexity and those with similar specifications within the product family.

4. **Company**
Some of the main elements for the company are the identification of the current and future configuration process, and the identification of the objectives that want to be achieved through the use of the product configurator to be developed. For that, AS-IS and TO-BE process representations as presented by Shafiee et al. (2014) are used to show the current situation of the company with regards of the configuration process and the possible scenarios for the future one.
Other elements are the main stakeholders that are part of the product configurator development process, which normally contain, based on the literature, the customer, engineers, sales staff and suppliers. The actual configurator developer also needs to be taken into account, as stated by the author. The identification of the suppliers is especially relevant for the personalized modules following the ETO model. For the stakeholder identification, the use case diagrams are utilized as described by Kristjansdottir et al. (2015).
The product configurator developed by the company should cover the sales and technical stage of the product development process in order to improve the communication between departments with the customer as the main focus.
The company has to decide on the manufacturing technology needed to create the common modules (MTS parts), the customized modules (ATO and MTO parts) and the personalized modules (ETO parts). All these processes are defined based on the maximum level of customization that the company can achieve, for which the framework (with activity diagrams) is used.

4.2 Development and implementation

The framework presents the advice for companies on the decision process for the planning of a product configurator that can let the end user engineer-to-order the final product. The guidelines presented in the framework assist companies to balance the different variables from the four main pillars to deliver further customization as pulled by the customer with a product configurator. As stated and defined in section 1.2, this thesis and framework are focused on consumer goods. The framework is a result of the research performed in section 2 and section 3. The framework is divided into four consecutive phases that are connected with each other (1. Plan, 2. Organize, 3. Classify and 4. Adapt). The structure of the framework with its four phases is based on a combination of the frameworks and steps presented in the literature from, for the most part, the works of Zheng et al. (2017a) and Shafiee et al. (2014) described in section 3.2 and Fuerstner et al. (2012) described in section 3.3, as well as the rest of the findings from the literature study (chapter 3).

The graphical representation of the full framework is shown in figure 25 with the four phases previously described. These are explained in detail later in sub-section 4.2.1 for phase 1 (figure 26 and figure 27), sub-section 4.2.2 for phase 2 (figure 28 and figure 29), sub-section 4.2.3 for phase 3 (figure 31) and sub-section 4.2.4 for phase 4 (figure 32). Each of the phases take into account the 4 main pillars (and their capabilities) that were described with the framework's elements (section 4.1) and throughout the rest of the chapters. The ovals in figure 25 represent the relation and balance of the pillars in the different phases of the framework. Each of the phases leads to one specific outcome and is centered on one of the pillars, even though the other ones are also included in all of them. Phase 1 is related to the initial plan of the company regarding the maximum level of customization, phase 2 with the product modules/parts organization based on the different business models and the maximum level selected in phase 1, phase 3 with the customer profile classification and the connection with the maximum level of customization that the user can achieve, and phase 4 with the adaptation of the product configurator based on the outcomes from the previous three phases. The structure of the different tasks presented in phase 1 and phase 2 is based on the framework elements described in Shafiee et al. (2014) and Kristjansdottir et al. (2015) combined with the information regarding business models and modules/parts presented in Zheng et al. (2017a). The third phase is mostly based on the approach presented in Fuerstner et al. (2012) and Weinmann et al. (2011a) regarding the relation between the customer and the product configurator. The fourth phase, regarding the decision-making for the adaptation of the product configurator, is a result of the three previous phases and is evolved from the adaptability approach presented in Zheng et al. (2017a) and Zheng et al. (2017b). Accordingly, these are the papers that influence the most the organization of the framework, nevertheless as previously described in section 4.1, the different elements of the framework are based on all the findings from the literature study. After the framework and its phases are described, in sub-section 4.2.5 the impact model is updated based on the support created with the framework.

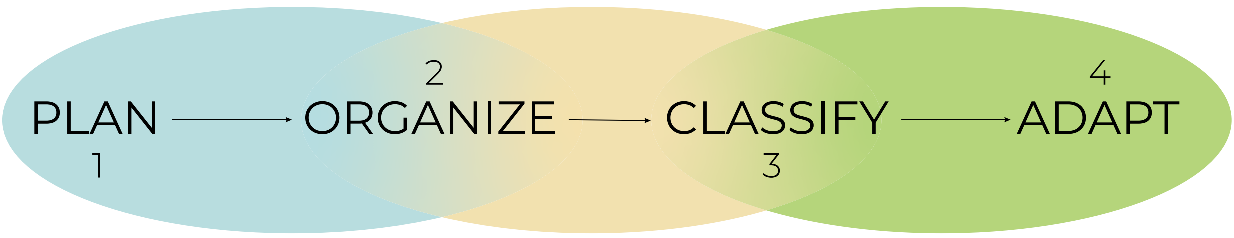


Figure 25: Full framework

The main aim of providing the capacity to the customer of engineering-to-order the final product is to improve the customization possibilities during the configuration process. In order for the companies to be able to use the framework properly, they are given a framework manual (included in Appendix A), which is very similar to this section and walks through the different steps of the framework as well as the models and methods used.

The phases of the framework utilize activity diagrams, as mentioned in sub-section 3.4.4, to describe and represent the different decision workflows that are presented in each phase. The different elements of an activity diagram are described in sub-section 3.4.4 and in Creately (2021). In this framework when the word "identify" is used, this means that the task has to be performed before starting the step of the activity diagram, and when the word "select" is used, the task is performed with the help of the activity diagram.

4.2.1 Phase 1: Plan

The first phase of the framework (Plan), shown graphically in figure 26 and figure 27, consists of an activity diagram (divided into 3 sub-activity diagrams) that helps the company frame itself into the maximum level of customization that should and can be achieved with the use of the product configurator for the chosen product. These levels can be very high (up to ETO), high (up to MTO) and average (up to ATO). The framework also has another possible outcome for which the company is advised to keep the current configuration process instead of aiming to achieve a higher level of customization.

In each of the sub-activity diagrams, the company is directed into either continue using the framework or maintaining its current configuration process for the product. In the last sub-activity diagram, if reached, the maximum level of customization for the product configurator to be developed is established. It is advised to try and aim for the highest level of customization in the configurator, since the goal of the framework is to be able to let end users engineer-to-order the final product to some extent. The sub-activity diagrams are depicted from the 4 pillars and the main one for phase 1 is the company, since this first phase helps to set its customization plan:

1. The first task in the diagram is depicted from the customer pillar (figure 26). The company has to identify the current target group for the selected product and decide if this target group would benefit from having more customization possibilities in this specific item. If the answer is no, it should be checked if the current target group can be expanded so this increment would be beneficial. If the answer is still no, then it is advised to keep the current configuration process and stop using the framework. On the other hand, if the answer is yes, the company can continue using the framework taking into account this customization pulled by the target group. As stated in the literature, customers aim at having a wider range of choices for their personalized product, which is the overall aim of the framework.

2. The next two tasks are related to the product configurator pillar (figure 26). The two tasks are concurrent and that is why the fork symbol

is utilized at the start of this sub-activity diagram. One of the tasks is related to the product configurator and its current integration with other IT systems in the company, such as CAD, ERP or PLM as identified in the literature. If the current integration or a potential future one allows the company to cover the sales stage (which communicates the product to the customer and provides real-time information to the company) and the technical stage (that checks the validity of the product variants and generates the bill of materials according to the customer's configuration), the company can continue the activity diagram and reach the joint node. On the other hand, if the answer is negative, the current configuration process is maintained and there is no need to continue using the framework.

The other concurrent task, also related to the product configurator, identifies the current configuration process that the user goes through for the creation of the product. For that, an AS-IS process representation is advised to be created. If it is possible to modify the process and this change is expected to potentially provide more customization possibilities to the customer, the joint node is reached. If there is no room for alterations and improvements, the current configuration process is kept. If both tasks have come to the joint symbol, the activity diagram can be continued.

3. The following two tasks are part of the final sub-activity diagram of phase 1, which is depicted from the company and the product pillars (figure 27). These two tasks are also concurrent and a fork symbol is used. The first of the two, related to the product, requires the company to identify the different product modules/parts and the possible physical or regulatory constraints. This process is associated with the creation of the part-of structure of the Product Variant Master, which is advised to be used. If no modules/parts have the potential to be customizable, the current process is maintained. If some of the potentially customizable modules/parts can be unique for each product variant while maintaining the product structure, the joint node that continues to the (C) start symbol is reached. If the module/part versions are expected to allow a certain physical or graphical change, the joint node that continues to the (D) start symbol is attained. If the answer to this last question is negative, the current configuration process is maintained.

   The other task is related to the company and the current manufacturing techniques and technologies used to develop the product. First, it is selected whether more customization as pulled by the target group can be achieved with the current approach, or if new technologies or manufacturing methods that could provide more customization can be adopted and used. If not, the ongoing configuration process is kept. If the current or future setup can provide unique modules/parts for each order, the joint node with the following (C) start symbol is reached. If certain changes to the module/part version based on the customer order can be performed before the manufacturing starts, the joint node that continues

*Maximum levels of customization: 1. Up to ATO (Average); 2. Up to MTO (High); 3. Up to ETO (Very High)

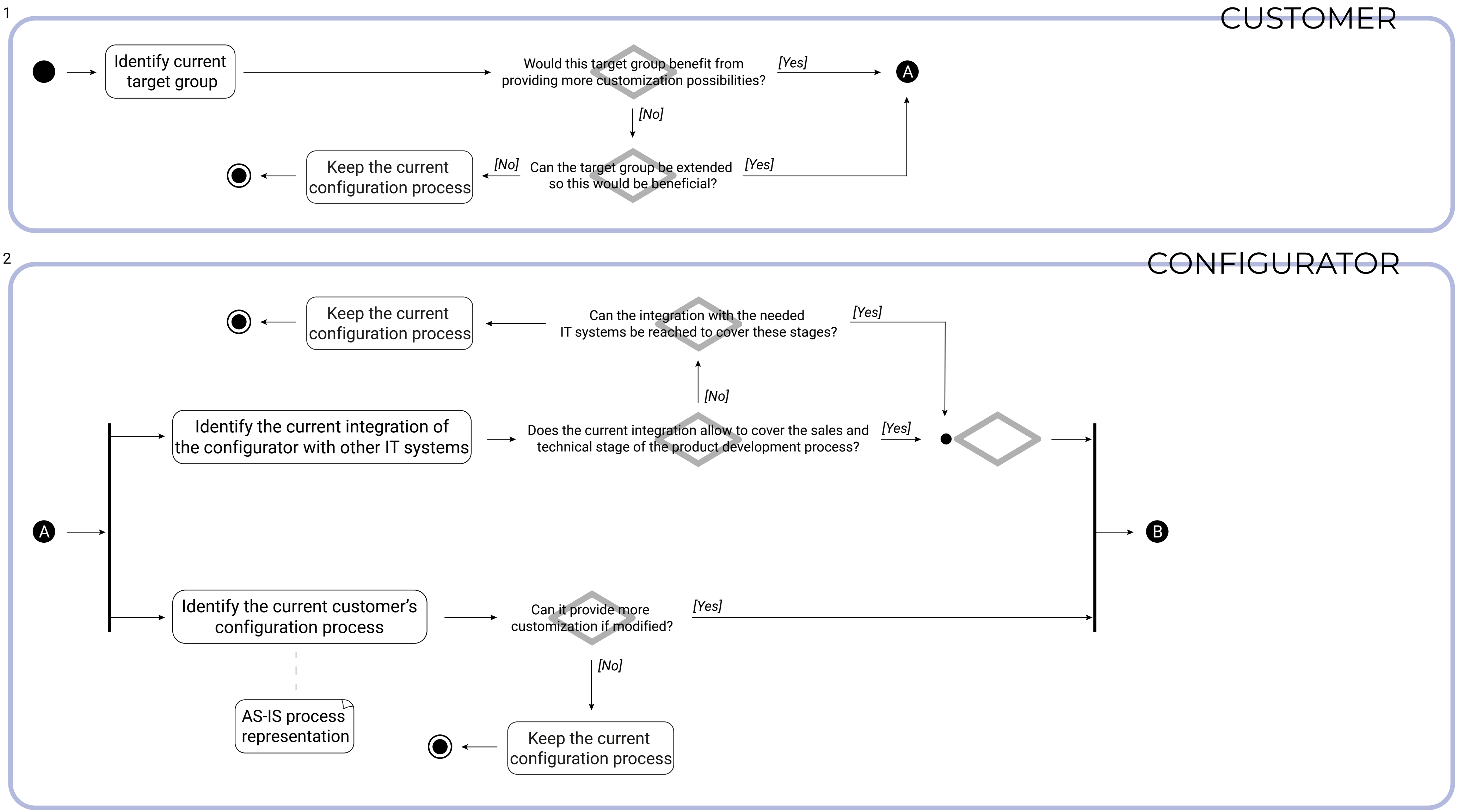


Figure 26: Framework phase 1 (PLAN) (1/2)

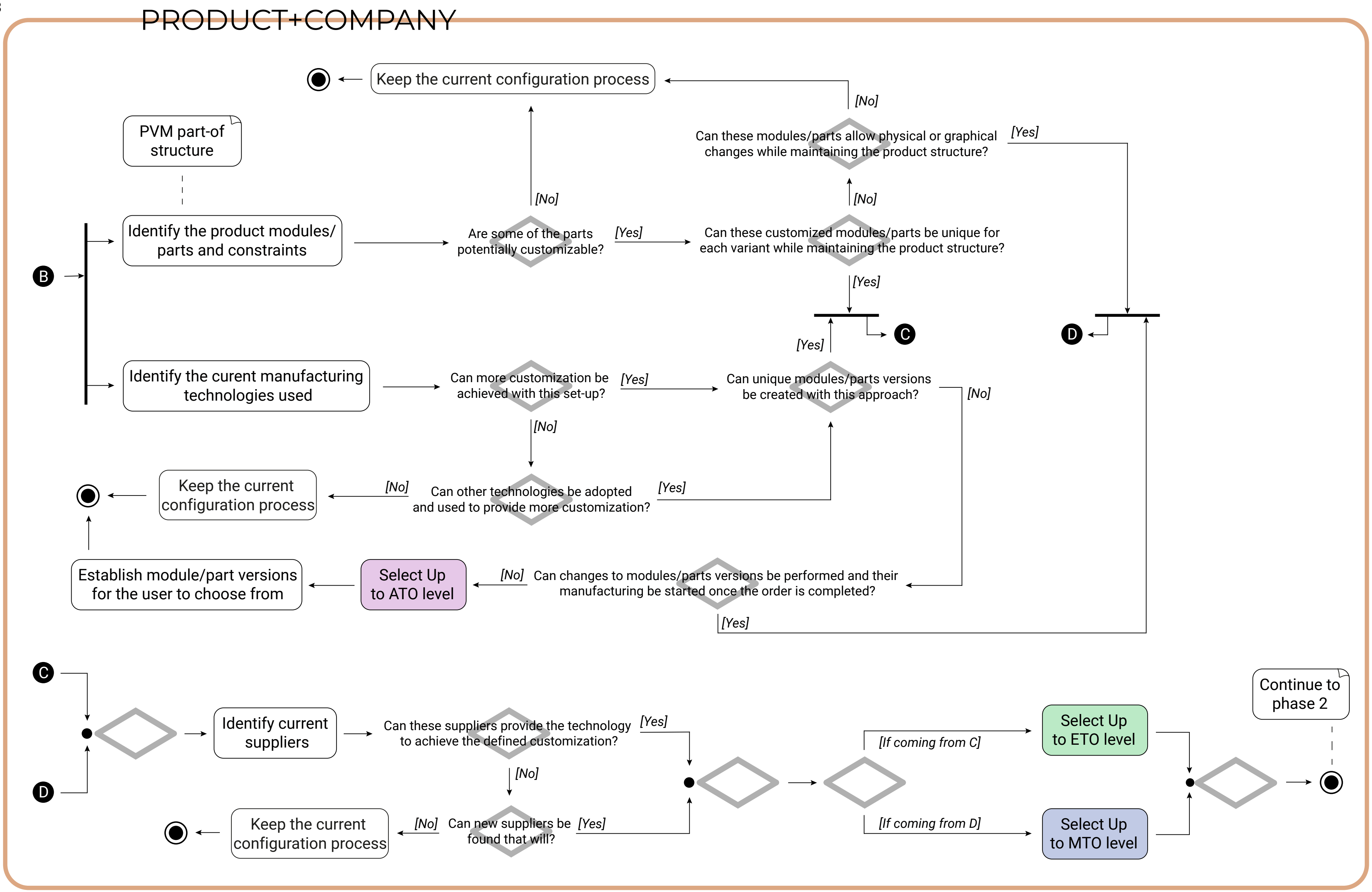


Figure 27: Framework phase 1 (PLAN) (2/2)

to the (D) start symbol is attained. If otherwise, this last option is not possible, the company selects an up to ATO level where the user is able to select between certain predefined module/part versions within the product configurator. When the final outcome is up to ATO, the framework also advises to stop its use, since this level of customization is the average for product configurators and this framework aims for a high (MTO) or very high (ETO) possible customization.

If the two tasks have reached either the (C) start symbol or the (D) one (both of them must have come to the same joint node), the company needs next to identify the current suppliers. If these suppliers or new ones established by the company can provide the technology and have the capabilities to achieve the customization defined in the previous tasks, the activity diagram can be continued, otherwise it is advised to maintain the current process. Subsequently, if the answers to these last activities are positive, when coming from the (C) start symbol, the company selects an up to ETO level of customization and when coming from the (D) one, an up to MTO level is selected.

Continuing to the next phase means that the company has the current or future capability to create a product configurator that can be used to configure a product in which the maximum level of customization that can be achieved is either up to ETO (ideally) or up to MTO, and this level of customization is beneficial for the target group.

4.2.2 Phase 2: Organize

Phase 2 (Organize) has the goal of framing the product modules or parts into either MTS (common modules), which do not provide any possibility for customization, ATO and MTO (customized modules), that provide average and high customization respectively, or ETO (personalized modules), which offers very high customization. As described in section 2.2, and as a refresher, the MTS modules/parts are those that are created before the customer order and are replenished through production orders based on the forecast. Thus, these are the modules/parts that are always present in all the product orders and can not be customized. The ATO modules/parts are those in which the customer can select among different module/part versions which are already built by the company and are assembled once the order is placed based on the customer configuration. The MTO modules/parts are similar to the ATO ones, but do not necessarily have to be already built, only created/designed by the company and may have to be manufactured and assembled upon the customer's order. They are associated with the selection and change of the module/part versions that can be performed by the customer, but always within the company's established product variants. The ETO modules/parts are those which are different in each product variant and have to always be manufactured after the customer order since the company can not foresee what they are going to be like. Nevertheless, limits for the creation of the ETO module/part versions should be established so they are in line with the capabilities of the company and with the rest of the product structure.

To frame the different modules or parts, the Product Variant Master (explained in sub-section 3.4.2) is finished with the development of the kind-of structure in which the possible module/part versions are explored and established based on the business model that best fits the specific module or part. If a module is certainly known to be associated with the MTS business model, there is no need to identify all the parts of that module, since they all follow the same approach. The kind-of structure in this thesis is focused on the potentially customizable modules or parts of the product in which the product configurator is going to be used. As described in the literature study by Bredahl et al. (2021), a product with similar specifications to others in the product family and not a high complexity is the best candidate to be used for a configurator with ETO possibilities.

The guide in figure 28 and figure 29 can be used to help in the decision-making to frame the potentially customizable modules/parts. This guide does not need to be utilized for every module and/or part, only those that the company is uncertain about which business the module/part should be associated with. Using the guide can facilitate the development of the kind-of structure of the PVM, which is the main outcome of this phase. For the aforementioned guide, an activity diagram similar to the one in phase 1 is used. In phase 2, the main pillar is the product, since the organization of the modules and parts is the main goal. If the maximum level of customization selected in the previous phase is MTO, then the company can only sort the modules/parts into MTS, ATO or MTO. Accordingly, the ETO modules/parts can only be selected if the maximum level achieved in the previous phase is up to ETO. The activity diagram in the guide has three concurrent tasks that are explained next:

The first task is associated with the product, the company and the customer. It is based on the previously identified product modules/parts and their constraints in the part-of structure of the Product Variant Master. If the module or part, depending on the product structure and constraints, allows the possibility to let the customer create unique versions of that module/part for each product in order to benefit the company and the user, the (A) start symbol is reached. If it is possible and it makes sense for the company to let the user make some parametric or design changes to the module/part version, then the (B) start node is attained. If it is possible and it makes sense to let the user choose between different module/part versions, the diagram leads to the (C) symbol. If the answer to this last question is negative, the module/part follows an MTS approach and there is no need to continue using the guide (figure 28).

The second concurrent task is related to the company and the previously identified suppliers from the first phase. If they can provide a unique module/part version (within limits established by the company) for each product order created by the customer, the (A') start symbol is reached. If they can supply versions of a module/part in which the customer can decide on some dimensions or design changes (previously predefined by the company) before the order is placed and the manufacturing started, the diagram leads to the (B') start node. If only settled versions of a module/part can be provided, the (C') start symbol is attained. If none of these scenarios is possible, the part follows the MTS business model and the use of the diagram is finished.

Guide to help in the decision-making for the creation of the kind-of structure of the PVM

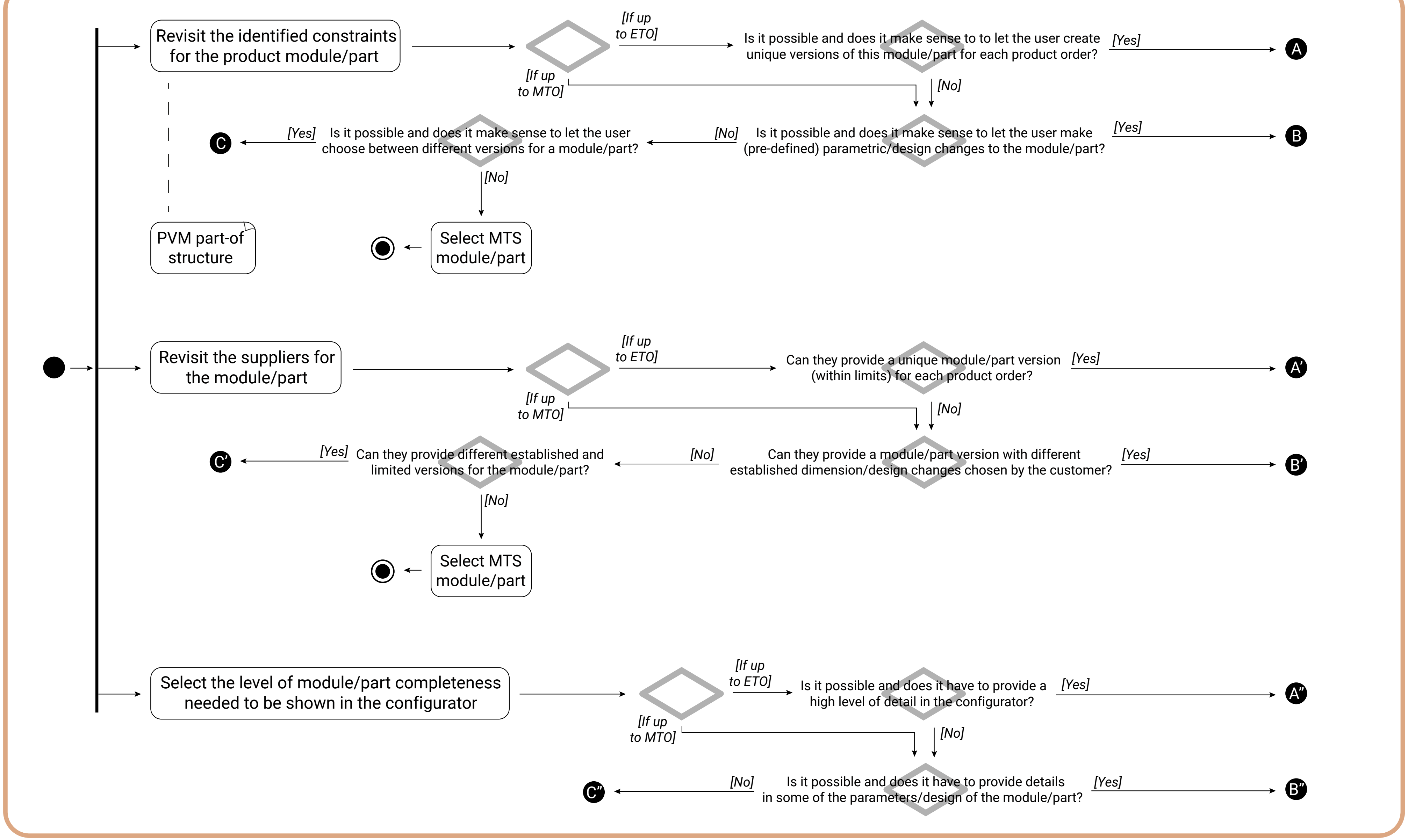


Figure 28: Framework phase 2 (ORGANIZE) guide (1/2)

Guide to help in the decision-making for the creation of the kind-of structure of the PVM

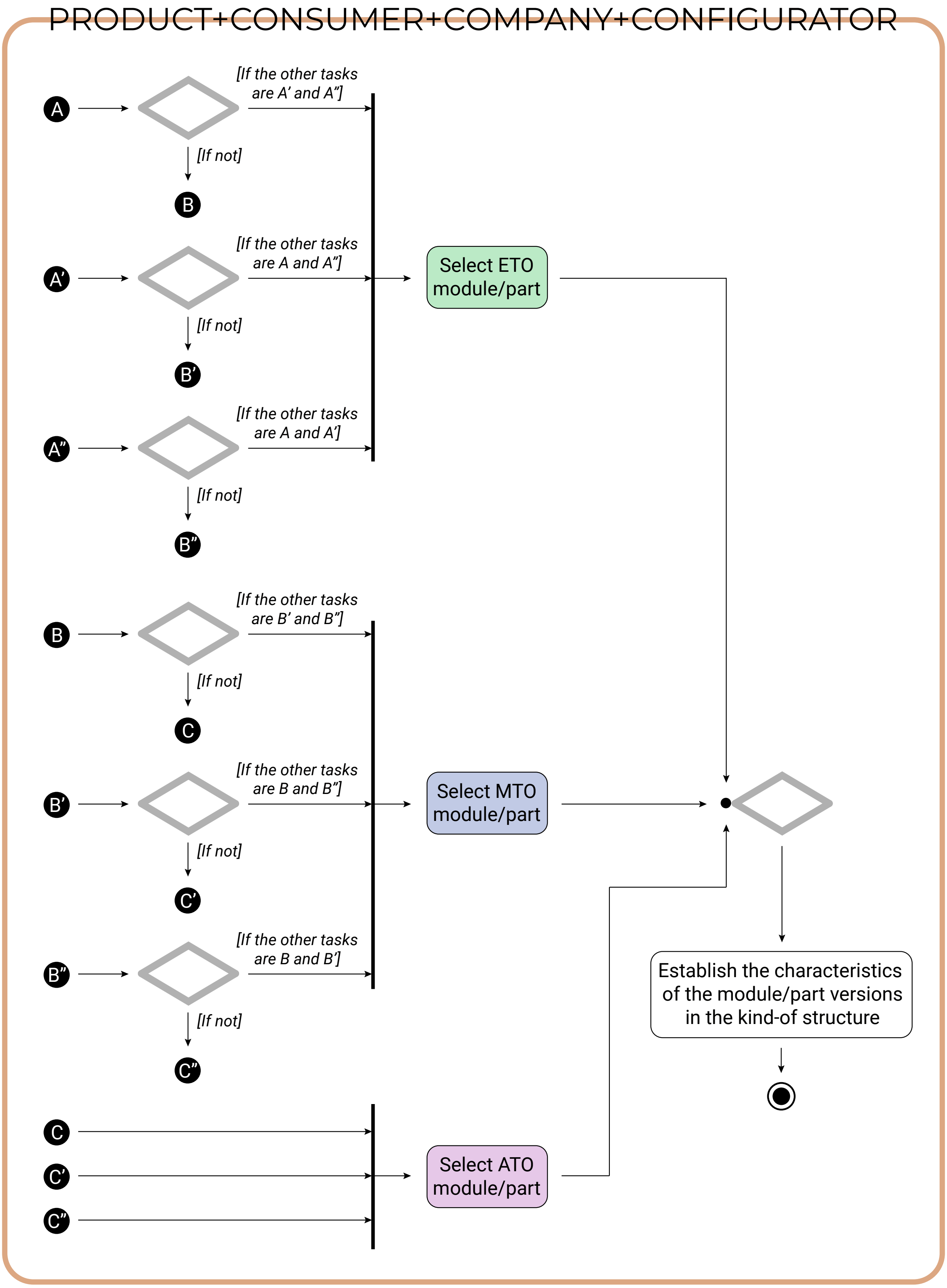


Figure 29: Framework phase 2 (ORGANIZE) guide (2/2)

The last concurrent task is related to the configurator and the level of part completeness that is shown in the configuration process. The part completeness is associated with the amount of detail of the module/part digital twin that is displayed to the customer when using the product configurator. If a high level can be achieved in which the module/part is modeled in detail and this is needed for the user to go through the configuration process, the diagram leads to the (A") start symbol. If it is possible and the module/part needs to provide details in some dimensions or other aspects, the (B") is attained. If not, the (C") start symbol is reached (figure 28).

Next, if all the previous outcomes are (A), (A') and (A"), the module/part is selected as ETO; if all the outcomes are (B), (B') and (B"), an MTO module/part is selected; and if they are all (C), (C') and (C"), the part is selected as ATO (figure 29). All three outcomes must finish in the same letter in order to select the business model for that module/part, if there are outcomes that end up in different letters, the less restrictive one is chosen due to the impossibility of achieving the more complex business model. For example, if the outcomes are (B), (A') and (B"), the one that ends up in (A') needs to be changed to (B') if the other ones can not be modified upwards to be able to select the MTO module/part. Afterwards, the kind-of structure of the PVM needs to be finished with the remaining modules/parts and the different versions have to be established. As previously described, this guide can be used for all the modules/parts that the company is unsure of to which business model they should be associated. It is advised to go for the most customizable level. If a module/part is selected for an ETO level, this part should also be able to fulfill an MTO and ATO approach based on the customer predilection, which is further explained in phase 4 (Adapt) (sub-section 4.2.4). This way, there is a higher amount of parts and designs reused and a higher standardization can be achieved.

Continuing to the next phase means that at least one of the modules/parts of the product for which the configurator is going to be used, can follow an either ETO (ideally) or an MTO approach.

4.2.3 Phase 3: Classify

The third phase of the framework (Classify) is associated with the process of determining the customer profile of each end user based on his/her level of knowledge and motivation. This phase is placed after phase 1 and phase 2 since it is only valuable for the company to learn how to classify the customer profiles for the different users once it has been established that the maximum level of customization is either up to MTO or ETO and that there are MTO and/or ETO modules/parts in the product to be configured. The reason for this is the adaptation of the configuration process described in phase 4 (Adapt) (sub-section 4.2.4) in which the outcomes from the first two phases and the one from phase 3 (the customer profile) are used as an input for the adaptation.
For the classification of the users, the Mamdani's fuzzy inferences method explained in sub-section 3.4.3 is meant to be utilized by the company. The possible customer profiles in this framework are either "beginner", "intermediate" or "advanced". Figure 31 shows a quick guide to help in the use of the Mamdani's fuzzy inferences method along with its 4 steps (A more detailed explanation

can be found in sub-section 3.4.3). As previously defined, the percentages shown in figure 31 and also in sub-section 3.4.3, are defined by the author and are based on the work from Fuerstner et al. (2012), Torres & Krishnankutty (2008) and the statement from Weinmann et al. (2011a) that define that the level of customer motivation is of more importance than the level of knowledge when determining the customer profile. Furthermore, an excel file (that can be found in Mamdani's automated excel and screenshot in figure 30) is created by the author with an automation of the method. It can be used by the company to quickly determine the profile based on the different answers. It is also possible for the company to alter the values and percentages in the different formulas, as well as some aspects of the questions or the resulting profiles (if for instance the maximum level of customization achieved in phase 1 is MTO) in order to adapt the method to its unique situation (with this version of the file: Mamdani's automated excel [edit version]). The regional format for the excel file to properly work should be "English (United States)". It should also be remembered to change from "visualization only" to "edit" mode in both files. In the third phase, the main pillar is the customer, since the main goal is the customer profile classification. Next, the 4 steps in the guide are briefly described:

1. The first step consists of the request to the customer to answer 4 questions with a numerical answer that can range from a minimum of 0 to a maximum of 1. These are asked to obtain his/her level of knowledge in the product and the product configurator (questions 1 and 2), and the level of motivation to go through the configuration process (questions 3 and 4). The answers result in four logistic variables (k, l, m & n) with different established numerical values.

2. The second step consists of the formulation of the implication operator for the logistic variables, which in this case a percentage product is used.

3. Step nº3 comprises the aggregation of all the previous conclusions into one. For this, the sum is used as an aggregation operator.

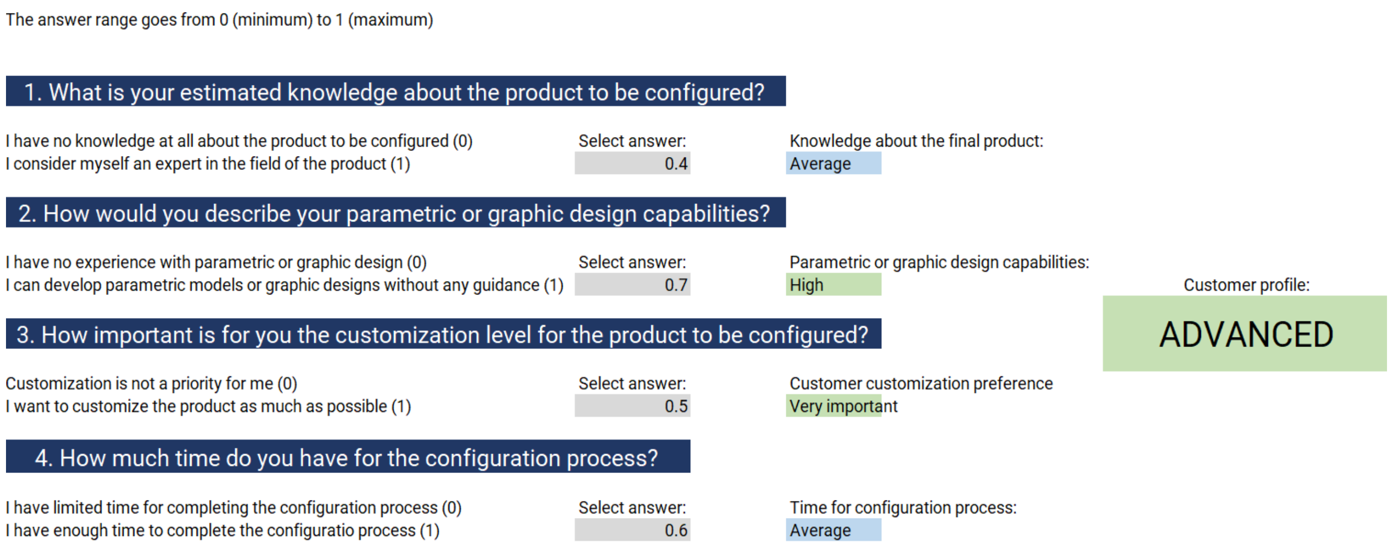


Figure 30: Screenshot of the excel file used to automate the Mamdani's fuzzy inferences method

Guide to help in the use of the Mamdani's fuzzy inferences method

CONSUMER+PRODUCT+CONFIGURATOR

Step 1: Ask and evaluate answers (x) from customers

1. What is your estimated knowledge about the product to be configured?
Knowledge about the final product: k

$$\mu_k(x_k) = \begin{cases} Poor\ (0{,}3) & 0 \leq x_k < 0{,}3 \\ Average\ (0{,}6) & 0{,}3 \leq x_k < 0{,}6 \\ Good\ (0{,}8) & 0{,}6 \leq x_k \leq 1 \end{cases}$$

2. How would you describe your parametric or graphic design capabilities?
Parametric or graphic design capabilities: l

$$\mu_l(x_l) = \begin{cases} Low\ (0{,}2) & 0 \leq x_l < 0{,}2 \\ Medium\ (0{,}6) & 0{,}2 \leq x_l < 0{,}7 \\ High\ (1) & 0{,}7 \leq x_l \leq 1 \end{cases}$$

3. How important is it for you the customization level for the product to be configured?
Customer customization preference: m

$$\mu_m(x_m) = \begin{cases} Irrelevant\ (0) & 0 \leq x_m < 0{,}1 \\ Important\ (0{,}7) & 0{,}1 \leq x_m < 0{,}5 \\ Very\ important\ (0{,}9) & 0{,}5 \leq x_m \leq 1 \end{cases}$$

4. How much time do you have for the configuration process??
Time for the configuration process: n

$$\mu_k(x_k) = \begin{cases} Poor\ (0{,}3) & 0 \leq x_k < 0{,}3 \\ Average\ (0{,}6) & 0{,}3 \leq x_k < 0{,}6 \\ Good\ (0{,}8) & 0{,}6 \leq x_k \leq 1 \end{cases}$$

Step 2: Establish and obtain conclusions (β)

$$\beta(y) = \begin{cases} 20\% & y = k \\ 25\% & y = l \\ 35\% & y = m \\ 20\% & y = n \end{cases}$$

Step 3: Aggregate all conclusions (z)

$$\mu_k(x_k)[\beta(k)] + \mu_l(x_l)[\beta(l)]$$
$$+\mu_m(x_m)[\beta(m)] + \mu_n(x_n)[\beta(n)] = z$$

Step 4: Deffuzify and obtain the customer profile (δ)

$$\delta(z) = \begin{cases} Beginner & 0 \leq z < 0{,}3 \\ Intermediate & 0{,}3 \leq z < 0{,}7 \\ Advanced & 0{,}7 \leq z \leq 1 \end{cases}$$

Figure 31: Framework phase 3 (SELECT) guide

4. Lastly, the fourth step obtains the customer profile by framing the previous outcome into a numerical value associated with the profile "beginner", "intermediate" or "advanced".

As previously stated, these 4 steps are explained in more detail and with more technical terms in sub-section 3.4.3, which can be reviewed for a better understanding. This guide is meant to be used as a quick help for the companies in the utilization of the Mamdani's fuzzy inferences method. As with the previous phase, if the maximum level of customization chosen in phase 1 is up to MTO, the possible customer profiles can only be "beginner" or "intermediate", thus in the case that a customer is classified as "advanced" it would be considered as "intermediate" for phase 4. It is suggested in this project for companies to create customer personas built from the target group to check what customer profile they would be assigned based on assumed answers that would recreate their journey map.

Once again, continuing to the next phase means that the company is able to identify the level of knowledge and motivation of its target group, and classify and frame the potential customers into different customer profiles that will determine the use of the product configurator.

4.2.4 Phase 4: Adapt

The last phase of the framework (Adapt) is about the company's arrangement of the customer configuration process based on the balance from the 4 pillars and the outcomes from the previous phases. Therefore, the main pillar in this phase is the configurator. Based on the maximum level of customization settled by the company in phase 1, the types of product modules/parts selected in phase 2 and the obtained customer profile in phase 3, the product configurator is adapted accordingly. After the questions that are asked to the customer, the configurator obtains the customer profile and then adapts the following configuration process based on this result. There are three configuration cases for this phase based on the customer profile and the outcomes from phase 1 and 2. These configuration cases are the main pieces of advice and guidelines given to the company resulting from the use of the framework. These guidelines (along with the rest of the advice provided in the framework) would be the ones used to fulfill the identified research gap from section 2.3. Figure 32 presents an activity diagram that illustrates the decision-making for the three cases and the corresponding following steps. These 3 cases are explained next.

1. If the customer profile is "beginner", the company can only let the customer follow an ATO approach in which he/she can uniquely proceed with the configuration of certain modules/parts established by the company by selecting among different module/part versions. This first case is possible for both cases This first case is possible whether the company has obtained an up to ETO level or an up to MTO level in phase 1. Accordingly, the selection for the customer between module/part versions is only available for the ATO and above (MTO and ETO) modules/parts selected in the kind-of structure of phase 2.

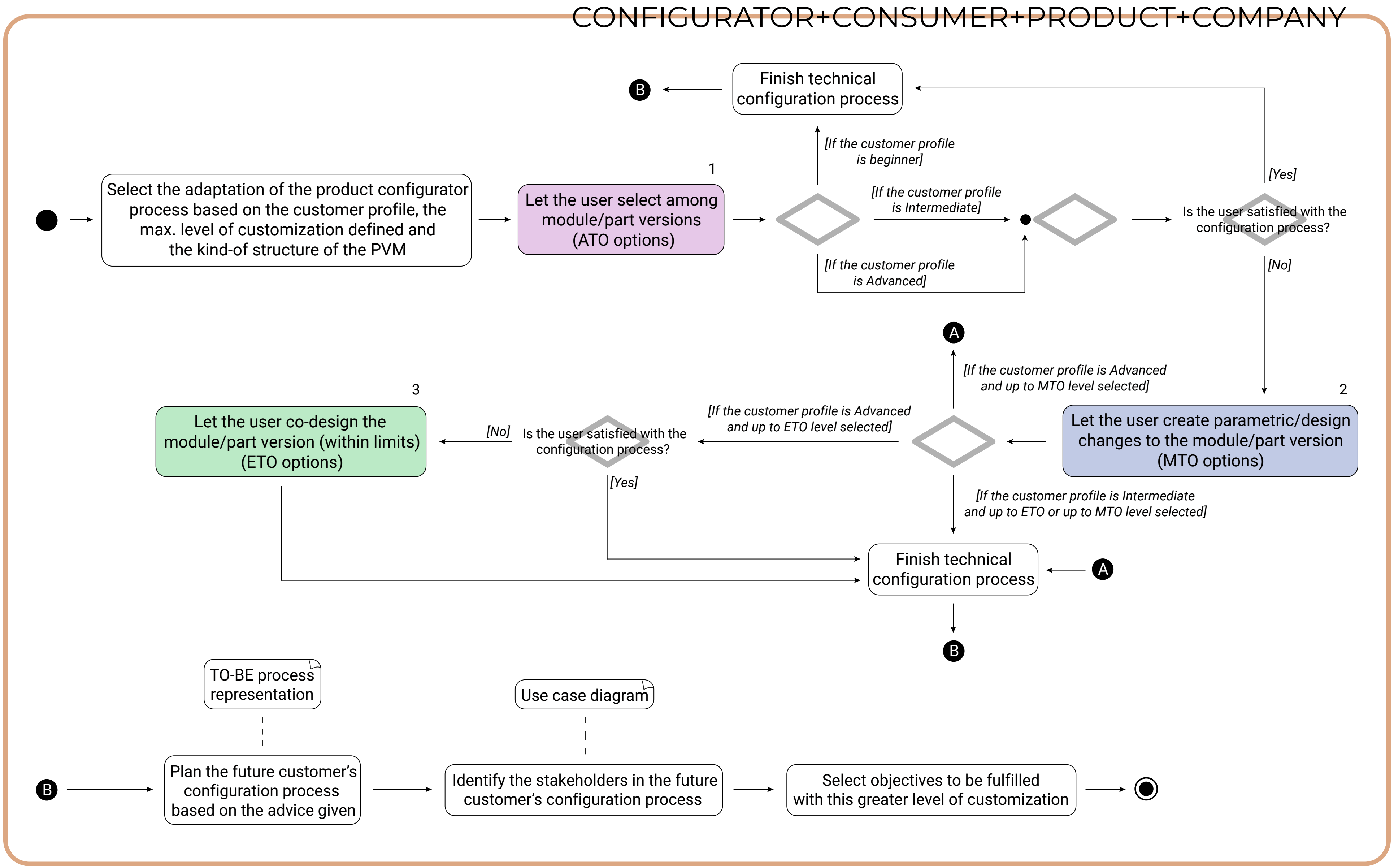


Figure 32: Framework phase 4 (ADAPT)

2. If the customer is considered to have an "intermediate" level, the company can let the user opt for the ATO approach just explained or select an MTO one if the customer is not satisfied with the configuration solution achieved with the first option. If MTO is chosen, the customer can create configuration changes to the selected module/part versions, which could be, for example, parametric adaptations or graphical changes to the version. These possible adaptations are predefined by the company, but they are not created and manufactured until the customer order is placed. This possibility is also available whether the maximum level of customization obtained in the first phase is up to MTO or up to ETO. Nevertheless, the user can only perform the parametric/design changes to the MTO and above (ETO) modules/parts selected in the kind-of structure.

3. Finally, if the obtained customer profile is "advanced", the company allows the customer to go through the same process as the "intermediate" profile and if the customization level still does not satisfy him/her, an ETO approach is followed. In this case, the customer can then create to some extent the module/part version inside the configurator (co-designing the module/part within the configurator) or outside the product configurator (e.g. the product configurator can have the option to upload a 3D model in different formats and once uploaded it is connected to the rest of the product in the configurator, it can let the customer upload a graphic design that is directly printed onto a part, etc.). The creation of this part, even though it is mainly developed by the customer, must remain within certain limits established by the company to assure the product's physical structure (E.g. a maximum diameter or height for a part) and comply with regulatory constraints. In this case, the ETO customization possibility is only available when the maximum level of customization obtained in phase 1 is up to ETO level and for the defined ETO modules/parts from phase 2 selected in the kind-of structure of the PVM.

The fact that a customer with an "advanced" profile is first given the option to start with an ATO approach and finish the configuration process there if satisfied, is related to the aim for a reusability strategy. This allows the possibility for the customer to engineer-to-order the final product to some extent, but this possibility is not directly proposed in favor of ATO or MTO options in order to save costs and intend for more standardization as defined in the literature. All this configuration process must be supported by a visual user-friendly interface for the product configurator in which most of the product modules/parts are presented as 3D models with the completeness level established in the last task of phase 2 (Organize) (sub-section 4.2.2).

After the three configuration cases regarding the adaptation of the product configurator are discerned, the company should then plan the future customer's configuration process based on the advice provided. For this, a TO-BE process representation is created. This future configuration process should cover the sales + technical stages of the product configuration process as it was already established in the second sub-activity diagram from phase 1. Afterwards, a use case diagram is utilized to identify the stakeholders that need to be taken into account to achieve the future customer configuration process established with the TO-BE process representation. Among these stakeholders, the customer or the suppliers should always be present since they are explicitly mentioned throughout the framework and are a direct input. Along with this, the objectives that the company wants to obtain with the development of this product configurator are established. This last task should be then revisited once the configurator is developed to check its effectiveness.

Once the framework has been used, the company should then have the necessary information to be able to plan a product configurator that can let the end user engineer-to-order the final product to some extent based on the balance of the 4 main pillars. It is important to state that the ETO possibilities are the maximum level of customization that can be achieved with this framework, but it also allows the prospect of obtaining only MTO possibilities, so that the framework can be used by a wider amount of companies. As described in phase 1, the company is aimed to always go for the maximum level of customization (up to ETO) when possible.

The product configurator to be developed varies for each company, but it can be mostly classified (based on the categories defined in sub-section 2.1.1) as an external, model-based, ATO/MTO/ETO, single-use, and interactive configurator.
External because it is used to assist the end user in the configuration of the product and, furthermore, also covers the sales and technical stage of the product configuration process.
Model-based because it uses logic and constraint-based approaches to obtain the configuration knowledge. ATO/MTO/ETO because the three main business strategies in the mass customization paradigm are included in the product configurator which is then adapted according to the customer profile.
Single-use because it is developed for the technical and sales-delivery process of a specific product of the company, and not for the whole product family; and interactive because it checks the configuration decisions of the customer and guides the user to create the correct ones.

4.2.5 Updated impact model

Chapter 4 marks the end of the Prescriptive Study (PS) stage of the DRM described by Blessing & Chakrabarti (2009) in section 1.3. The main goal of this stage is to develop support in a systematic way, reaching the defined goal and taking into account the results of the Research Clarification and the Descriptive Study I (DS-I). Another of the goals of the PS stage is the update of the initial impact model from section 2.3 based on the updated reference model created at the end of the DS-I (sub-section 3.5.2) and the developed framework.

This final and updated impact model (figure 33) is the one used for the evaluation plan of the Descriptive Study II (DS-II) stage in chapter 5. The key factor(s) and success criteria should, at this point, remain unchanged, but additional factors and links may have to be introduced to reflect and evaluate the possible effects of the developed support (Blessing & Chakrabarti, 2009).

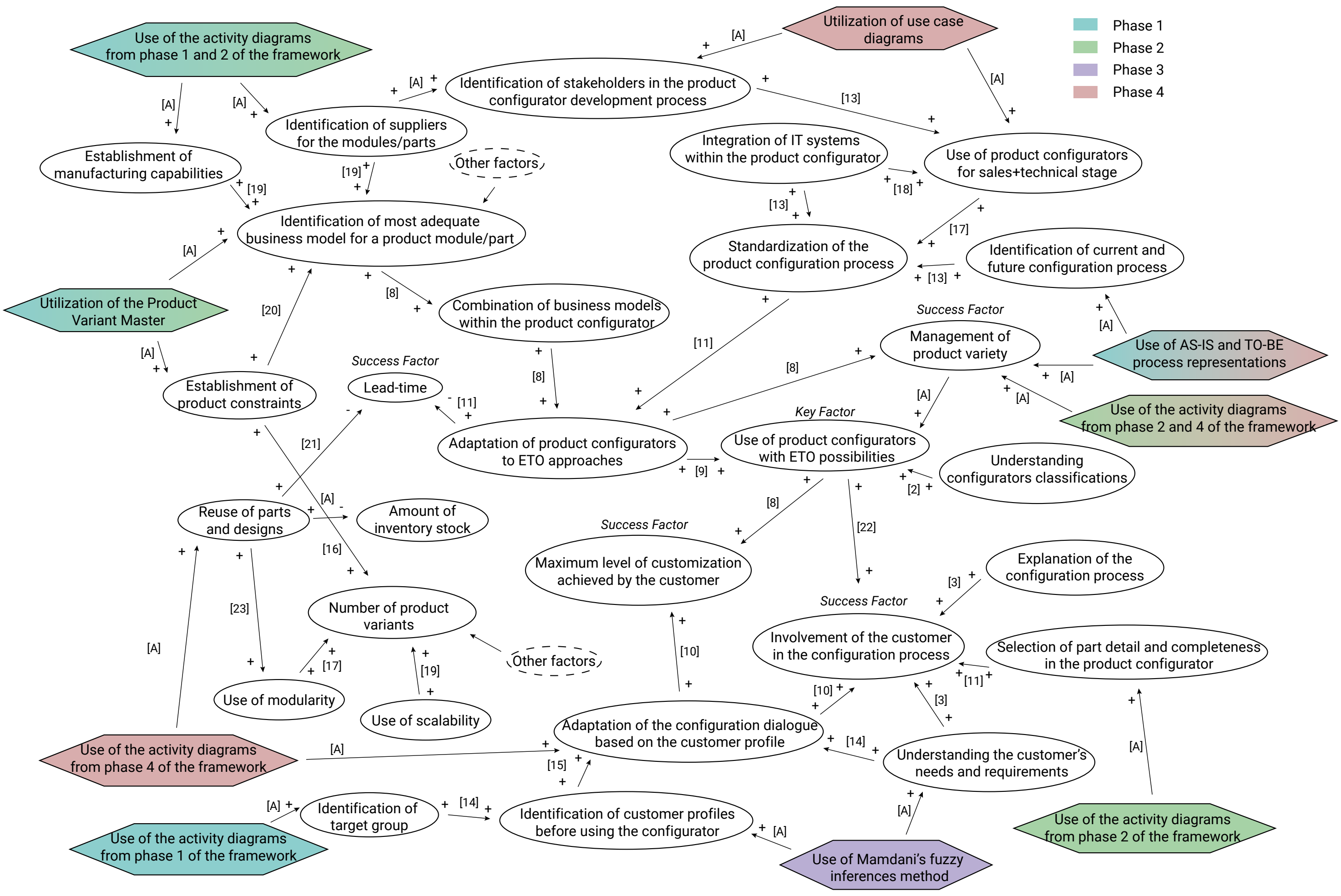


Figure 33: Updated impact model

The developed and selected supports in this project are:

1. The use of the activity diagrams from phase 1 of the framework.
2. The use of AS-IS and TO-BE process representations.
3. The use of the activity diagrams from phase 2 of the framework.
4. The use of the Product Variant Master.
5. The utilization of the Mamdani's fuzzy inferences method.
6. The use of the activity diagram from phase 4 of the framework.
7. The utilization of use case diagrams.

In figure 33, these supports are color-coded based on the phase of the framework where they are used. Some may be combined and therefore used in more than one phase. It is important to note that this color-coding does not have any relation with the color-coding from the updated reference model (figure 24) shown in section 4.1. Furthermore, the color-coding from figure 24 is not included in the updated impact model in order to focus on the outcomes of the framework and, thus, the Prescriptive Study (PS) stage of the DRM.
The expected results from these supports can be seen in the updated impact model and focus on, among others:

1. Better understanding the importance of the identification of the target group, the manufacturing capabilities or the suppliers, to also help with (5) and (6) results respectively.

2. Properly identifying the current and future configuration process to better manage the product variety and adapt product configurators to ETO approaches.

3. Better selecting the part detail in the configurator to improve the involvement of the customer and achieve a better management of the product variety.

4. Better establishing the product constraints and accurately identifying the most adequate business model for the modules/parts in order to better adapt product configurators to ETO approaches.

5. Properly identifying the customer profiles before using the configurator to improve the involvement of the customer in the configuration process.

6. Better adapting the configuration process based on the customer profile to achieve a higher level of customization, a bigger reuse of parts and design, and a better management of the product variety with the goal of accomplishing a better use of product configurators with ETO possibilities.

7. Correctly identifying the stakeholders involved in the configurator development process to ensure the use of the configurator in the sales and technical stage, and achieve better standardization of the product configuration process.

As described by Blessing & Chakrabarti, in the updated impact model, the key factor (in this case the use of product configurators with ETO possibilities) remains the same from the updated reference model, as well as the success factors. The desired values of the success factors (success criteria) also stay unaltered, which are achieving a higher maximum level of customization achieved by the customer, obtaining a better involvement of the customer in the configuration process, a reduction of the lead time and better management of the product variety. As described in the updated reference model (sub-section 3.5.2), the results of these success criteria in the updated impact model are the ones used to develop the success evaluation in chapter 5, and they are compared with the situation and statements of the preliminary key and success factors introduced with the initial reference model.

5. Case study and Evaluation

CASE STUDY & EVALUATION

5

Chapter 5 describes the application and the evaluation of the framework developed in chapter 4 in the case of a consumer good. For the selection of the product, a company has been chosen in which no product configurator is currently used, but aims at creating one in the future.

The goal of this chapter is to check the usability, applicability and usefulness of the framework by developing a case study for a real consumer good based on the decisions and capabilities of the company. Chapter 5, and also chapter 6, comprise the Descriptive Study II (DS-II) stage from the DRM by Blessing & Chakrabarti (2009) in which the developed support is evaluated. The decision-support framework is tested on the company and one of its products, but the product configurator is not actually developed afterwards due to a lack of resources to do so; it is only planned based on the company's capabilities to do so. Therefore, this chapter can be considered an Initial Descriptive Study II since, as described by Blessing & Chakrabarti (2009), the outcome from the support (the support meaning the framework and the outcome the corresponding product configurator that would be created based on its use) has not been developed and realized to the extent that the support can be applied by future users as intended, but the author wants to be able to evaluate at least some of its applicability, usability and if possible, its usefulness.

Section 5.1 describes the case study for the product. In section 5.2, the effectiveness of the framework is evaluated on whether the framework actually helps the company to plan a product configurator that can let the end user engineer-to-order the final product based on the customer profile. For section 5.2, an application evaluation and a success evaluation are employed. The information shared about the company in order to use the framework is provided during a workshop session in which the framework was tested.

5.1 Haverland - Radiator

Haverland (figure 34) is a medium-sized Spanish enterprise focused on the design, manufacturing and sale of different types of heaters and radiators. It was founded in 1971, and it has grown from being a small family company to an enterprise that sells products in more than 30 countries (Haverland-About us, 2021)

Figure 34: Haverland logo (Haverland-About us, 2021)

The author reached the company due to an internship performed with Haverland during the Bachelor's focused on product engineering and product design. It was established by the author that this company was a potential candidate for the application of the framework due to their intention of creating a product configurator and the potential customization of some of its products. In order to reach them, the author got first in contact with the human resources staff and then with the product engineering responsible.

Figure 35: RCWave+ radiator (Haverland-Product, 2021)

The product selected from the company is one of their best sellers: the RCWave+ radiator (figure 35), which is a heater manufactured with an inertia block of cast aluminum with properly calibrated shielded resistors (Haverland-Product, 2021).

The company does not currently a have product configurator of their own for the sale of this product, even though different variants of the product can be purchased by the customer. Furthermore, the product is only described on the company's website; the sales stage, where the variant is chosen and the price is shown, is performed on other external websites. It is in these other websites where product configurators are utilized to some extent. They can be considered as external (only sales), single-use, mainly ATO (some also work as MTS) and primitive configurators. Some of these external websites where it can be bought are, "storageheatersdirect.com" (figure 36), "mundocalefaccion.com" or "klimaelectric.com", among others. These websites utilize configurators of their own, only the product variants are established by the company. The framework is applied to Haverland and the RCWave+ on July 2021. As of September 2021, Haverland updated the website and now permits the user go through the sales stage in their own webpage. This addition is not taken into account in the case study.

There are other products in the company, like the WI and the RCW, that share most of the modules and parts with the RCWave+, but are sold as different products, and not as variants of the same one. This information is considered for the use of the framework.

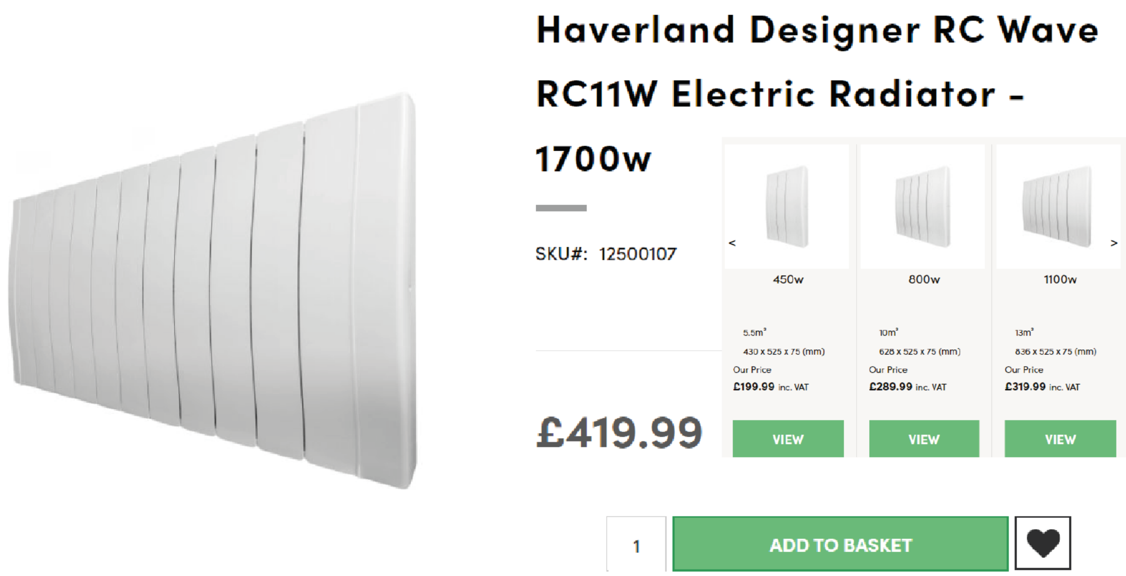


Figure 36: Sales stage on external website (Storageheatersdirect, 2021)

In order to apply the framework to this product, first, the framework manual (Appendix A) is sent to the company for them to gather all the necessary information, and then a workshop is organized to test the framework on the RCWave+ heater from Haverland. Therefore, all the decisions, actions and information explained in this section regarding Haverland are based on the company's own resolutions.
The workshop is performed with the product engineer responsible and the manufacturing specialist of the company in July 2021. The four phases of the framework are then followed for this product to check its applicability and usefulness.

5.1.1 Phase 1: Plan

The first phase is surrounding the plan of the company to select the maximum level of customization that Haverland is going to be able to achieve for the RCWave+ with the use of a product configurator. The seven tasks in the sub-activity diagrams are then described for the specific case of this product and company. The outputs are also represented graphically (based on phase 1 of the framework - sub-section 4.2.1) in figure 37 and figure 38.

1. The first task comprises the identification of the current target group for the product. The identified target group are male and female users with an approximate age of between 30 and 60 years, that want proper control of the heater and the possibility of connecting to it.
   It is established by the company that this current target group would greatly benefit from providing more customization possibilities when buying the product.
   By investigating the product line, it is also identified by the company and the author that the buyers from the WI product (that shares most of the modules and parts with the RCWave+) could be combined with the RCWave+'s target group. These buyers are of the same age range as the ones from the RCWave+, but look for a heater that is simple to use and that does not need manually programming from the user side. This last target group usually lives alone or with a partner, since the WI product has a sensor that can tell when the user is at home and learns from the daily user's activity to create the heating program, and this could be counterproductive for the sensor's self-learning if many people lived in the house where the heater is.
   Therefore, the current target group is suitable for the creation of a product configurator that could provide more customization and also the combination of this target group with the second one seems to also be beneficial. Thus, the company continues to the (A) start symbol of the activity diagram.

2. The next two tasks are related to the product configurator and happen concurrently. The first of the tasks comprises the identification of the product configurator integration with other IT systems in the company. In the case of this Haverland's product, the current integration is null, since there is not an actual product configurator developed. Nevertheless, it has been planned to create one several times, even though it did not come to practice in the end. For the planned product configurator, the main needed integration would be

*Maximum levels of customization: 1. Up to ATO (Average); 2. Up to MTO (High); 3. Up to ETO (Very High)

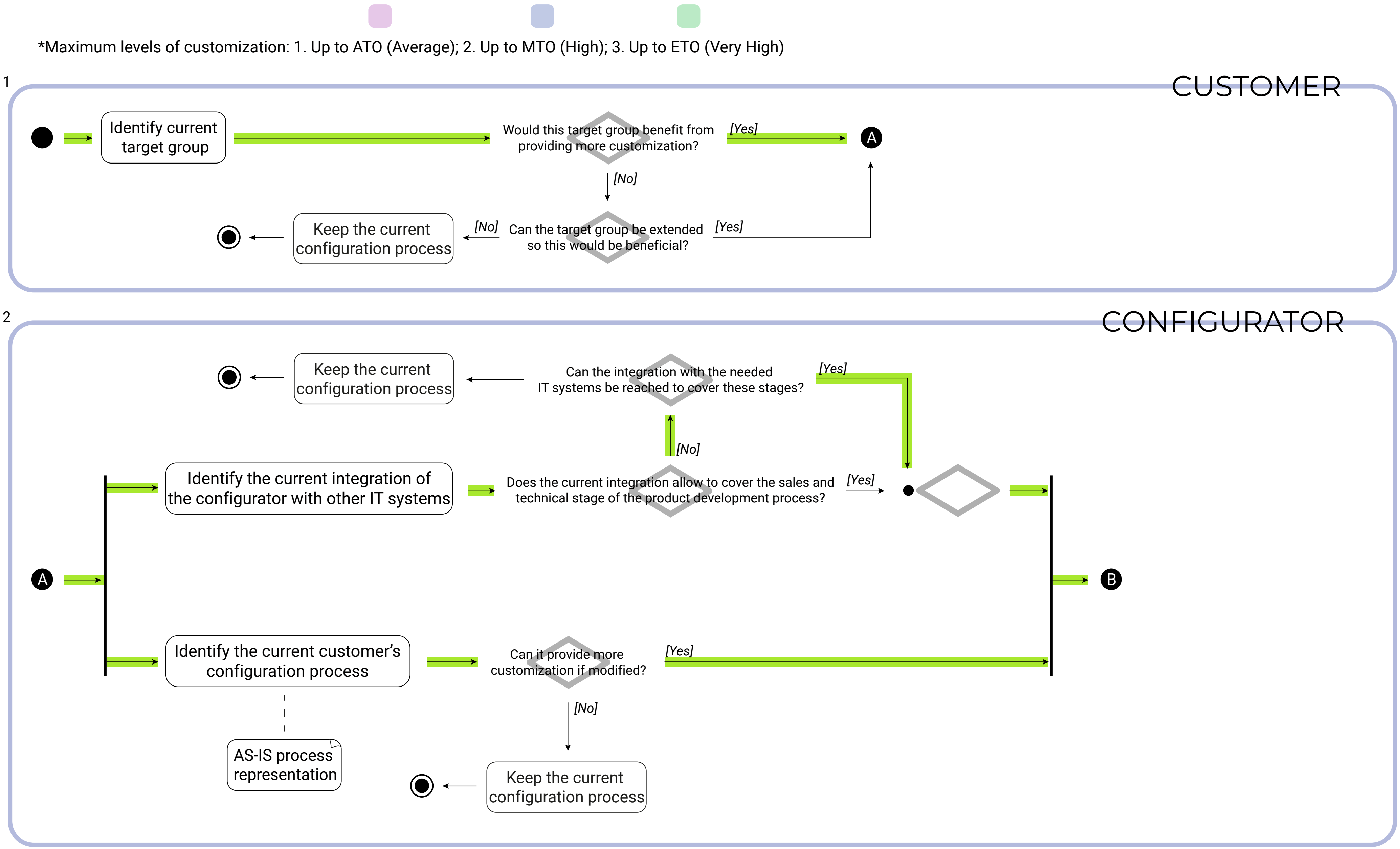


Figure 37: Framework phase 1 (PLAN) (1/2) for Haverland's RCWave+

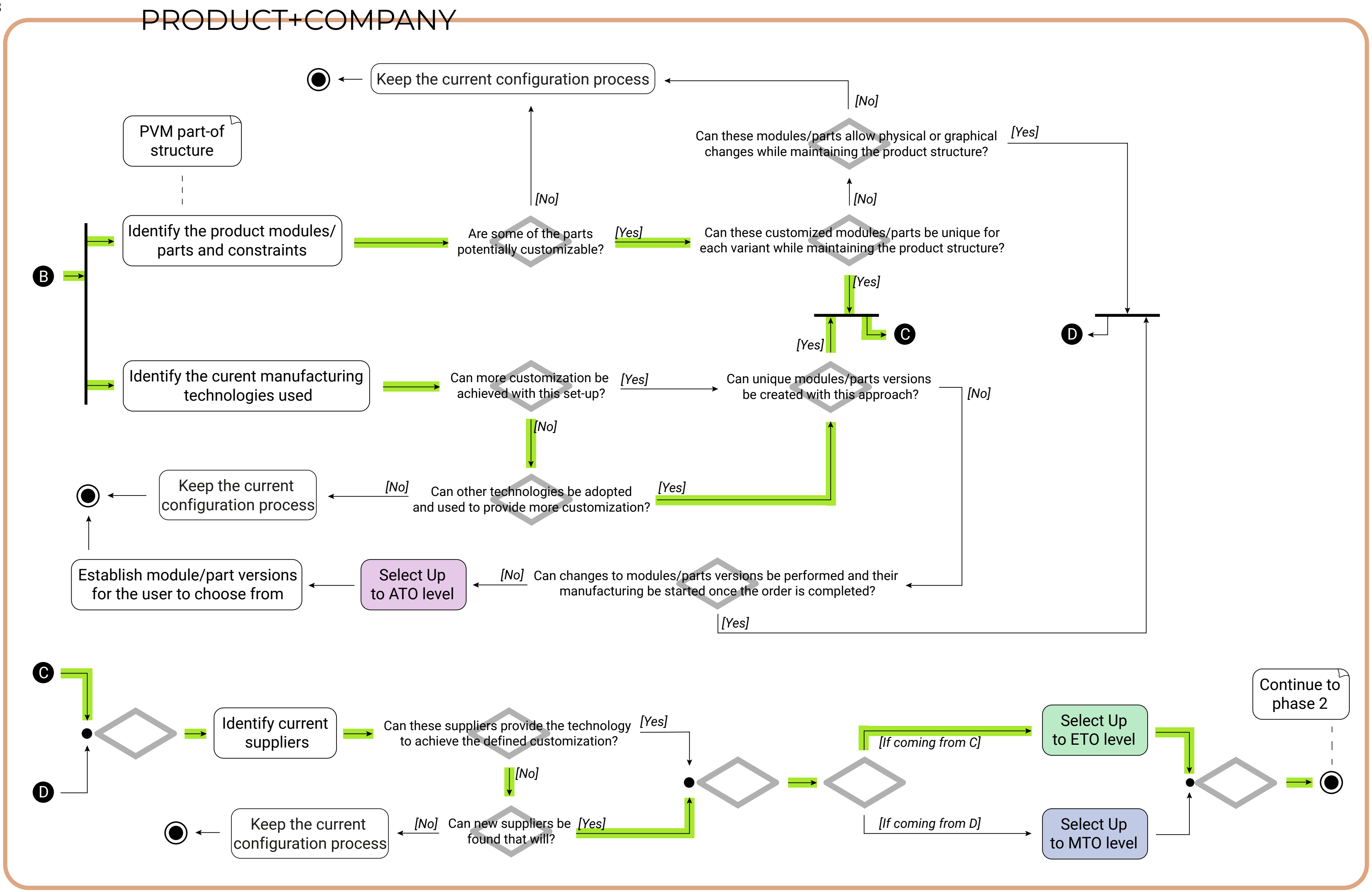


Figure 38: Framework phase 1 (PLAN) (2/2) for Haverland's RCWave+

with the current ERP system in the company. This system manages all the stock and sales of the products based on customer orders. Therefore, in order for the product configurator to be successful and cover the sales stage of the product development process, it would have to be fully integrated with the Enterprise Resource System. Furthermore, since the company aims to offer modules and parts of the product that can be customized by the customer, it is stated that the product configurator would also have to be connected with a CAD system. This way, the product configurator would cover both the sales and the technical stages of the product development process. The company then reaches the joint node of this sub-activity diagram.

The other task consists of the identification of the current configuration process that the user goes through. This is visualized with the creation of an AS-IS process representation (figure 39). As described in sub-section 3.4.4, to illustrate the workflow of the AS-IS and TO-BE process representations, activity diagrams are employed. In the case of the current configuration process for the RCWave+ from Haverland, the user first enters the company's website and looks for the type of product. If satisfied with what is found, the user can select a specific product to view its characteristics and check the different variants that are offered. Nevertheless, there is no current possibility to proceed with the variant selection and purchase of the product on Haverland's website. For that, the customer has to head to a seller website such

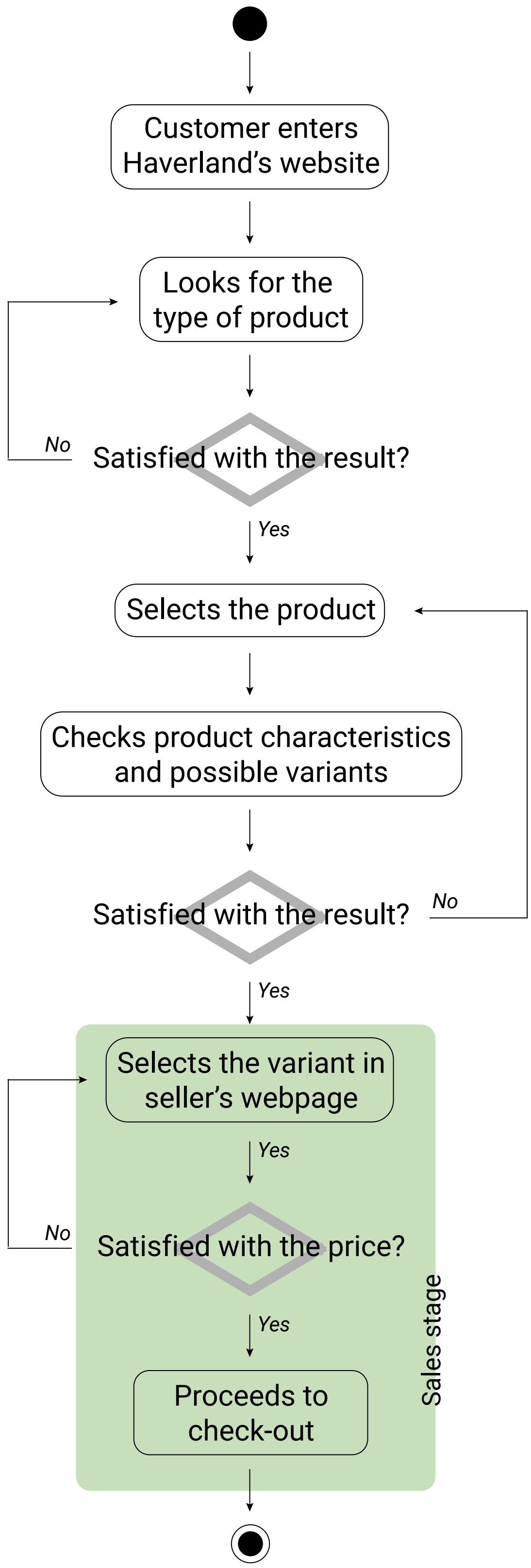


Figure 39: AS-IS process representation for Haverland's RCWave+ product

as "storageheatersdirect.com", as previously described, where the user can go through the sales stage. On this website, the customer can select the variant and check the respective price points. If satisfied with the selection, the user can proceed to check out and finish the purchase of the product. The price points for the different variants of the products are established by the sales staff of the company. These seller websites work as intermediaries for the e-commerce business of the company, since Haverland does not offer a product configurator of their own. Some of these seller websites work in an MTS model with Haverland and others in an ATO model. This is one of the reasons that the company accepted to try and use the framework, to see how they could create a product configurator of their own and what requirements this would entail. Therefore, it is stated that the current configuration process could be improved to provide more customization. Thus, both tasks reach the joint node and the (B) start symbol to continue using the activity diagram.

3. The next two concurrent tasks are part of the last sub-activity diagram of phase 1 and end up providing the maximum level of customization that Haverland can achieve. The first task consists of the identification of the product modules/parts and their constraints. For that, the part-of structure of the Product Variant Master is developed. In order to create the PVM, the ERP system of the company managed by the manufacturing specialist is used to observe the different modules and parts of the product. The knowledge from the product engineer who designed the product also played an important role in the creation of the PVM. The part-of structure of the PVM for the RCWave+ product from Haverland can be seen in figure 40. For this part-of structure, it is used as an example the product variant with 5 aluminum elements. The packaging module is included in their ERP system, but it is not shown in figure 40. The part-of structure of the PVM shows the generic structure of the product modules/parts and their relation. The different versions of the modules/parts are established later in phase 2 with the kind-of structure of the PVM. As described in the literature, to describe the constraints in the PVM, verbal, logical and calculation constraints can be utilized, as well as combination tables. Since the product to be analyzed does not have a big amount of modules/parts and constraints, the verbal approach is chosen. The main constraint in the product is the fixed relation between the aluminum blocks and the resistors. When the number of blocks is increased or decreased (different established variants), the resistors change accordingly to provide higher or lower power. The right, and left fairing module and the wall bracket module can be combined with any number of aluminum blocks. The bases for the right and left fairing modules are used to join these fairing modules to the central body. The controls' right fairing needs to have a minimum width and length to be able to store the thermostat module, the thermal limiter and the rest of the parts of the right fairing module. Furthermore, it also needs to include specific cutouts for the control keyboard, the switch and the hose. After developing the part-of structure, the company considers the possibility

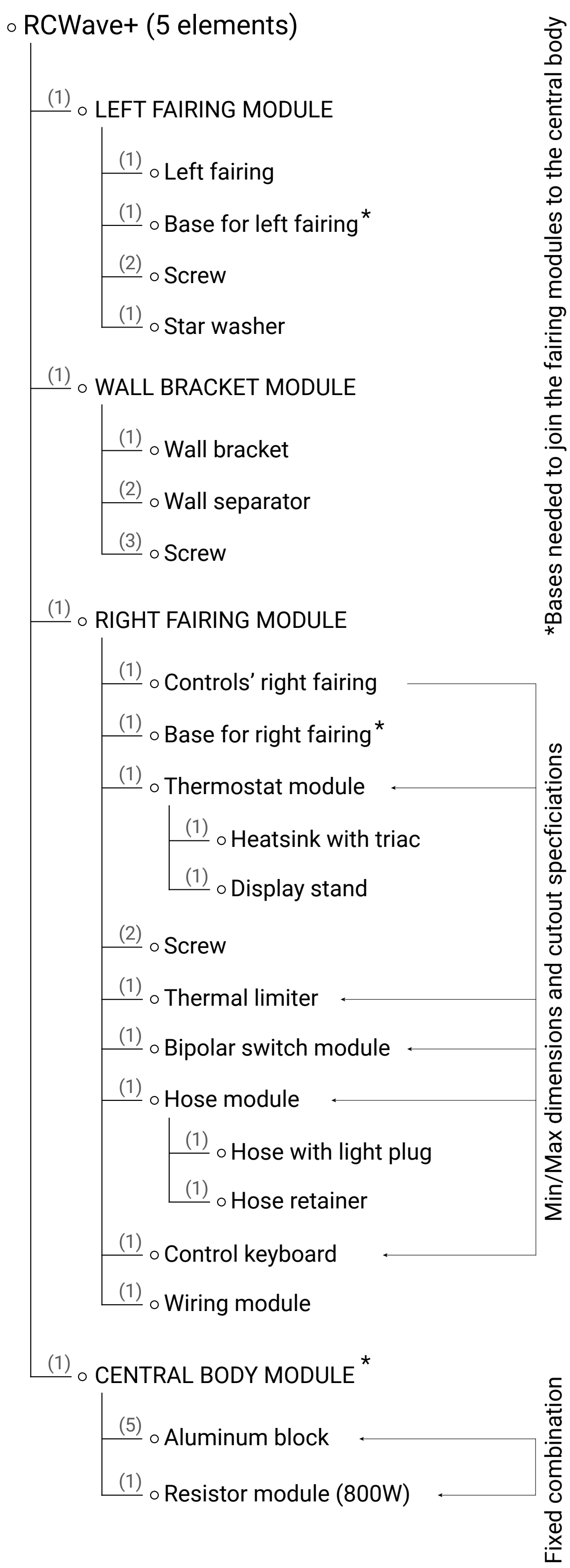


Figure 40: Part-of structure (PVM) of Haverland's RCWave+

of offering as module/part versions the different thermostat modules that can be found in either the RCWave+, the WI and the RCW, instead of selling them as completely different products.
It is in the left and right fairings that the company sees the possibility of offering a higher level of customization, since they consider that it is plausible to create unique versions of these parts for each product variant without altering the overall product structure. Therefore, the joint node that precedes the (C) start symbol is reached.

The other concurrent task consists of the identification of the current manufacturing technologies used by the company for the specific product. It can be considered for this identification that the main parts of the heater are the aluminum blocks, the resistors, the thermostat and the left and right polymer fairings. The rest of the parts are not considered in this task, since it is stated by the company (during this phase) that they most probably can not provide a higher level of customization. The aluminum blocks are manufactured through die casting; the tubular resistors follow different manufacturing techniques like coating, capping, soldering and wrapping; and the fairings are manufactured through injection molding.
With these current manufacturing technologies, it is established in the framework that it is not possible to achieve more customization. Nevertheless, other technologies are considered to achieve more customization. In this case, it is proposed by the company to use additive manufacturing for the creation of both the left and the right fairing. This approach could provide

unique part versions of the fairings for each customer order and therefore, increase the level of customization. Thus, the joint node before the (C) start symbol is also attained.

The sub-activity diagram is then continued with the identification of the current suppliers that are used by the company. For the case of Haverland's RCWave+, all the modules and parts are outsourced and only the final assembly is performed within the company's facilities. The names of the suppliers were not provided by the company, but it is established that, for instance, the thermostat module comes from either Portuguese or French suppliers, the finished aluminum blocks come from Italy or China, the screws and washers are bought from a Spanish supplier and in the case of the fairings, the mold is purchased from a Chinese supplier and the injection process is performed in Spain.
For the new manufacturing technology identified in the previous step, additive manufacturing suppliers have to be selected in order to produce the fairing part versions that would follow this approach. It is mentioned that new suppliers that can 3D print parts to an industrial level are already available and could be found, but they also remark that these 3D printed parts would also increase the overall price of the product compared to the injection molding approach. Nevertheless, this option is highly considered since they think that in the near future this will be the new norm and prices will drop for this type of manufacturing.

Therefore, the (C') start symbol is reached by Haverland, which means that the maximum level of customization that the company could achieve by the means of the product configurator is up to ETO, and this level of customization would be beneficial for the target group.

5.1.2 Phase 2: Organize

The next phase consists of the association of the different modules/ parts with the most appropriate business model (MTS, ATO, MTO or ETO) based on the company's capabilities, the customer's needs, the product constraints and the maximum level of customization selected in the first phase. Moreover, the identification of the different module/part versions according to this association is also performed.

For that, the Product Variant Master is finished with the creation of the kind-of structure, which can be seen for Haverland's RCWave+ in figure 43 and figure 44. Since the previous maximum level of customization selected was up to ETO, the modules/parts can be identified as common modules (MTS), customized modules (ATO & MTO), and/or personalized modules (ETO), as described in sub-section 4.2.2. The company can use the guide from sub-section 4.2.2 to help in the task of classifying a module/ part with the corresponding business model. In the case of Haverland and the RCWave+, the left and right fairings were the parts mentioned in the first phase to be more potentially customizable. Therefore the guide is used in the workshop for the classification of the controls' right fairing. The workflow of the guide's activity diagram is presented in this sub-section. The guide's outputs obtained for the right fairing are represented in figure 41 and figure 42, and

Guide to help in the decision-making for the creation of the kind-of structure of the PVM

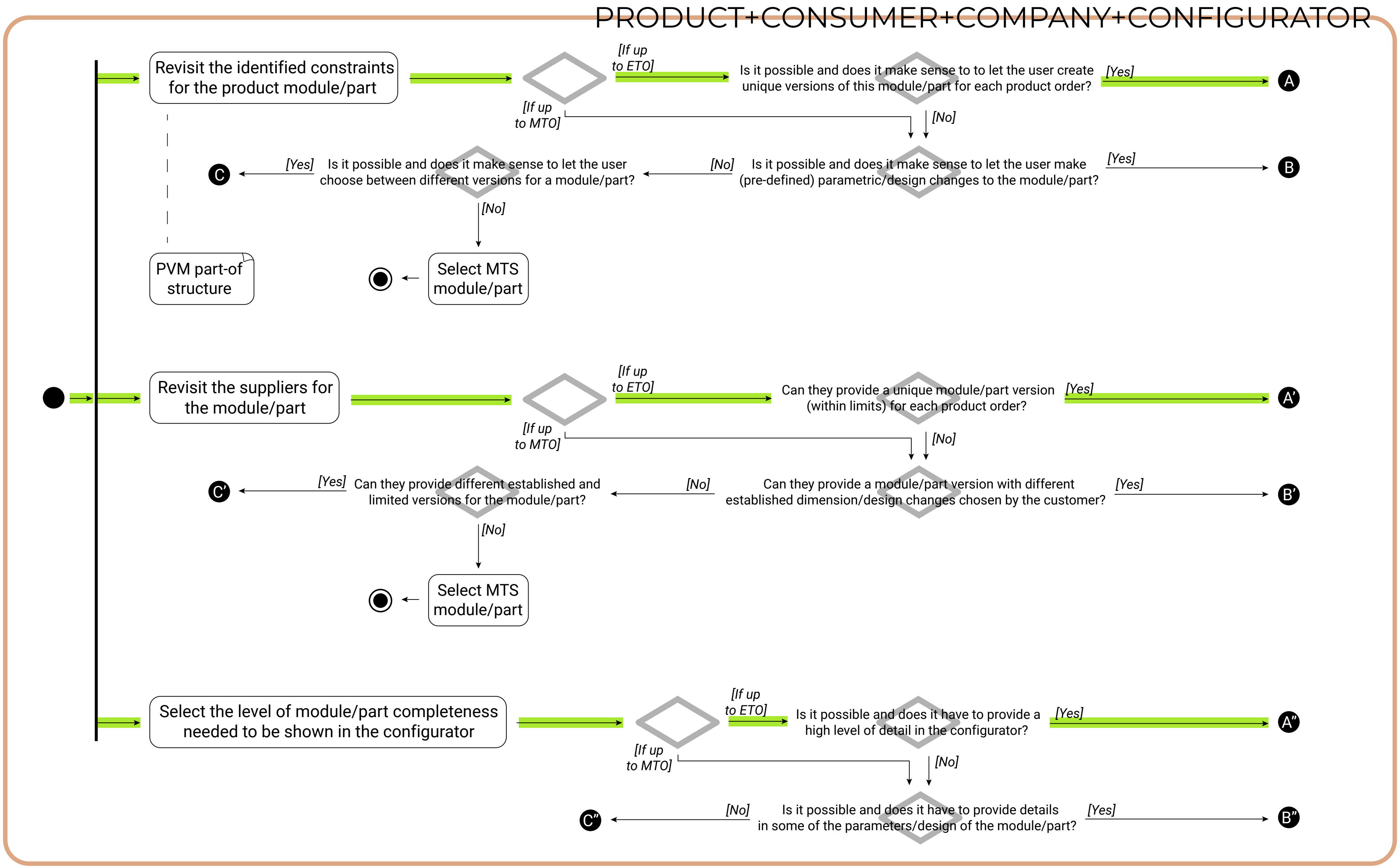


Figure 41: Framework phase 2 (ORGANIZE) guide for controls' right fairing (1/2)

Guide to help in the decision-making for the creation of the kind-of structure of the PVM

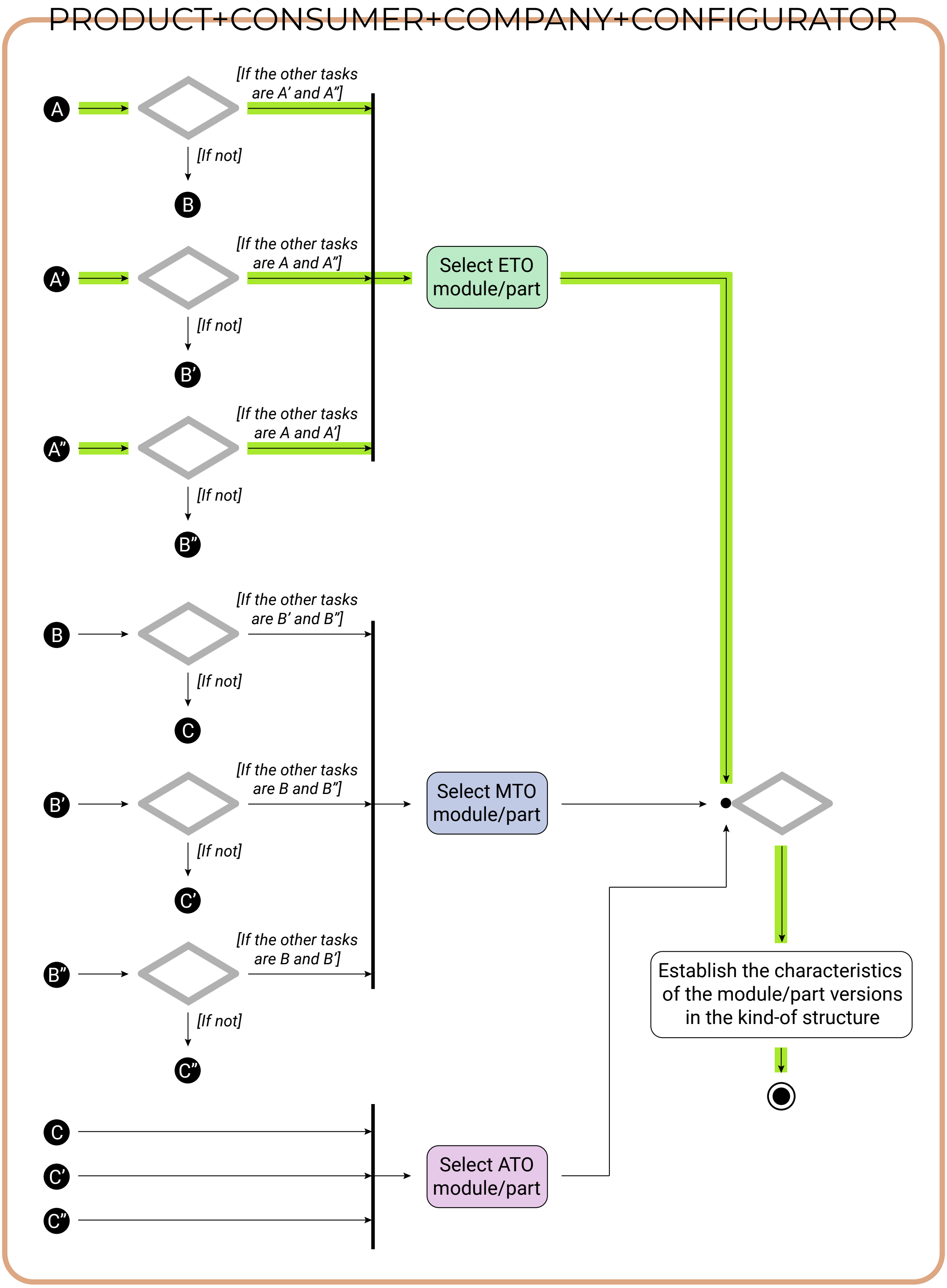


Figure 42: Framework phase 2 (ORGANIZE) guide for controls' right fairing (2/2)

are explained next:

There are three concurrent tasks in the guide's activity diagram. First, the previously identified constraints for the controls' right fairing are revisited. The right fairing is connected to the body of the heater through the base for the right fairing, therefore this connection needs to be maintained. The controls' right fairing also needs to store the thermostat, the thermal limiter, the hose and the wiring, thus there must be some minimum dimensions to fit them, as well as some maximum ones established by the company to limit the possible creations by the customers. Furthermore, this part has specific cutouts for the switch or the control keyboard that also need to be always present.
Therefore, even though there are certain constraints, it is established by the company that it is structurally feasible to create unique part versions for the right fairing. Furthermore, since it is one of the most visible parts of the product, it is the perfect candidate to provide the possibility to the customer of customizing it to a high extent. The company then reaches the (A) start node in the activity diagram.

The second concurrent task in the guide revisits the suppliers for the selected part. In the case of the right fairing, the current suppliers are the ones that create the mold (developed in China) and the ones that proceed with the injection (developed in Spain). It was stated in the previous phase that these current suppliers could not provide unique versions of the part for each product order, but the identified additive manufacturing suppliers would be able to achieve this goal. Therefore, the (A') start symbol is attained.

The third task is related to the product configurator and the digital representation of this part in it. In the case of the right fairing, it has been established that it is planned for the user to be able to create unique part versions. For that, the part needs to be 3D modeled and represented in the configurator with a high level of detail so the customer can have the possibility of modifying or co-creating it. Furthermore, it also needs to be modeled in detail in order to check the validity with the rest of the product structure, which in this case would be the connection to the base, the specific cutouts or the minimum dimensions. This task is related to the product configurator developer (and also the product engineer), that in the case of Haverland would have to be outsourced, since they do not have an employee on their staff capable of performing this task. Nevertheless, it is considered possible and the (A'') start node is reached.
Accordingly since the outputs of the tasks were the (A), (A') and (A'') start symbols, the controls' right fairing is finally selected as an ETO part. Next, the characteristics of the part versions need to be established (described below). It is important to remember that, as described in sub-section 4.2.2, If a module/part is selected for an ETO level, this part should also be able to fulfill an MTO and an ATO approach based on the customer profile (process defined in phase 4). This way, there is a higher amount of parts and designs reused and a higher standardization can be achieved.

Once the business model is selected, the different module/part versions are established. Figure 43 shows the kind-of structure for the right fairing module. The kind-of structure is also performed during the workshop with the product engineer responsible and the manufacturing specialist. The controls' right fairing

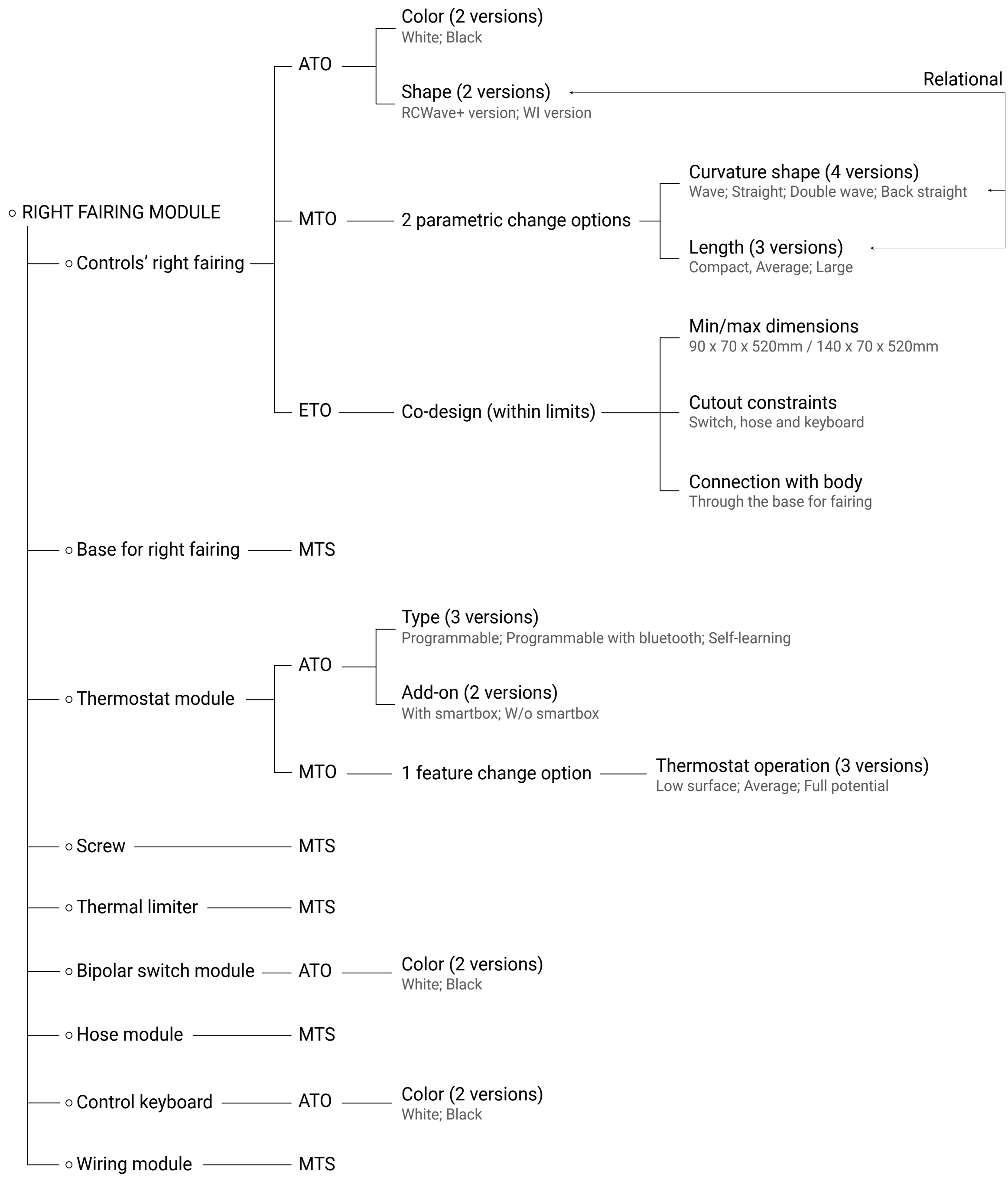


Figure 43: Kind-of structure (PVM) of Haverland's RCWave+ (1/2)

part is established as an ETO part as previously explained. The ATO option offers 2 configuration possibilities with different versions. The first one is related to the color of the part, for which the user can select either a white or a black version, and the other one is related to the shape of the part, which can be like the one on the RCWave+, in which the control keyboard is placed on top of the part, or like the one on the WI, in which it is placed on the front and the overall shape is more rounded.

For the MTO option, two different parametric changes are offered to the customer. The first one is related to the curvature shape, which can be with a shape of "wave", "straight", "double wave" or "back straight". This parametric change is related to the ATO shape possibility.

Naturally, if the user has selected the RCWave+ version in the ATO stage, the "straight" curvature shape in the MTO option would not create any change to the part since it would be the same version. This MTO option with the different established possibilities provide the user the perception that he or she is creating the part, but they are, in reality, designs previously established by the company which are built based on the customer's order. The other parametric change option is the total length of the fairing, which can be compact, average or large. Like in the previous case, the average one would be coincident with the ATO option.
Lastly, the ETO option offers the customer the possibility of co-designing the fairing within some limits. These limits are (1) minimum and maximum dimensions shown in figure 43, so the fairing can fit the required parts, (2) the cutout specifications for the switch, hose and control keyboard, and most importantly, (3) the connection to the base that has to be maintained no matter the shape of the fairing. All of the ETO options would be manufactured through 3D printing, as well as some of the MTO options.

Regarding the thermostat module within the right fairing module, it is established by the company as an MTO module, based on the potential customization established for this part in phase 1. The ATO option offers two configuration possibilities. One is related to the type of the thermostat, which could be the programmable one (currently offered in the RCW product), the programmable with Bluetooth (currently used in the RCWave+) and the self-learning one (the one used in the WI item). This way the company can combine and offer within the configurator three products that are currently sold separately but share most of the product parts with one another.

The second ATO possibility is whether to include a Smartbox, which lets the user control the heater from a distance and not only manually or through Bluetooth. The MTO option provides the user with one feature change option. The user can select between three different types of thermostat operation features that are predefined but have to be programmed to the thermostat once the product order has been performed. One is called "low surface" in which, as the name suggests, the thermostat makes sure that the surface of the aluminum blocks is always below 45ºC no matter the power. Another one is the average one in which the thermostat uses an automated "switch on and off" program. The third option is called "full potential" in which the surface temperature is not controlled in favor of achieving more heat.

The bipolar switch module and the control keyboard are both ATO modules/parts with one configuration possibility, which is the same color offering as the one on the fairing. The base, the screws, the hose module, the thermal limiter and the wiring module inside the right fairing module all follow an MTS approach since these parts are always present in all the product orders and can not be configured by the customer.

Figure 44 shows the kind-of structure for the rest of the modules in the product: the central body module, the wall bracket module and the left fairing module. In the central body module, the aluminum blocks have two ATO configuration possibilities, one is related to the same color options as the other modules and parts, and the other one to the number of predefined blocks that the user can select based on his/her needs. As established in the part-of structure (sub-section 5.1.1), the resistor module is connected

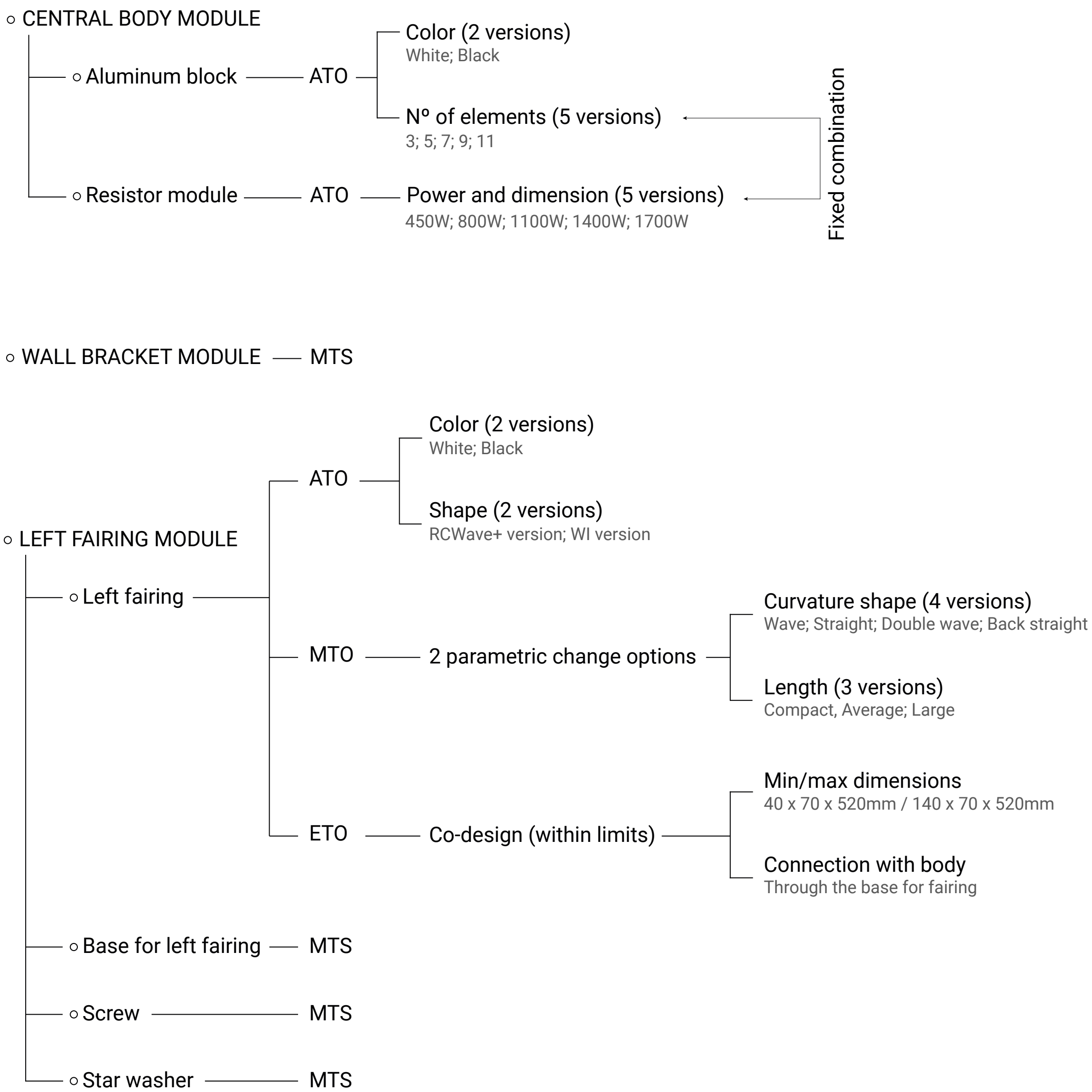


Figure 44: Kind-of structure (PVM) of Haverland's RCWave+ (2/2)

to the aluminum blocks in terms of combinations, and the 5 power versions of the resistors are based on the number of blocks selected.

The whole wall bracket module is established as an MTS module. For the left fairing module, the left fairing part shares the same specifications as the right fairing one except for the minimum dimensions in the ETO option and also the lack of cutout constraints due to not having to store other parts or have specific cutouts. The rest of the parts in the left fairing module follow an MTS approach.

Continuing to the next phase means that the kind-of structure is developed and all the modules and parts are associated with the different business models where at least one module/part follows an ETO or MTO approach. In the case of the RCWave+, the right and left fairing are ETO parts and the thermostat is an MTO part.

5.1.3 Phase 3: Classify

In this phase, the company is shown how to classify/frame the different users of the product configurator to be developed into different customer profiles based on their level of knowledge and motivation taking into account the outputs from the previous phases. This classification is only relevant when the company has obtained an up to MTO or ETO level in phase 1 (up to ETO in this case), and has identified at least a module/part as MTO or ETO in the phase 2, since these outputs, as well as the customer profiles obtained in this phase, are the ones influencing phase 4 (Adapt).

The Mamdani's fuzzy inferences method is used in this phase. As defined in sub-section 4.2.3, the company can choose to keep the questions and parameters of the Mamdany's fuzzy inferences method version created for the framework or can choose to alter some of them. In the case of Haverland and the RCWave+, the same questions, membership functions and operators are kept. Along with the framework manual, and as proposed in sub-section 4.2.3, in order to indicate to the company how the method works, two simple customer personas are created in the workshop to see what customer profile they would have based on their assumed answers to the different questions. These answers, and also the following actions from the personas described in phase 4 involve the journey map for this customer process. This is performed since no real feedback from customers can be achieved until the actual configurator is developed.

The two customer personas are based on the identified target group for the product. The first customer persona created by the company and the author is Julia, a 35 years old interior designer based in Canterbury, UK who lives in an apartment with her dog and is looking for a new electric heater for her living room. Julia proceeds to enter the product configurator to buy the RCWave+ and is prompted with 4 questions to answer before starting the configuration process. The questions, answers and her corresponding customer profile can be seen in figure 45. The excel file with the automated Mamdani's fuzzy inferences

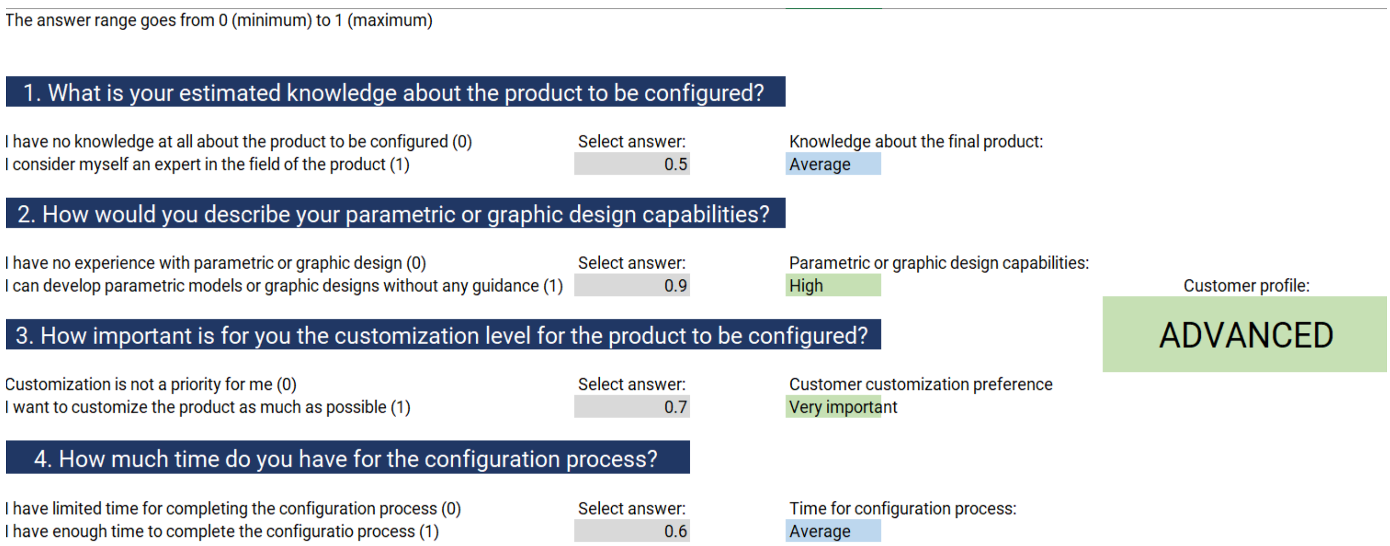


Figure 45: Screenshot of the excel file used to automate the Mamdani's fuzzy inferences method for the first customer persona

method (Mamdani's automated excel) is utilized to quickly identify the customer profile. For the first question, her answer is 0.5, since her knowledge of heaters is based on her previous experience with other models previously bought. Her answer for the second question is 0.9, since her graphic and modeling skills are very good due to her job as an interior designer. The answer to the third question is 0.7, due to the fact that Julia wants a customizable product that can fit in with the rest of the items in her living room. For the last question, 0.6 is selected, since she considers that she has some time for the configuration process, but does not want to spend a whole day on this task.

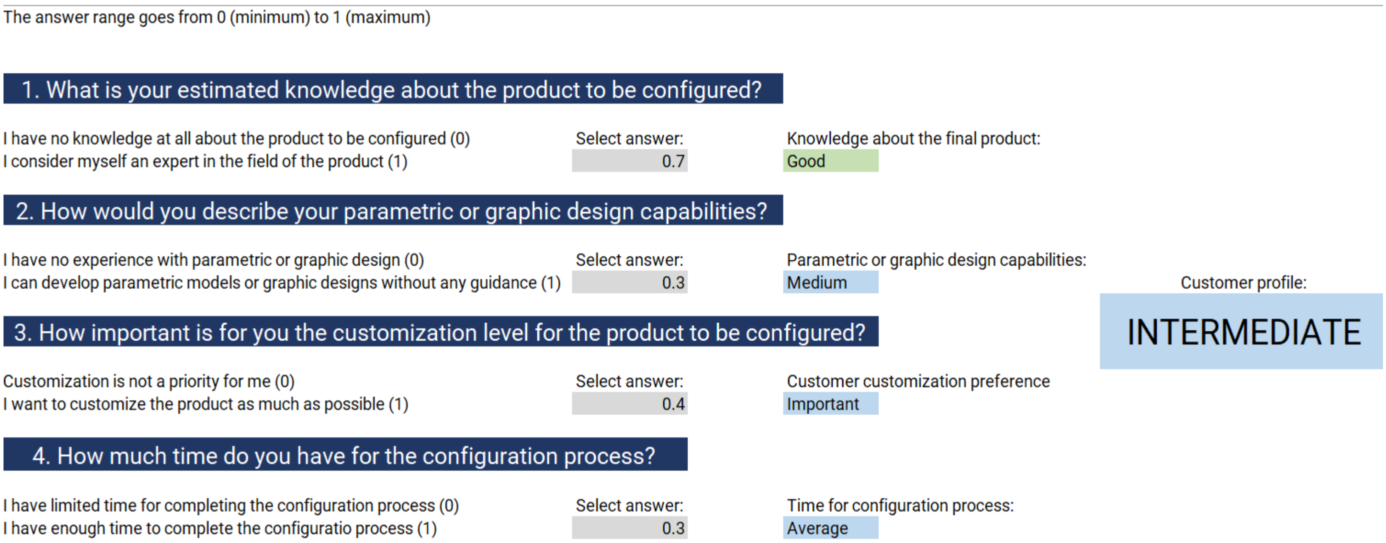
Then, based on the membership functions, percentages and operators established in sub-section 3.4.3, the corresponding customer profile for Julia based on her answers is "Advanced".

In the next phase, the consequences of obtaining one profile or another in the case of Haverland and the RCWave+ are further explained with the continuation of the journey map.

The second customer persona is Lucas, a 45 years old banker who lives with his partner in Galicia, Spain. He is looking for a new heater for their bedroom. The same 4 questions are asked to him before the configuration process. As before, the outcome of these answers can be seen in figure 46.

In this case, for the first question, Lucas answers with a 0.7, since he considers himself a handyman with the different appliances in his house. For the second question, his answer is 0.3, since he is not an expert in design. In the third question, he answers with a 0.4, due to the fact that he believes it is a good idea to have a customized product for their bedroom, but does not consider it a very important aspect. For the last question, Lucas answers with a 0.3, since he does not want to spend a long time configuring the product. Then, based on these answers, the customer profile for Lucas would be "Intermediate".

The third phase shows the company how to classify the customers and frame them into different profiles by means of an adapted Mamdani's fuzzy inferences method taking into account the previous


The answer range goes from 0 (minimum) to 1 (maximum)

1. What is your estimated knowledge about the product to be configured?

I have no knowledge at all about the product to be configured (0)
I consider myself an expert in the field of the product (1)
Select answer: 0.7
Knowledge about the final product: Good

2. How would you describe your parametric or graphic design capabilities?

I have no experience with parametric or graphic design (0)
I can develop parametric models or graphic designs without any guidance (1)
Select answer: 0.3
Parametric or graphic design capabilities: Medium

Customer profile:
INTERMEDIATE

3. How important is for you the customization level for the product to be configured?

Customization is not a priority for me (0)
I want to customize the product as much as possible (1)
Select answer: 0.4
Customer customization preference: Important

4. How much time do you have for the configuration process?

I have limited time for completing the configuration process (0)
I have enough time to complete the configuratio process (1)
Select answer: 0.3
Time for configuration process: Average

Figure 46: Screenshot of the excel file used to automate the Mamdani's fuzzy inferences method for the second customer persona

phases. Nevertheless, as in other tasks from previous phases, the framework is used to advise the company in the decision-making, it does not show how to actually program the different elements into the product configurator, since this would be out of scope for the thesis. The outcome from this phase is the capacity for the company to classify the users into three customer profiles based on the level of knowledge and motivation of the user, which in this case study is endorsed with the creation of two customer personas.

5.1.4 Phase 4: Adapt

The last phase of the framework shows the company guidelines in the case of the three configuration cases presented in sub-section 4.2.4. These configuration cases are based on the balance from the 4 main pillars that result in the outcomes from the previous phases. In the case of the RCWave+ and Haverland, the two previous personas created in the third phase are used during the workshop to illustrate what their hypothetical customer configuration process would look like based on their corresponding configuration case, finishing this way their journey map.

To summarize the outcomes from the previous phases of the framework, the company obtained in the first phase a maximum level of customization of up to ETO. Then, in the second phase, the modules and parts are divided into the different business models with the kind-of structure of the PVM, in which two of them are selected as ETO parts. Afterwards, in the third phase, the Mamdani's fuzzy inferences method is understood by the company and two hypothetical personas are created. Finally, in this last phase, the guidelines for the three configuration cases used to adapt the product configurator are presented to the company. The customer configuration process is based on the customer profile and the outcomes from the two other phases. It is then adapted to fit the requirements of the customer, provide an adequate involvement with the product configurator, avoid possible configuration process abortions and match with the capabilities of the company, the configurator and the product.

The assumed customer configuration process for one of the created personas (Julia) would match the third configuration case presented in sub-section 4.2.4. The following hypothetical statements of the journey map are defined by the company and the author during the workshop. In the case of Julia, as established in the previous phase, her customer profile is "Advanced". She first starts with the configuration of the right fairing module, and, more specifically, the controls' right fairing part. She first selects, between the ATO configuration possibilities, the black part to fit the furniture in her living room, and the RCWave+ shape, because she wants the control keyboard to be on top of the part. Since her profile is "Advanced", the product configurator then asks her if she is satisfied with the customization for that part or wants to customize it to a higher extent, for which she answers positively. The configurator then unlocks the MTO configuration possibilities, in which Julia changes the parametric option of the curvature shape from "average" to "double wave" and the length to "large". Once this is performed, due to her "advanced" profile, the configurator asks again whether the customization level is satisfactory for her or wants to customize the part more. Julia selects again the possibility of customizing it further. Once this is done, the product configurator shows the ETO configuration possibility of co-designing the part. The limits for the creation of the 3D model are shown to Julia in the configurator. Then, she proceeds to 3D model the part (outside of the configurator) and uploads it to the product configurator. If it is valid with the established limits and the product structure, the configuration process can be continued.

The next module/part that can be configured from the right fairing module is the thermostat module. From the ATO configuration possibilities, she chooses the programmable thermostat with Bluetooth and chooses not to include the Smartbox, since she considers that it is enough to control it from a short distance with Bluetooth. She also checks the MTO configuration possibilities for which she selects the "low surface" option, since she considers that it is the best option to assure the safety of the dog that lives with her. The rest of the customizable modules/parts of the right fairing module are the bipolar switch and the control keyboard that only offer ATO configuration possibilities for which Julia chooses the black version to go in accordance with the controls' right fairing.

Regarding the body module, Julia selects the black version once again and uses a heating calculator, currently included in Haverland's website (Haverland-Heating calculator, 2021) and that would also be included within the configurator, in order to see the amount of aluminum elements and power she would require for her living room. After using the calculator, it is established that the ideal heater is the 7 elements one with 1100W resistors. The last configurable module is the left fairing module in which the only customizable module/part is the left fairing. In the case of this part, Julia chooses the same options as for the right fairing part and creates a symmetric version to match with the other one. After this step, the configuration process would be complete for Julia and the final price would be shown to her in order to proceed to the check-out.

In the case of Lucas, the assumed customer configuration process would be related with the first configuration case presented in sub-section 4.2.4. His customer profile is "intermediate", thus he can only select up to MTO configuration possibilities, not ETO ones. In the right fairing module, Lucas selects within the ATO configuration possibilities the white version and the WI shape. As well as with Julia, the configurator asks him whether he is satisfied with the configuration of the part or wants to keep customizing it. In the case of Lucas, he is content with the customization of the right fairing part and does not continue with the MTO configuration possibilities. Regarding the thermostat module, he selects the self-learning version in order to facilitate the usage of the heater and without the Smartbox add-on. Once again, due to not having a long time for the configuration process, he continues with the use of the configurator without checking the MTO configuration possibilities. For the switch and the control keyboard, he opts for the white version. In the case of the body module, he chooses the same color and also uses the heating calculator to check the amount of power he would need for his bedroom, which in this case is a 800W resistor module with the 5 aluminum elements. Finally, regarding the left fairing module, he chooses the same options as for the right one. After that, the technical configuration process would be over for Lucas.

The creation of the customer personas and their journey map in phases 3 and 4 is used in the workshop to better explain these phases to the company even though it is not necessary in order to implement the framework. It has been stated in this phase, and in previous sections, that even if a customer has an "Intermediate" or "Advanced" customer profile, he/she can be satisfied with the ATO configuration possibilities and not reach the MTO or ETO approaches. As explained in section 4.2, this is performed in order to try and achieve a higher standardization in the configuration process and a bigger reusability of parts and designs that can also save costs to the company.

After presenting the guidelines in the case of the three configuration cases, the framework is concluded with three tasks, which are the result of the use of the framework. The first one is the creation of the future configuration process that the user would go through with the creation of the product configurator. For that, a TO-BE process representation (figure 47) is created considering the current configuration process (figure 39) and the guidelines provided. This TO-BE process representation is developed during the workshop in July 2021. In this future configuration process, the customer enters Haverland's website and looks for the product. Once found, the customer enters an adapted product configurator on the Haverland's website based on his/her customer profile (process explained in phase 3 and phase 4). Then, the client chooses, modifies and/or creates the module/part versions established by the company (depending on his/her customer profile). This is connected with the integration of the CAD system which would have two goals: (1) validating the design so it is in order with the rest of

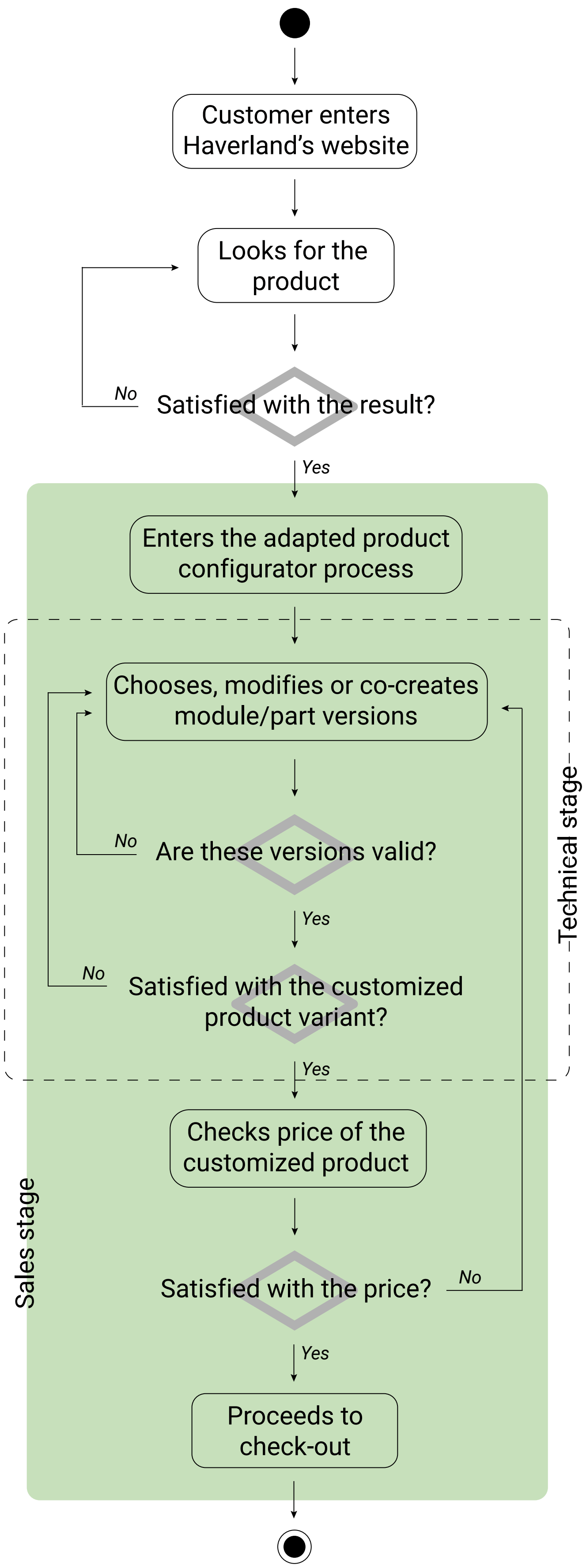


Figure 47: TO-BE process representation for Haverland's RCWave+ product

the product structure and in accordance with the product constraints; and (2) providing the possibility to directly use the developed 3D model as a final model for the supplier to 3D print the part. The 3D modeling of the module/part would be done outside the configurator and then uploaded onto it. Afterwards, the created part would have to be validated. If the configurator confirms that the versions are valid with the rest of the product structure and the customer is satisfied with the product variant, the final price is displayed. If content with the price, the customer proceeds to check-out to finish the purchase. This product configurator can be considered a sales+technical configurator, therefore it would be valid according to the second sub-activity diagram (figure 37) from the first phase.

The second task is the creation of a use case diagram for the identification of the involved stakeholders in the future configuration process. For that task, a use case diagram (figure 48) is created in which the customer's product configuration process is displayed. The use case diagram is also generated during the workshop. The main use cases of the customer (in the sales + technical stages) are included as well as their association with other use cases and actors (stakeholders). As it can be seen in figure 48, the main stakeholders identified in the case study that would be involved in the product configurator process for the RCWave+ are (apart from the customer), the product engineer, the manufacturing specialist, the product configurator developer, the supplier and the sales staff.

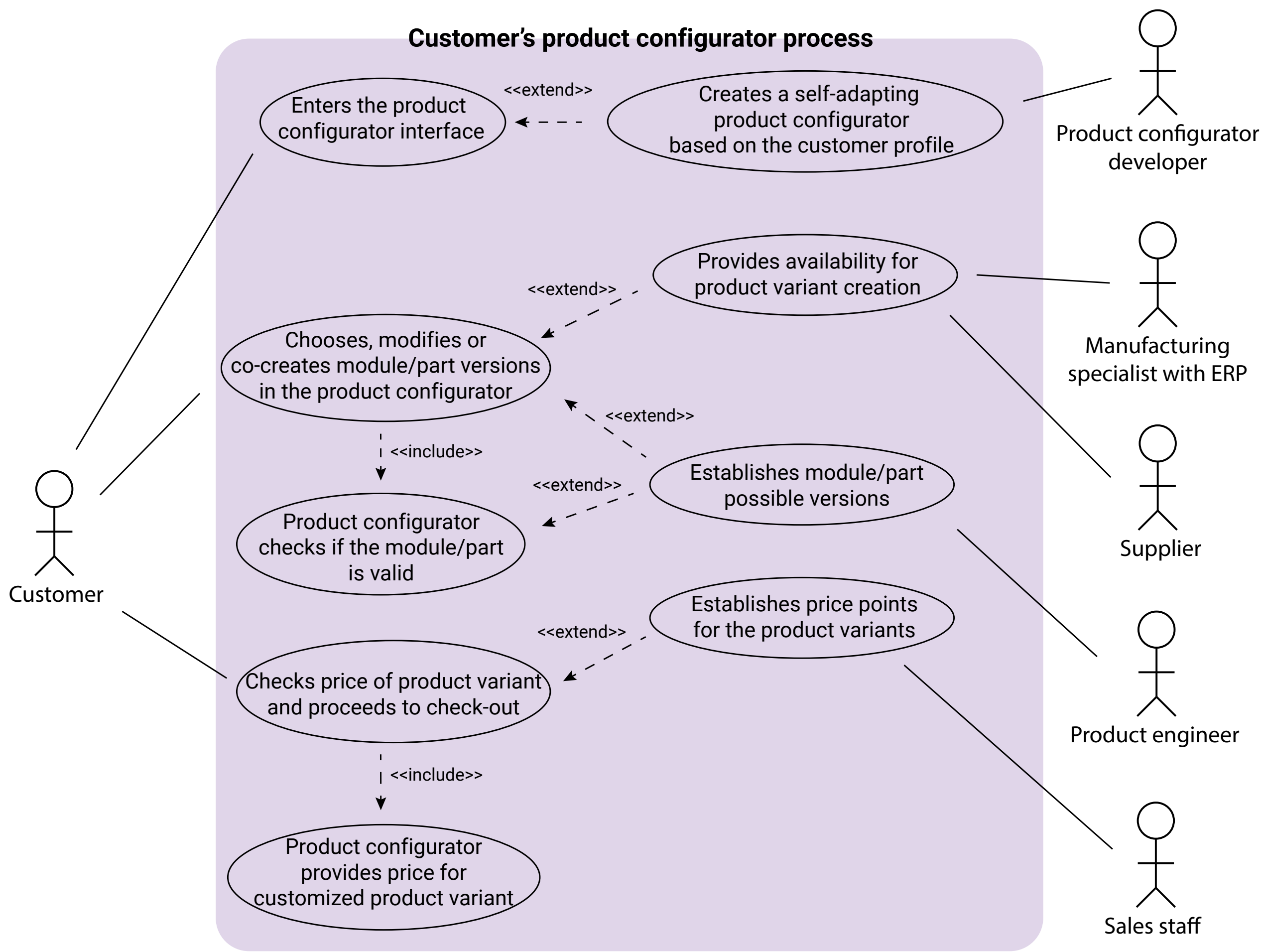


Figure 48: Use case diagram for Haverland's RCWave+ product

As described in sub-section 3.4.4, when "include" is used, one of the use cases is conditioned by another one to be performed, it denotes a full dependency to another use case. In the case of "extend", the association is an addition to a use case, not always dependent on the other every time the first use case is performed.
The initial use case of the customer is entering the product configurator interface. For this task, the product configurator developer has had to program a configurator that can be adapted to the profile of the customer (phase 3 and phase 4 of the framework helps with the planning of this process).
The customer also chooses, modifies or co-creates the product versions based on the customer profile. For this to be performed, the product engineer has to previously establish the different possible module/part versions including, to some extent, those which work in an ETO environment and that are different for each product order. Along with this, the manufacturing specialist has to provide and plan, along with the supplier's information and the ERP system, the availability of the product variants to be manufactured. Every time the user chooses, modifies or co-creates a module/part version, the product configurator checks if that version is valid based on the constraints defined by the product engineer.
The last of the customer use cases described in this use case diagram is checking the price of the configured product variant and proceeding to check-out if satisfied. The sales staff needs to establish the different price points for the various product variants, including those where some modules/parts are created in an ETO environment and can vary in each order. The product configurator then displays the price to the customer based on the information provided by the sales staff.

The last task of the framework is the establishment of the objectives that the company aims to fulfill with the development of this planned product configurator. In the case of Haverland's RCWave+, there are 5. Some of them are taken as an inspiration from table 5, which is also included in the framework manual (Appendix A), and others are established by the company. These are: (1) being able to provide more customization, (2) achieving a better sales and market's differentiation, (3) being able to listen better to the voice of the customer, (4) providing exclusivity and empowerment to the user and (5) improving the communication between departments in the company. These objectives should then be taken into account when actually creating the product configurator and to assess it once it is being used.

After displaying the guidelines and obtaining these last results, the use of the framework would be finalized by the company. The different guidelines presented to the company with the framework are based on the balance of the capabilities of the four main pillars and used to deliver further customization to plan a product configurator that can let the end user engineer-to-order the final product.

5.2 Evaluation

As described by Blessing & Chakrabarti (2009), in most design research projects only demonstrators or concepts are available. The project and thus the evaluation is aimed at obtaining a proof-of-concept. This is especially relevant for initial Descriptive Studies II like this one in which, as described at the start of chapter 5, the outcome from the support created is not developed and realized to the extent that the support can be applied by future users as intended, but it is aimed to evaluate at least some of its applicability, usability and if possible, its usefulness.

Consequently, at least an initial evaluation is required to round off a research project like this one in order to be able to draw conclusions about the relation between the support and the aims of the research project (Blessing & Chakrabarti, 2009).

There are, according to Blessing & Chakrabarti (2009), two main types of evaluation: application evaluation and success evaluation. In the case of an initial DS-II, the evaluation is performed mainly based on the application evaluation due to the impossibility of developing a detailed success evaluation which is derived from the links of the success criteria with the literature and it can only be used for reflection. Accordingly, the goal of the application evaluation is to identify whether the support can be used for the task for which it is intended and has the expected effect on the key factors from the updated impact model. The goal of the success evaluation is to identify whether the support indeed contributes to success and whether the expected impact, as represented in the updated impact model, has been realized (Blessing & Chakrabarti, 2009).

Therefore, both types of evaluation (application evaluation in sub-section 5.2.1 and success evaluation in sub-section 5.2.2) are presented in this section, even though the main focus is on the application evaluation due to the fact that chapters 5 and 6 are based on an initial approach.

5.2.1 Application evaluation

The focus of the application evaluation is on the usability and applicability of the developed support (Blessing & Chakrabarti, 2009). In this thesis, the success criteria for the application evaluation is based on the fulfillment of the research gap introduced in section 2.3. As a refresher, the identified gap is the lack of efficient guidelines for companies to understand to which extent customization can be achieved in product configurators by integrating them with ETO processes; considering in this process the capabilities of the customer, the product and the company, as well as the balance between these elements. The success criteria of the application evaluation, as described by Blessing & Chakrabarti (2009) also depends on the identification of the expected effect of the support on the key factors from the updated impact model.

Blessing & Chakrabarti (2009) propose different data collection methods for the application evaluation, including direct observation, document analysis, interviews or questionnaires. Since the outcome of the support is not fully developed and its results can not be captured through observation, the interview method is chosen for the application evaluation performed with Haverland.

The purpose of interviewing is similar to that of questionnaires, but is carried out face to face. They are used to collect thoughts, beliefs or opinions about past, present or future facts and events, with a focus on data that cannot be observed or was not captured in the past (Blessing & Chakrabarti, 2009). Patton (2002) and

Blessing & Chakrabarti (2009) distinguish between different types of interviews in which the standardized open-ended interview is chosen for this evaluation. This type of interview consists of carefully worded questions (fundamentally a questionnaire) that are asked to the interviewee in the order given in the list (Blessing & Chakrabarti, 2009). The standardized open-ended interviews are also referred to as semi-structured interviews (Blessing & Chakrabarti, 2009).

The interview is performed during the workshop (July 2021), after testing the framework on the RCWave+ and a short break. As well as with the case study, the interview is performed with Haverland's product engineer responsible and with the manufacturing specialist. After each question is asked, note-taking, as described by Blessing & Chakrabarti (2009), is utilized to record the information and relevant observations, and to have an overview of the direction of the interview. The questions are developed by the author to assess the usability and applicability of the created support, which is the framework just applied. The answers are based on the company's own resolutions. The interview, as well as the case study, is developed with the manufacturing specialist and the product engineer responsible. These answers are written in the third person founded on the replies given by the company and the notes taken. Next, the questions and their corresponding answers are shown along with the matching evaluation. There are a total of 5 open-ended questions in which the second one is divided into 4 sections corresponding to the 4 phases of the framework.

1. *Did this framework provide the necessary advice to help in the planning of a product configurator that can let end users engineer-to-order the final product?*
   It is stated by Haverland that the framework is useful but, at least in their case, for a future state in order to better organize the decision-making to plan a product configurator, but not at the current time.
   They consider that the development of this type of configurator permits the possibility of offering customers a product variety that it would not be possible to offer otherwise. Moreover, it provides the chance to innovate and create more technologically advanced products.
   They also consider interesting the adaptation of the configuration process based on the different types of clients, even though, they believe that the customer should be fully aware that these higher customization levels and variety also increase complexity and costs.

2. *What would you say are the main positive and negative aspects of each of the phases of the framework?*
   Phase 1 - Positive:
   They consider that this phase provides various benefits, especially the fact that it encourages to think out of the box and not stay in the comfort zone by checking what possibilities could be achieved by the company with the configurator and, at least hypothetically, see up to what extent customization could be accomplished based on the capabilities of the company or the customer needs, among others. They establish that other benefits are, for example, better communication between departments and also the possibility of having

more control of the product life cycle and the different potential product variants.

Phase 1 - Negative:
The main challenge that arises during this phase is the digitization and investment that the implementation of the product configurator would suppose. They do not have the means within the company to develop the configurator, it would have to be outsourced and it would have to be connected to their current ERP system and also to a CAD system to be able to provide unique 3D printed parts.

Phase 2 - Positive:
One of the positive aspects mentioned by Haverland is the chance of improving the customization of the product. They consider that the main benefit of this phase is to obtain a bigger market differentiation and penetration compared to other competitors. They find interesting the separation of modules and parts according to their possible level of customization and business model, since it can provide new ideas.

Phase 2 - Negative:
It is established that the supply chain can become more complicated and this can increase the delivery time. They especially consider that the ETO modules/parts would increase the overall lead time as well as the cost both for the company and the customer. Nevertheless, they comment that the lead time that could be obtained would be lower than if all the modules/parts followed only an ETO approach.

Phase 3 - Positive:
The main benefit for them is to better understand the different types of customers in the target group and to avoid possible frustrations in the configuration process that could happen if all users were treated equally.

Phase 3 - Negative:
They see as a possible challenge the fact that the customer may not even start the configuration process altogether when realizing that he/she has to answer some questions before being able to start customizing the product.

Phase 4 - Positive:
The main positive aspect stated is the opportunity to increase the customization possibilities of the customers and adapt them to their capabilities. It shows a clear understanding of what each of the profiles can perform based on their possibilities and what is established by the company. They consider a good aspect how the different outcomes from the other phases show their implication in this last phase. It is also stated that it would be useful to digitally store the types of modules/ parts co-created by the customers when choosing an ETO approach to be able to establish patterns and end up offering them as an ATO module/part if a shape is repeated several times. They see it as a potential company improvement tool.

Phase 4 - Negative:
They consider that allowing the customer to customize to a high extent (talking about the ETO modules/parts), may result in dissatisfied clients when they see the real actual outcome of their creation. They state again that this level of customization is translated into higher

costs and lead time.

3. *Was this framework easy to use and understand?*
   They state that it was easy to understand and use the framework, even though sometimes the author had to answer some questions that came up to them when testing the framework. They consider that it is a good idea to graphically arrange the decision process into activity diagrams and that the framework could be adapted to the particularities of each company; it opens the door to innovation.

4. *Had you considered the development of product configurators before the use of this framework?*
   They state that the intention of implementing a product configurator within the web page had been raised in the past, but it stayed just as an idea, since they felt it was too complicated to actually perform this task. This framework was considered a good way to start with the implementation and to facilitate the decision-making process for the planning.
   Furthermore, the main reason a product configurator had been proposed in the past is that there are different products (within the product family) with different names that share most of the parts with one another and it would be interesting for the customer to be able to select the different modules/parts, instead of selling them as completely different products.

5. *Had you considered the introduction of customer profiles to adapt the level of customization before using the framework?*
   It had not been considered, but they believe it is a very good idea, since you are giving the possibility to achieve more customization, but only for customers that are actually interested in it and that are capable of achieving it.
   They also propose that maybe with the questions, the configurator could directly propose a fully finished and personalized product variant instead of the customer having to select, modify and/or create the different modules and parts.

Through this standardized open-ended interview, the usability and applicability of the framework are assessed. In brief, it is stated by Haverland that the framework is helpful to organize the decision-making for the planning of the product configurator, and seeing what configurator elements can be included based on the specific situation of the company in order to explore the customization possibilities. Therefore, it can be claimed, based on the interview with the company, that the framework provided the necessary guidelines to fulfill the identified research gap. Nevertheless, it is also stated by the company that even though the organization for the product configurator is well established after using the framework, the actual creation and implementation of the configurator for the company is still a big challenge at least for them (this aspect would be out of the scope for the framework and the thesis).
The other main challenges mentioned were that an increase of the customization levels also imply a higher cost for the customer and a longer delivery time compared to their current state.
The main positive aspects that they realized after using the framework

were the following: (1) the framework encourages to think outside of the box and come up with new ideas; (2) it can provide a market differentiation by being able to increase the customization level achieved by the customer; (3) it provides the possibility to have better control of the product life cycle than at the current time; and (4) it allows to listen better to the voice of the customer and adapt the buying experience based on the customer profile and the capabilities of the company and the product. These positive aspects would have to be then revisited and compared with the objectives presented in sub-section 5.1.4 once the product configurator is actually developed.

From the results of the case study and the feedback gathered during the interview, it can also be asserted that the supports described in the framework affect positively the different factors that are linked to them in the updated impact model. The different supports presented in the updated impact model and their outcome for the case study are presented next:
The activity diagrams from phase 1 help to guide the company providing important factors to take into account like the identification of the target group, the suppliers or the manufacturing capabilities in order to set the customization basis for the next phases.
Specifically, the AS-IS process representation from phase 1 helps the company to understand the current configuration process and set the possibilities to better manage the product variety.
The part-of structure of the PVM in phase 1 assists with the comprehension of the product being analyzed in terms of modules/parts and constraints, as well as with checking whether it could provide more customization.
The kind-of structure of the PVM along with the activity diagram from phase 2 helps to frame the different modules/ parts into the different business models and establish the different versions of the modules/parts based on the potential customization capability.
Phase 3 with the Mamdani's fuzzy inferences method helps to show the company how to classify the users into the customer profiles before using the configurator to improve the involvement of the customer in the configuration process.
The guidelines with the activity diagram from phase 4 help the company to define the plan for the configurator to be developed by displaying the possible adaptation of the configuration process based on the results from the three previous phases. It is stated that these guidelines can help to obtain a higher reuse of parts and designs, and a better management of the product variety, obtaining this way a better use of product configurators with ETO possibilities.
The TO-BE process representation in phase 4 assists with the organization of the future configuration process which is a result of the use of the framework.
The use case diagram in phase 4 helps to identify the stakeholders involved in this configurator development process, making sure the sales and the technical stage are covered to obtain a better standardization of the product configuration process, even for the ETO activities within the configurator.

5.2.2 Success evaluation

The success evaluation aims to identify whether the support indeed contributes to success and whether the desired situation represented in the updated Impact Model has been realized (Blessing & Chakrabarti, 2009). The goal of the success evaluation is to check the usefulness of the support (Blessing & Chakrabarti, 2009). For the case study, it is established based on the application evaluation that the framework successfully provides the advice to understand how the balance of the 4 main pillars influences the planning of a product configurator that can let end users engineer-to-order the final product. Nevertheless, the actual product configurator is not actually developed, therefore it can not be fully evaluated through the success evaluation.

This type of evaluation is based on the data gathered with the creation of the support and the links from the literature to the presented situation and the previous ones. In this case, this data is not fully created nor exact since the outcome from the support is not developed in all respects. Nonetheless, a reflection is performed with a comparison between the results of the situation presented in the updated impact model, and the situations introduced in the initial reference model. This comparison is developed based on the outcomes of the application evaluation just described and the results of the literature study. The success evaluation then evaluates whether the support has the overall effect defined by the success criteria and if all the factors involved in the updated impact model achieve their desired values. It basically tests the strength of the links in the updated impact model (Blessing & Chakrabarti, 2009).

The situation in the initial reference model presented as key factors the use of product configurators without ETO possibilities, and companies with the implementation of only the ETO business model. The key factor is then changed in the rest of the models to the use of product configurators with ETO possibilities. Therefore, these situations are the ones compared based on the created support and the success criteria with their corresponding success factors. These success factors are the ones presented in the initial and the updated reference model. Next, the different success factors are introduced with the corresponding comparison:

- The first success factor selected is the involvement of the customer in the configuration process. The success criterion was to achieve a higher involvement. It can be established that the supports of the Mamdani's fuzzy inferences method and the use of the activity diagrams in phases 1, 2 and 4 impact positively on the factors of the updated impact model that influence this involvement. For the situation in which the use of product configurators with ETO possibilities is established as the key factor, it can be stated based on the updated impact model and the application evaluation, that the involvement of the customer in the configuration process is better compared to the situation where product configurators are used without ETO possibilities, and it is equal or worse compared to companies that only use the ETO model. On the one hand, when using the developed support that allows the development of product configurators with ETO possibilities, the users have, compared to using product configurators without ETO possibilities, a wider range of options to communicate their needs and requirements due to the possibility of co-designing the parts and also because the configuration process is adapted based on the capabilities of the customer. On the other hand, in ETO-only approaches, the user has even bigger freedom when creating the product since he/she is in direct contact with the company instead of using a product configurator, and can usually better translate his/her requirements into a bigger number of parts compared to product configurators with ETO possibilities.

- The second success factor is the management of the product variety. The selected success criterion was to accomplish better management of the product variety. The use of AS-IS and TO-BE process representations, the use case diagram, and the utilization of the activity diagrams of phase 4 of the framework are considered supports that improve this management and subsequently provide a better use of product configurators with ETO possibilities. Based on the updated impact model and the application evaluation, it can be established for the situation in which the use of product configurators with ETO possibilities is settled as the key factor, that there is an achievement of a better management of product variety when comparing it with the situation in which companies use ETO-only approaches. This is due to the fact that the developed solution allows the customer to engineer-to-order the product to some extent, but standardizes the procedure of the customization which is translated in a better management of the product variety compared to the creation of project-based approaches for each product. If compared with the situation of product configurators without ETO possibilities, the management of the product variety can be stated as equal, since even though some modules/parts are co-created by the customer to some extent, these are previously selected by the company and their creation is restricted within certain limits to also improve this variety management.

- The third success factor selected in the models is the lead time. Accordingly, the success criterion was to achieve a lower lead time. The use of the activity diagram of the fourth phase and also the Product Variant Master are stated as helpers in the achievement of a higher reuse of parts and designs which improves the lead time. For product configurators with ETO possibilities, based again on the updated impact model, the product lead time is lower when compared to companies that only use the ETO model, but it is higher than in those where the product configurator does not have ETO possibilities. In the first case, the standardization of the product configuration and development reduces the lead time compared to the project-based procedures that are utilized in ETO-only companies. When comparing it with companies that employ product configurators without ETO possibilities, the lead time in the situation of the updated impact model is still higher, since although the ETO modules/parts creation is relatively more regulated than in the previous case, the fact that it has to be uniquely designed and manufactured for each order inevitably increases the lead time compared to only using ATO or MTO. This remark is also stated by the company (Haverland) several times during the interview in the application evaluation.

- The final success factor, and the most important, is the maximum level of customization that can be achieved by the customer. The success criterion was to accomplish a higher maximum level of customization. All the different supports created (the activity diagrams in the framework, the AS-IS and TO-BE process representations, the use case diagram, the Product Variant Master and the Mamdani's fuzzy inferences method) influence directly or indirectly in the achievement of a higher maximum level of customization achieved by the customer when examined in contrast with certain previous cases. When comparing the situation in which product configurators with ETO possibilities are established as a key factor, and the situation of configurators without ETO possibilities, in the first case the maximum level is higher since the customer has greater freedom when configuring and creating the final product, even if it is only for the ETO modules/parts that the company allows the user to co-create based also on his/her customer profile. Nevertheless, when compared with companies that use only the ETO model, the potential maximum customization level that can be achieved is still lower. Consequently, when using only the ETO model, the customers have greater possibilities of communicating their needs and requirements to the company, which is then translated into highly customized products against which product configurators can not compete, even if they have ETO possibilities as it has been investigated in this thesis.

Since the Descriptive Study II (DS-II) follows an initial approach, the success evaluation can not fully evaluate the usefulness of the project as described by Blessing & Chakrabarti (2009). Nevertheless, it is evaluated to some extent and it is useful as a reflection to provide some insights on the result of the support and the different findings. As a summary, it can be stated that compared to one of the original situations (companies that only use the ETO model), the situation in the updated impact model (companies using product configurators with ETO possibilities) along with the created support, improves the success factors of lead time and management of product variety while the maximum level of customization and the involvement of the user in the configuration process is poorer. When comparing the situation in which companies use product configurators without ETO possibilities and the one where they use product configurators with ETO possibilities, it can be established that the second one produces a higher lead time and an equal management of product variety, but it improves the success factors of involvement of the customer in the configuration process and the maximum level of customization the user can achieve.

6. Final remarks

FINAL REMARKS

6

With the preliminary research, the literature study, the development of the framework, the case study and the evaluation, this last chapter reflects back on the objective and sub-objectives of the thesis. The objectives and the conclusion are discussed in section 6.1 and section 6.2 presents the limitations and recommendations for future work based on this research as described by the author.

6.1 Conclusion

The objective of this thesis was "*To investigate, develop and evaluate a decision-support framework to advise companies in the planning of product configurators that can let the end user engineer-to-order the final product*". As described in chapter 1, this objective is visualized with the creation of the aforementioned framework that underlays the relation among the four pillars mentioned throughout the research that play a role in this scheme: the customer with its needs and knowledge, the product configurator itself, the degree of customization the product can deliver and the capability of the company to achieve that customization. The decision-support framework helps companies to balance these different variables to deliver further customization as pulled by the customer with a product configurator.

In order to fulfill this objective, a strategy consisting of 6 sub-objectives was created. For the convenience of the reader, the 6 sub-objectives are summarized once more:

1. Research the problem context and identify the research gap.

2. Identify guidelines, best practices and outcomes for the relation between product configurators and ETO.

3. Identify guidelines, best practices and outcomes for the relation between product configurators and the customer knowledge.

4. Select suitable models and methods from the literature to apply in the framework.

5. Create the framework.

6. Evaluate the framework.

Next, the outcomes of these sub-objectives are summarized followed by a conclusion of the overall objective of the research.

The first sub-objective, *Research the problem context and identify the research gap*, is fulfilled by performing a preliminary research on the topics of product configurators with their classifications and challenges, and engineer-to-order with its weaknesses, strengths and some potential improvements. After performing the preliminary research and identifying requirements and capabilities of both ETO and product configurators, it is identified as the research gap the lack of efficient guidelines for companies to understand to which extent customization can be achieved in product configurators by integrating them with ETO processes, considering in this process the capabilities of the customer, the product and the company, as well as the balance between these elements. To integrate the benefits and taking into account the challenges of these approaches, the next two sub-objectives focus on researching the relation between product configurators and engineer-to-order as well as the relation between product configurators and the customer knowledge, to let end customers directly engineer-to-order the final product with the use of a product configurator. By the means of this preliminary research, an initial reference model is created representing the problematic initial situation along with an initial impact model. The identified key factors (to be improved) in the initial situation are the use of product configurators without ETO possibilities and companies implementing only the ETO business model. The key factor is then changed on the initial impact model to the use of product configurators with ETO possibilities. The main success factor in both models is the attainment of a higher maximum level of customization that the user can achieve with the use of a product configurator.

The second sub-objective, *Identify guidelines, best practices and outcomes for the relation between product configurators and ETO*, and the third sub-objective, *Identify guidelines, best practices and outcomes for the relation between product configurators and the customer knowledge*, are fulfilled by performing a systematic literature study with two search queries and their respective research questions; one for each of the sub-objectives. The capabilities of the company, the product, the configurator and the customer are taken into account when developing the research. Nevertheless, most of the practices found in the first search query do not take much into account the customers with regards to their relationship with the configurator and their own knowledge level, which is the reason the second search query is performed. As identified in the literature, the combination of business models within the configurator, the identification of the level of customization of the modules/parts with their corresponding business model, the use of the configurator for the sales and technical stage of the product development process, or the adaptation of the configuration process based on the customer profile are, among others, procedures that enable the creation of product configurators with ETO possibilities.

Sub-objective number four, *Select suitable models and methods from the literature to apply in the framework*, reflects on the systematic literature study to identify which of the described methods and models are the most appropriate to use in the framework. There are a total of 5 models/methods selected: AS-IS and TO-BE process representations, the Product Variant Master, the Mamdani's Fuzzy inferences method, Use case diagrams and Activity diagrams. This sub-objective describes the selected models or methods to be used in the framework, the criteria as to why they are selected based on the literature, and how they are planned to be used in the framework. The AS-IS and TO-BE process representations are used to describe the current and the future/planned configuration process that the user goes through when creating and purchasing the product. The Product Variant Master (PVM) is used to classify the modules and/or parts of the product to help in the identification of which business model works best for each product module/part. The "part-of" structure of the PVM shows the components included in the product along with its constraints, and the "kind-of" structure the versions and variables of the modules/parts. The Mamdani's fuzzy inferences method is used in this thesis to determine the customer profile based on the level of knowledge and motivation of the product configurator user. The use case diagram is utilized to identify the relevant stakeholders in the configuration process that the user goes through. Activity diagrams are utilized to organize the different phases of the framework, since they offer a visual and standard method to visualize the framework's workflow, and help to provide an intuitive way to understand the decision-support framework. They are also utilized to represent the information of the AS-IS and TO-BE process representations previously described.

The literature study is concluded with an overview of the main guidelines, best practices and outcomes regarding the aforementioned relations across the literature. The combined findings from the investigation of the two search queries serve as a basis for the identification of the elements and the development of the framework. After the literature study, the reference model is also updated with new factors and statements added to the model and other ones deleted based on the results of these last three sub-objectives.

The fifth sub-objective, *Create the framework*, first identifies the elements of the framework, and then it is developed with its different phases explained. The framework presents the advice for companies on the decision process for the balance of the four main pillars in order to plan the defined product configurator.
The identification of the elements of the framework is based on the basic guidelines and best practices found in the systematic literature study as well as on the updated reference model. To organize this information, the elements are decoupled from the four main pillars and this is represented through a mind map. The framework is divided into four consecutive phases that are connected with each other (1. Plan, 2. Organize, 3. Select and 4. Adapt). Each of the phases leads to one specific outcome and is centered on one of the pillars, even though the other ones are also included in all of them. Phase 1 is related to the initial plan of the company regarding the maximum level of customization that can be achieved, phase 2 with the product modules/parts organization based on the different business models and the maximum level selected in phase 1, phase 3 with the customer profile classification and the connection with the maximum level of customization that the user can accomplish, and phase 4 with the adaptation of the product configurator based on the outcomes from the previous three phases.
After the framework is explained, the impact model is updated based on the creation of the support developed with the framework. In the updated impact model, the expected effect of the support on the different factors is displayed. The main expected effect is to accomplish a better use of product configurators with ETO possibilities to achieve a higher level of customization.

The sixth and last sub-objective, *Evaluate the framework*, first describes the application of the framework in the case of a consumer good and then it is evaluated by means of an application evaluation and a success evaluation. The case study is performed with the company Haverland, a medium-sized Spanish enterprise focused on the design, manufacturing and sale of different types of heaters and radiators. The application of the framework is

aimed at the RCWave+, one of the most popular heaters in their product family. The case study is performed during a workshop session with the product engineer responsible and the manufacturing specialist of the company. The four phases of the framework are then followed for this product to check its applicability and usefulness.
For this task, the framework is evaluated through an application evaluation and a success evaluation. The focus of the application evaluation is on the usability and applicability of the developed support (Blessing & Chakrabarti, 2009). The success criteria for the application evaluation is related to the fulfillment of the research gap. The chosen data collection method for the application evaluation is a standardized open-ended interview. Haverland assesses during the interview that the framework is helpful to organize the decision-making for the planning of the product configurator based on the situation of the company. Some of the identified challenges are the higher costs and longer delivery times due to the increase of customization. Other positive aspects mentioned are the market differentiation due to the increase of the customization level achieved by the customer, a better control of the product life cycle or the possibility of being able to listen better to the voice of the customer, among others. It can be then stated according to the feedback, that the framework fulfills the identified gap. Furthermore, it is established based on the case study and the feedback that the supports created affected positively on the factors linked to them in the updated impact model.
The goal of the success evaluation is to check the usefulness of the support (Blessing & Chakrabarti, 2009).
The evaluation section of the research follows an initial approach as described by Blessing & Chakrabarti (2009) and, thus, the results of the success evaluation can not be considered decisive due to the outcome from the support not being fully developed, which is the reason that the application evaluation is the main type of evaluation in this research.
Nevertheless, the results can be used for reflection based on the success criteria defined in the reference and impact models. It can be stated that compared to one of the original situations presented in the initial reference model which presents companies that only use the ETO model, the situation in the rest of the models (companies using product configurators with ETO possibilities), along with the created support improves the success factors of lead time and management of product variety while the maximum level of customization and the involvement of the user in the configuration process is poorer. When comparing the other original situation in the initial reference model in which companies use product configurators without ETO possibilities and companies that use product configurators with ETO possibilities (the situation presented in the rest of the models), it can be established that the second one produces a higher lead time and an equal management of product variety, but it improves the success factors of involvement of the customer in the configuration process and the maximum level of customization the user can achieve.

With the six sub-objectives answered, the main objective of the thesis is fulfilled. A decision-support framework is created that advises companies in the balance of the four main pillars previously described to organize the planning of a product configurator that can let the end user engineer-to-order the final product to some extent. This framework helps

companies to balance the capabilities of the company, the product configurator, the customer and the final product to deliver ETO possibilities and, hence, further customization as pulled by the customer with a product configurator.
It can be stated as the main conclusion of the research that the end user can not fully engineer-to-order the final product by means of a product configurator as a consequence of the framework developed. The results of the research point that only certain modules and/or parts of the product can be directly engineered-to-order by the end user with the use of a product configurator, and these modules/parts have to be previously established by the company with certain limits regarding their creation. Therefore, based on the findings, it is established that it is not possible to achieve as much customization through product configurators with ETO possibilities as the one that can be achieved in companies that only use the ETO business model (and no product configurator). Moreover, it is also advised to only let end users with an established "advanced" customer profile the possibility to engineer-to-order the modules/parts in order to avoid possible abortions of the configuration process and a better user experience. Nevertheless, it can also be stated according to the findings, that the customization level that can be achieved by the customer through product configurators with ETO possibilities is significantly higher than through configurators that only follow ATO or MTO approaches. Furthermore, it can be established that the product variety can be better managed and standardized in companies that adopt this type of product configurators with ETO possibilities than in those that choose to go through an only ETO approach. The results of this research highlight the challenges and the opportunities of one of the possible approaches to tackle the general market trend focused on the increasing demand for customized products based on the individual customer's needs.

6.2 Limitations and recommendations

After the development of the decision-support framework, it is established that future research needs to be performed to keep investigating how the balance of the different pillars can be improved to plan and develop product configurators that can let the end user engineer-to-order the final product to a higher extent and, thus, obtain greater customization. Due to the time and the resource constraints of this research, demarcation was required which resulted in certain assumptions that had to be made, as well as limitations. The following limitations are present in this research and should be taken into account:

- Even though during the research the 4 main pillars previously described are always taken into account, the investigation is performed with the terms "product configurator", "engineer-to-order" and "customer knowledge" as the main keywords in the search queries. This is performed due to the interest in the project of investigating the relation between these topics. If other keywords had been chosen or other pillars had been considered, probably other elements and procedures for the framework would have arisen.

- The application of the framework is performed only in the case of one company due to time constraints and the difficulty of finding companies willing to go through the process especially when performing the thesis internally and on remote. In order to be able to obtain more accurate results for the application evaluation, further feedback from companies with other types of consumer goods and various capabilities would be needed.

- The case study is performed on a Spanish medium-sized enterprise. It would be also left to see whether the geographical location or the size of the company influences the results obtained.

- Even though the framework successfully advises the company in the planning of a product configurator with ETO possibilities for the customer, the actual product configurator is not developed, it is only outlined. This is due to resource and time constraints for both the company and the research. This assumes that the results of the developed success evaluation can not be considered definitive and are used only to reflect when comparing the situation in the updated impact model (companies using product configurators with ETO possibilities) and the initial situations of companies using only the ETO business model or those using product configurators without ETO possibilities.

Accordingly, based on the defined limitations and the results of the research, some recommendations are proposed for future research on the topic:

First, it is proposed to expand the search query with other keywords to find which other elements also influence the planning of a product configurator that lets end users engineer-to-order the final product. By doing this and combining it with the results of this research, other approaches may arise that could expand more ETO possibilities into product configurators and increase the potential level of customization that the user can achieve.

In order to properly develop a success evaluation, it would be needed not only to go through the framework, but to actually create the product configurator and use it for the product that was selected and with actual customers. This would be needed in order to fully check the usefulness of the framework and to compare the results with the other situations previously mentioned.

It is needed to develop case studies in more companies in order to fully validate the framework and to obtain accurate results in the application evaluation. It is also proposed to expand the case studies to companies from different countries and with different types of consumer goods, as well as with different resources and capabilities.

These recommendations, in combination with the results of this research, hope to inspire companies and also the academic world to further investigate which factors and elements are relevant, and how their balance can be improved, to obtain a higher level of customization through product configurators when used in relation to the engineer-to-order business model.

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Appendix A: Framework manual

FRAMEWORK MANUAL

Appendix

A

This document walks through the different steps of the framework and explains them clearly to facilitate its use. The framework is targeted at consumer goods. The framework is intended for companies that want to improve, in terms of customization, their current product configurator for a certain product or for those that do not have a product configurator but want to enhance the configuration process and the customization possibilities for the customers. Nevertheless, these are recommendations for best use and if the company or product does not align with the previously described criterion, the framework can also be used and tested if desired.

The framework presents the advice for companies on the decision process for the planning of a product configurator that can let end users engineer-to-order the final product based on the balance of the capabilities of the customer, the product configurator, the own company and the product. The main goal is to let the customer achieve a higher level of customization than at the current time by the means of the product configurator.

This framework manual is based on the master thesis for the IDE MoPD track in the UT by Marcos Saiz. The thesis can be inspected for more information and to check the bibliography and the associated references, which are, for the most part, not included in the framework manual to facilitate the reading.

1. Framework explanation

The framework is divided into four consecutive phases that are connected with each other (Plan, Organize, Classify and Adapt). Each of the phases take into account the 4 main pillars in this scheme: the customer, the product configurator, the company and the product.

The representation of the full framework is shown graphically in image 1 with the four phases just described. These are explained in detail later in the sub-section for phase 1 (image 2 and image 3), the sub-section for phase 2 (image 4 and image 5), the sub-section for phase 3 (image 6), and the sub-section for phase 4 (image 8). The ovals in image 1 represent the relation and balance of the pillars in the different phases of the framework. Each of the phases leads to one specific outcome and is centered on one of the pillars, even though the other ones are also included in all of them. Phase 1 is related to the initial plan of your company regarding the maximum level of customization, phase 2 with the product modules/parts organization based on the different business models, phase 3 with the customer profile selection and phase

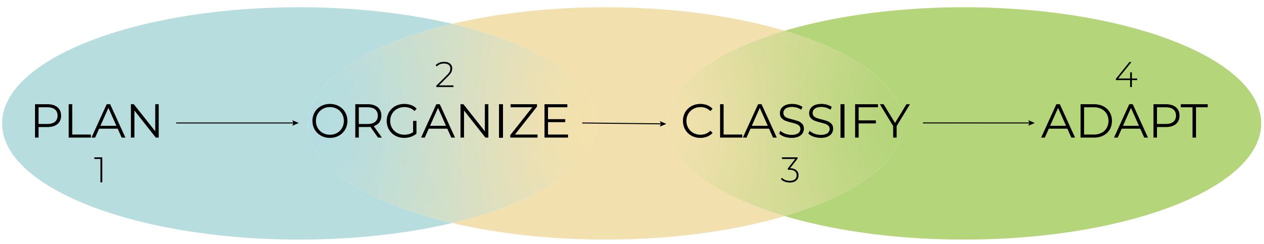

Image 1 (Framework manual): Full framework

4 with the adaptation of the product configurator based on the previous results.

The framework utilizes different models and methods (AS-IS and TO-BE process representations, use case diagrams, the Product Variant Master, and activity diagrams) the that are further explained and described in section 2 of the manual (Theoretical background). For instance, the workflow for the decision process in the framework is based on activity diagram elements that can be checked in section 2.

In this framework when the word "identify" is used, this means that the task has to be performed before starting the step of the activity diagram, and when the word "select" is used, the task is performed with the help of the activity diagram. Furthermore, the acronyms MTS, ATO, MTO and ETO stand for "Make to Stock", "Assemble to Order", "Make to Order" and "Engineer to Order", which are different business models with various strategies mainly based on the customer order.

Phase 1: Plan

The first phase of the framework (Plan), shown graphically in image 2 and image 3 consists of an activity diagram (divided into 3 sub-activity diagrams) that help the company frame itself into the maximum level of customization that should and can be achieved with the use of the product configurator for the chosen product. These levels can be very high (up to ETO), high (up to MTO) and average (up to ATO). The framework also has another possible outcome for which it is advised to keep the current configuration process instead of aiming to achieve a higher level of customization.

In each of the sub-activity diagrams, your company is directed to frame itself into either continue using the framework or maintaining its current configuration process for the product. In the last sub-activity diagram, if reached, the maximum level of customization for the product configurator to be developed is established. It is advised to try and aim for the highest level of customization in the configurator, since the goal of the framework is to be able to let customers engineer-to-order the final product to some extent. The sub-activity diagrams are depicted from the 4 pillars and the main one for phase 1, as previously described, is the company, since this first phase helps to set their customization plan:

1. The first task in the diagram is depicted from the customer pillar (image 2). The company has to identify the current target group for the selected product and decide if this target group would benefit from having more customization possibilities in this product. If the answer is no, it should be checked if the current target group can be expanded so this increment would be beneficial. If the answer is still no, then it is advised to keep the current configuration process and stop using the framework. On the other hand, if the answer is yes, the company can continue using the framework taking into account this customization pulled by the target group. As stated in the literature, customers aim at having a wider range of choices for their personalized product, which is the overall aim of the framework.

2. The next two tasks are related to the product configurator pillar (image 2). The two tasks are concurrent and that

is why the fork symbol is utilized at the start of this sub-activity diagram. One of the tasks is related to the product configurator and its current integration with other possible IT systems in the company, such as CAD, ERP or PLM. If the current integration or a potential future one allows the company to cover the sales stage (which communicates the product to the customer and provides real-time information to the company) and the technical stage (that checks the validity of the product variants and generates the bill of materials based on the customer's selection), the company can continue the activity diagram and reach the joint node. On the other hand, if the answer is negative, the current configuration process is maintained and there is no need to continue using the framework.

The other concurrent task, also related to the product configurator, identifies the current configuration process that the user follows for the creation of the product. For that, an AS-IS process representation (explained in section 2) is advised to be created. If it is possible to modify it and this change is expected to potentially provide more customization possibilities to the customer, the joint node is reached. If there is no room for alterations and improvements, the current configuration process is kept. If both tasks have come to the joint symbol, the activity diagram can be continued.

3. The following two tasks are part of the final sub-activity diagram of phase 1, which is depicted from the company and the product pillars (image 3). These two tasks are also concurrent and a fork symbol is used.

The first of the two, related to the product, requires the company to identify the different product modules/parts and the possible physical or regulatory constraints. This process is associated with the creation of the part-of structure of the Product Variant Master (explained in section 2), which is advised to use. If no modules/parts have the potential to be customizable, the current process is maintained. If some of the potentially customizable modules/parts can be unique for each product variant while maintaining the product structure, the joint node that continues to the (C) start symbol is reached. If the module/part versions are expected to allow a certain physical or graphical change, the joint node that continues to the (D) start symbol is attained. If the answer to this last question is negative, the current configuration process is maintained.

The other task is related to the company and the current manufacturing techniques and technologies used to develop the product. First, it is selected whether more customization as pulled by the target group can be achieved with the current approach, or if new technologies or manufacturing methods can be adopted and used that will. If not, the ongoing configuration process is kept. If the current or future setup can provide unique modules/parts for each order, the join node with the following (C) start symbol is reached. If certain changes based on the customer order can be performed before the manufacturing starts, the joint node that continues to the (D) start symbol is attained. If, otherwise, this last

*Maximum levels of customization: 1. Up to ATO (Average); 2. Up to MTO (High); 3. Up to ETO (Very High)

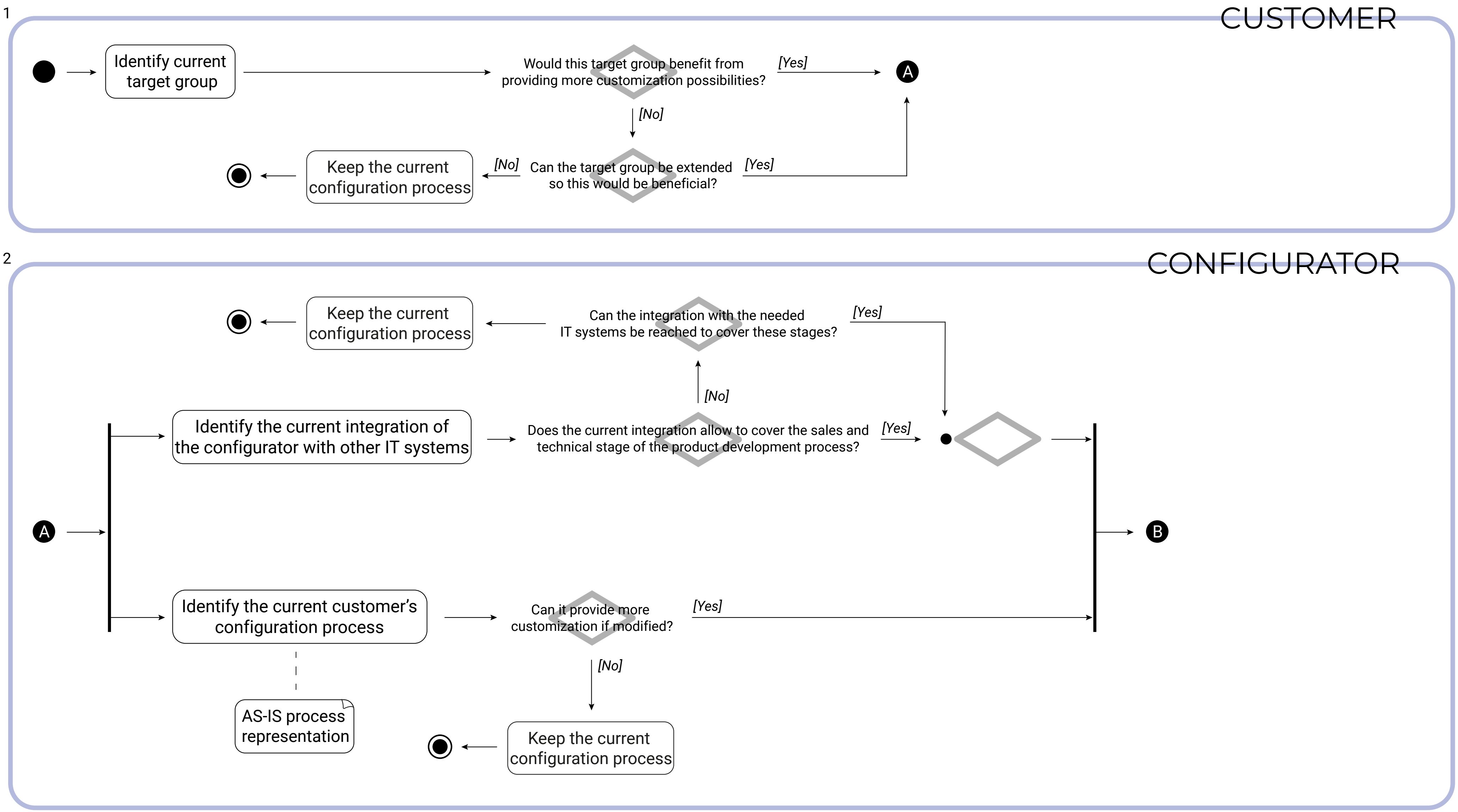

Image 2 (Framework manual): Framework phase 1 (PLAN) (1/2)

PRODUCT+COMPANY

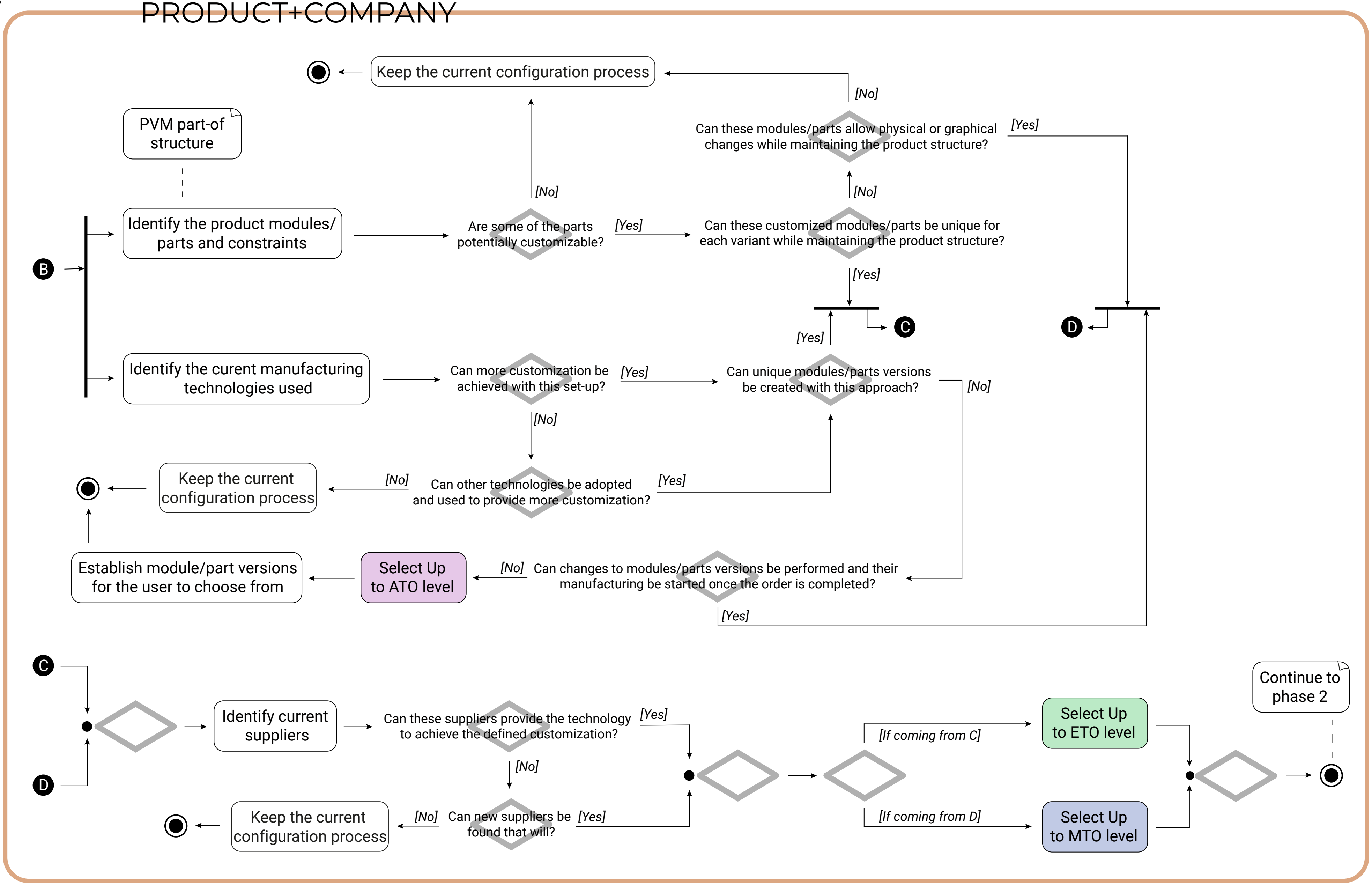

Image 3 (Framework manual): Framework phase 1 (PLAN) (2/2)

option is not possible, the company selects an up to ATO level where the user is able to select between certain predefined module/part versions within the product configurator. When the final outcome is up to ATO, the framework advises to stop its use, since this level of customization is the average for product configurators and this framework aims for a high (MTO) or very high (ETO) possible customization.

If the two tasks have reached either the (C) start symbol or the (D) one (both of them must have come to the same joint node), the company needs next to identify the current suppliers. If these suppliers or new ones established by the company can provide the technology and have the capabilities to achieve the customization defined in the previous tasks, the activity diagram can be continued, otherwise it is advised to maintain the current process. Subsequently, if the answers to these last activities are positive, when coming from the (C) start symbol, the company selects an up to ETO level of customization and when coming from the (D) one, an up to MTO level is selected.

Continuing to the next phase means that the company has the capability to create a product configurator that can be used to configure a product in which the maximum level of customization that can be achieved is either up to ETO (ideally) or up to MTO, and this level of customization is beneficial for the target group.

Phase 2: Organize

Phase 2 (Organize) has the goal of framing the product modules or parts into either MTS (common modules), which do not provide any possibility for customization, ATO and MTO (customized modules), that provide average and high customization respectively, or ETO (personalized modules), which offers very high customization. The MTS modules/parts are those that are created before the customer order and are replenished through production orders based on the forecast, thus these are the modules/parts that are always present in all the product orders and can not be customized. The ATO modules/parts are those in which the customer can select among different module/part versions which are already built by the company and are assembled once the order is placed and based on the customer configuration. The MTO modules/parts are similar to the ATO ones, but do not necessarily have to be already built, only created by the company and may have to be manufactured and assembled upon the customer order. They are associated with the customer's selection or creation of changes to the module/part versions, but always within the company's established product variants. The ETO modules/parts are those which are different in each version and have to always be manufactured after the customer order since the company can not foresee what they are going to be like. Nevertheless, the company can and should establish limits for the creation of the ETO module/part versions so they are in line with their capabilities and with the rest of the product structure.

To frame the different modules or parts, the Product Variant Master (explained in section 2) is finished with the development of the kind-of structure in which the possible module/parts versions are explored and established based on the business model that best fits the specific module or part. If a module is certainly known to be associated with the MTS business model, there is no need to identify all the parts of that module, since they all follow the same approach. The guide in image 4 and image 5 can be used to help in the decision-making to frame the potentially customizable modules/ parts and the creation of the kind-of structure. This guide does not need to be utilized for every module and/or part, only those that the company is uncertain about which business the module/part should be associated with. Using the guide can facilitate the development of the kind-of structure of the PVM, which is the main outcome of this phase. For the aforementioned guide, an activity diagram similar to the one in phase 1 is used. In phase 2, the main pillar is the product, since the organization of the modules and parts is the main goal. If the maximum level of customization selected in the previous phase is MTO, then the company can only sort the modules/parts into MTS, ATO or MTO. Accordingly, the ETO modules/parts can only be selected if the maximum level achieved in the previous phase is up to ETO. The activity diagram in the guide has three concurrent tasks that are explained next:

The first task is associated with the product, the company and the customer. It is based on the previously identified product modules/parts and their constraints in the part-of structure of the Product Variant Master. If the module or part, depending on the product structure and constraints, allows the possibility to let the customer create unique versions of that module/part for each product in order to benefit the company and the user, the (A) start symbol is reached. If it is possible and it makes sense for the company to let the user make some parametric or design changes to the module/part, then the (B) start node is attained. If it is possible and it makes sense to let the user choose between different module/part versions, the diagram leads to the (C) symbol. If the answer to this last question is negative, the module/part follows an MTS approach and there is no need to continue using the guide (image 4).

The second concurrent task is related to the company and the previously identified suppliers from the first phase. If they can provide a unique module/part version (within limits established by the company) for each product order created by the customer, the (A') start symbol is reached. If they can supply versions of a module/part in which the customer can decide on some dimensions or design changes (previously predefined by the company) before the order is placed and the manufacturing started, the diagram leads to the (B') start node. If only settled versions of a module/ part can be manufactured, the (C') start symbol is attained. If none of these scenarios is possible, the part follows the MTS business model and the use of the diagram is finished.

The last concurrent task is related to the configurator and the level of part completeness that is shown in the configuration process. The part completeness is associated with the amount of detail of the module/part digital twin that is shown to the customer when using the product configurator. If this needs to be high to go through the configuration process and it is possible to achieve it, the diagram leads to the

Guide to help in the decision-making for the creation of the kind-of structure of the PVM

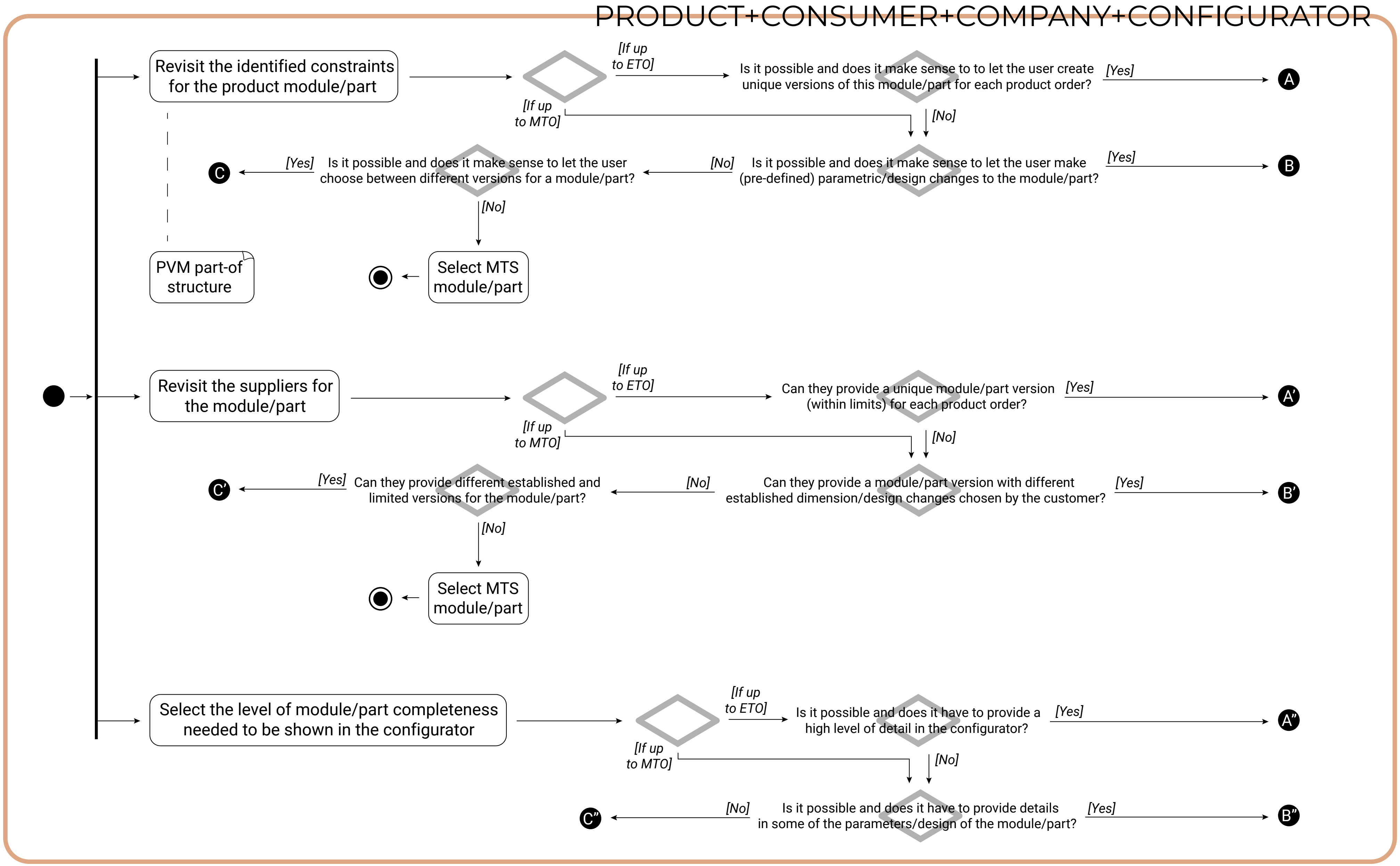

Image 4 (Framework manual): Framework phase 2 (ORGANIZE) guide (1/2)

Guide to help in the decision-making for the creation of the kind-of structure of the PVM

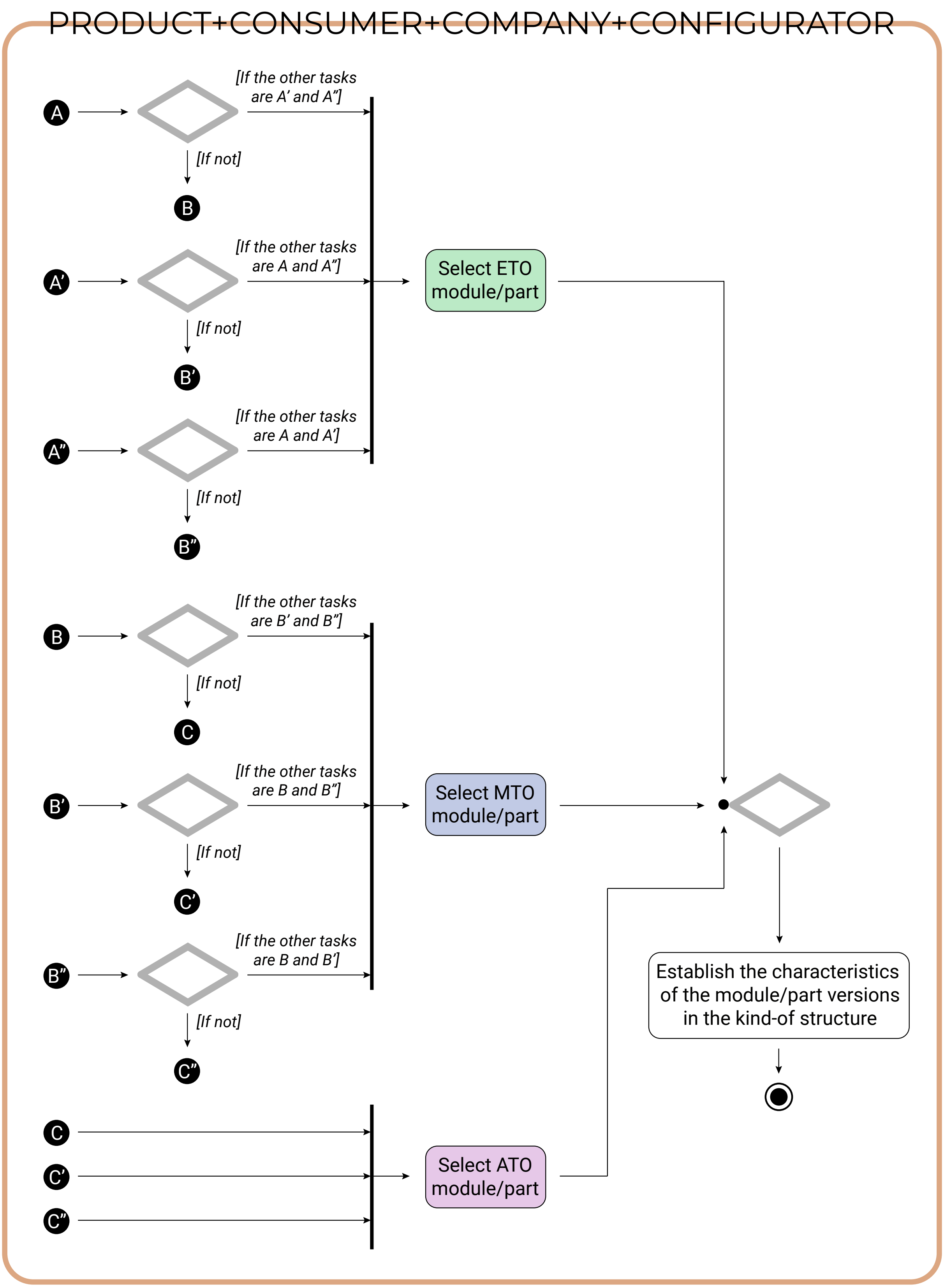

Image 5 (Framework manual): Framework phase 2 (ORGANIZE) guide (2/2)

(A") start symbol. If it is possible and the module/part needs to provide details in some dimensions or other aspects, the (B") is attained. If not, the (C") start symbol is reached (image 4).

Next, if all the previous outcomes are (A), (A') and (A"), the module/part is selected as ETO; if all the outcomes are (B), (B') and (B"), an MTO module/part is selected; and if they are all (C), (C') and (C"), the part is selected as ATO (image 5). All three outcomes must finish in the same letter in order to select the business model for the module/part, if there are outcomes that end up in different letters, the less restrictive one is chosen due to the impossibility of achieving the more complex business model. For example, if the outcomes are (B), (A') and (B"), the one that ends up in (A') needs to be changed to (B') if the other ones can not be modified upwards, to be able to select the MTO module/part. Afterwards, the kind-of structure of the PVM needs to be finished. This guide can be used for all the modules/parts that the company is unsure to which business model they should be associated. It is advised to go for the most customizable level. If a module/part is selected for an ETO level, this part should also be able to fulfill an MTO and ATO approach based on the customer predilection, which is further explained in phase 4 (Adapt). This way, there is a higher amount of parts and designs reused and a higher standardization can be achieved. Continuing to the next phase means that at least one of the modules/parts of the product for which the configurator is going to be used, can follow an either MTO or an ETO approach.

Phase 3: Classify

The third phase of the framework (Classify) is associated with the process of determining the customer profile of each user based on their level of knowledge and motivation. For that, the Mamdani's fuzzy inferences method explained in section 2 is meant to be utilized by the company. The possible customer profiles are either "beginner", "intermediate" or "advanced". Image 6 shows a quick guide to help in the use of the Mamdani's fuzzy inferences method along with its 4 steps (A more detailed explanation can be found in section 2). The percentages shown in image 6 and also in section 2, are defined by the author and based on the research performed. Furthermore, an excel file (that can be found in Mamdani's automated excel and screenshot in image 7) is created with an automation of the method. It can be used by the company to quickly determine the profile based on the different answers. It is also possible for the company to alter the values and percentages in the different formulas, as well as some aspects of the questions in order to adapt the method to its unique situation (with this version of the file: Mamdani's automated excel [edit version]). The regional format for the excel file to properly work should be "English (United States)". In the third phase, the main pillar is the customer, since the main goal is the customer profile selection. Next, the 4 steps in the guide are briefly described:

1. The first step consists of the request to the customer to answer 4 questions with a numerical answer that can range from a minimum of 0 to a maximum of 1. These are asked to obtain his/her level of knowledge in the product and configuration

Guide to help in the use of the Mamdani's fuzzy inferences method

CONSUMER+PRODUCT+CONFIGURATOR

Step 1: Ask and evaluate answers (x) from customers

1. What is your estimated knowledge about the product to be configured?
Knowledge about the final product: k

$$\mu_k(x_k) = \begin{cases} Poor\ (0{,}3) & 0 \leq x_k < 0{,}3 \\ Average\ (0{,}6) & 0{,}3 \leq x_k < 0{,}6 \\ Good\ (0{,}8) & 0{,}6 \leq x_k \leq 1 \end{cases}$$

2. How would you describe your parametric or graphic design capabilities?
Parametric or graphic design capabilities: l

$$\mu_l(x_l) = \begin{cases} Low\ (0{,}2) & 0 \leq x_l < 0{,}2 \\ Medium\ (0{,}6) & 0{,}2 \leq x_l < 0{,}7 \\ High\ (1) & 0{,}7 \leq x_l \leq 1 \end{cases}$$

3. How important is it for you the customization level for the product to be configured?
Customer customization preference: m

$$\mu_m(x_m) = \begin{cases} Irrelevant\ (0) & 0 \leq x_m < 0{,}1 \\ Important\ (0{,}7) & 0{,}1 \leq x_m < 0{,}5 \\ Very\ important\ (0{,}9) & 0{,}5 \leq x_m \leq 1 \end{cases}$$

4. How much time do you have for the configuration process??
Time for the configuration process: n

$$\mu_k(x_k) = \begin{cases} Poor\ (0{,}3) & 0 \leq x_k < 0{,}3 \\ Average\ (0{,}6) & 0{,}3 \leq x_k < 0{,}6 \\ Good\ (0{,}8) & 0{,}6 \leq x_k \leq 1 \end{cases}$$

Step 2: Establish and obtain conclusions (β)

$$\beta(y) = \begin{cases} 20\% & y = k \\ 25\% & y = l \\ 35\% & y = m \\ 20\% & y = n \end{cases}$$

Step 3: Aggregate all conclusions (z)

$$\mu_k(x_k)[\beta(k)] + \mu_l(x_l)[\beta(l)]$$
$$+\mu_m(x_m)[\beta(m)] + \mu_n(x_n)[\beta(n)] = z$$

Step 4: Deffuzify and obtain the customer profile (δ)

$$\delta(z) = \begin{cases} Beginner & 0 \leq z < 0{,}3 \\ Intermediate & 0{,}3 \leq z < 0{,}7 \\ Advanced & 0{,}7 \leq z \leq 1 \end{cases}$$

Image 6 (Framework manual): Framework phase 3 (SELECT) guide

The answer range goes from 0 (minimum) to 1 (maximum)

1. What is your estimated knowledge about the product to be configured?

I have no knowledge at all about the product to be configured (0)
I consider myself an expert in the field of the product (1)

Select answer: 0.4

Knowledge about the final product: Average

2. How would you describe your parametric or graphic design capabilities?

I have no experience with parametric or graphic design (0)
I can develop parametric models or graphic designs without any guidance (1)

Select answer: 0.7

Parametric or graphic design capabilities: High

Customer profile: ADVANCED

3. How important is for you the customization level for the product to be configured?

Customization is not a priority for me (0)
I want to customize the product as much as possible (1)

Select answer: 0.5

Customer customization preference: Very important

4. How much time do you have for the configuration process?

I have limited time for completing the configuration process (0)
I have enough time to complete the configuratio process (1)

Select answer: 0.6

Time for configuration process: Average

Image 7 (Framework manual): Screenshot of the excel file used to automate the Mamdani's fuzzy inferences method

process (questions 1 and 2) and the level of motivation to go through the configuration process (questions 3 and 4). The answers result in four logistic variables (k, l, m & n) with different established numerical values.

2. The second step consists of the formulation of the implication operator for the logistic variables, which in this case a percentage product is used.

3. Step n°3 comprises the aggregation of all the previous conclusions into one. For this, the sum is used as an aggregation operator.

4. Lastly, the fourth step obtains the customer profile by framing the previous outcome into a numerical value associated with the profile "beginner", "intermediate" or "advanced".

As previously stated, these 4 steps are explained in more detail and with more technical terms in section 2 for a better understanding. This guide is meant to be used as a quick help for the company in the utilization of the Mamdani's fuzzy inferences method. As with the previous phase, if the maximum level of customization chosen in phase 1 is MTO, the possible customer profiles can only be "beginner" or "intermediate", thus in the case that a customer is classified as "advanced" it would be considered as "intermediate" for phase 4. It is suggested to create customer personas built from the target group to check what customer profile they would be assigned based on assumed answers. Continuing to the next phase means that the company is able to identify the level of knowledge and motivation of its target group, and classify and frame them into 3 different customer profiles that will determine their use of the product configurator.

Phase 4: Adapt

The last phase of the framework (Adapt) is about the company setting up the customer configuration process based on the balance from the 4 pillars and the outcomes from the previous phases. Therefore, the main pillar in this phase is the configurator. Based on the maximum level of customization settled by the company in phase 1, the types of product modules/parts selected in phase 2 and the obtained customer profile in phase 3, the product configurator is adapted accordingly. After the questions that are asked to the customer, the configurator obtains the customer profile and then adapts the following configuration process based on this result. There are three configuration cases for this phase based on the customer profile and the outcomes from phase 1 and 2. Image 8 presents an activity diagram that illustrates the decision-making for the three cases and the corresponding following steps. These 3 cases are explained next.

1. If the customer profile is "beginner", the company can only let the customer follow an ATO approach in which he/she can uniquely proceed with the configuration of certain modules/parts established by the company by selecting among different module/part versions. This first case is possible for both the case that company has selected an up to ETO level and also if an up to MTO level has been chosen in phase 1. Accordingly, the selection for the customer between module/part versions is only available for the ATO and above (MTO and ETO) module/parts selected in the kind-of structure of phase 2.

2. If the customer is considered to have an "intermediate" level, the company can let the user opt for the ATO approach just explained or select an MTO one if the customer is not satisfied with the configuration solution achieved with the first option. If MTO is chosen, the customer can create configuration changes to the selected module/part versions, which could be, for example, parametric adaptations or graphical changes to the version. These possible adaptations are predefined by the company, but they are not created until the customer order is placed. This possibility is also available whether the maximum level of customization selected in the first phase is up to MTO or up to ETO. Nevertheless, the user can only perform the parametric/design changes to the MTO and above (ETO) modules/parts selected in the kind-of structure.

3. Finally, if the obtained customer profile is "advanced", the company allows the customer to go through the same process as with the "intermediate" profile and if the customization level still does not satisfy him/her, an ETO approach is followed. In this case, the customer can then create the module/part inside the configurator (co-designing the module/part within the configurator) or outside the product configurator (e.g. the product configurator can have the option to upload a 3D model in different formats that once uploaded it is connected to the rest of the product in the configurator, it can let the customer upload a graphic design that is directly printed onto a part, etc.). The creation of this part, even though it is mainly developed by the customer, must remain within certain limits established by the company to assure the product's physical structure (E.g. a maximum diameter or height for a part). In this case, the ETO customization possibility is only available when the maximum level of customization selected in phase 1 is

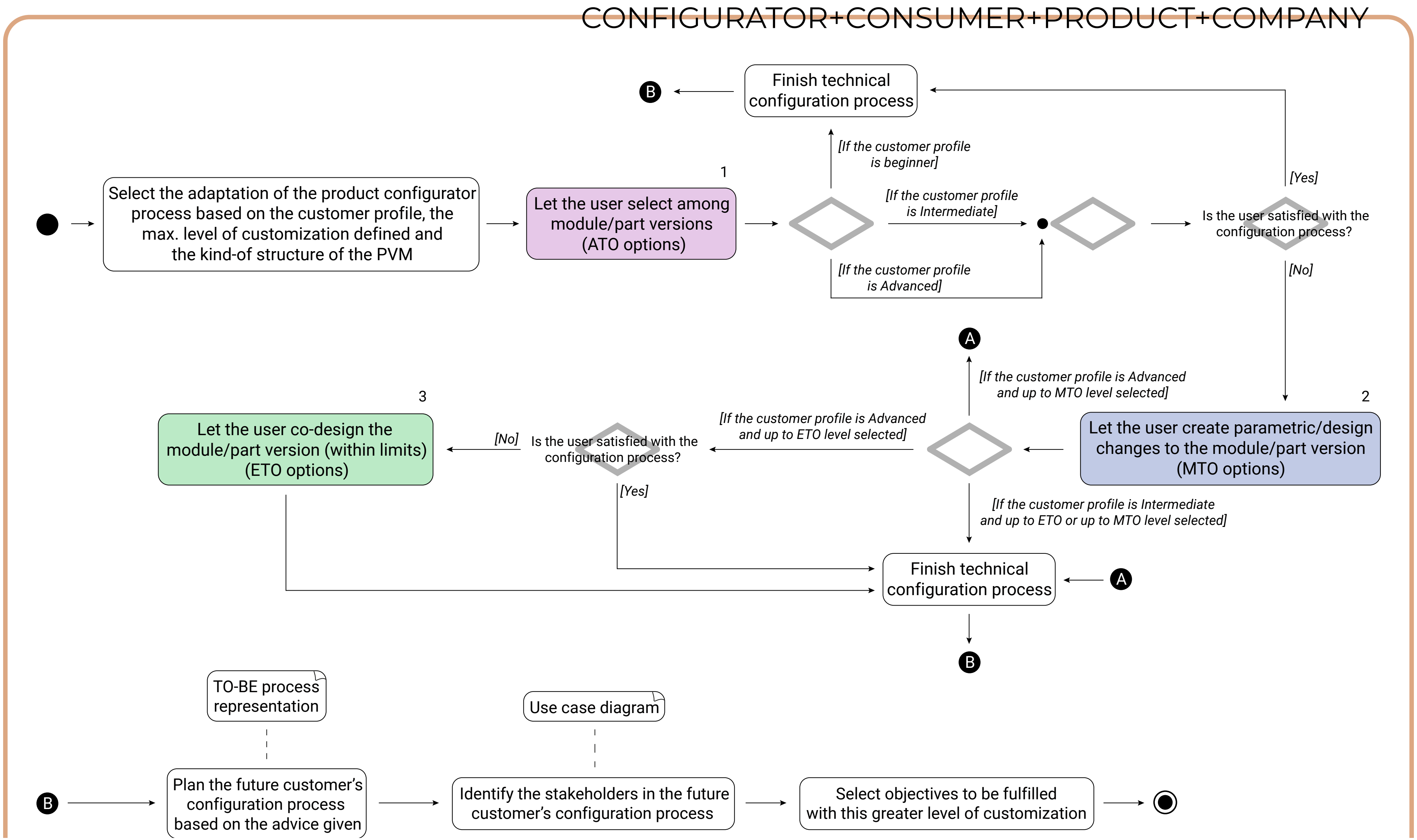

Image 8 (Framework manual): Framework phase 4 (ADAPT)

up to ETO level and for the defined ETO module/parts from phase 2 with the kind-of structure of the PVM.

The fact that a customer with an "advanced" profile is first given the option to start with an ATO approach and finish the configuration process there if satisfied, is related to the aim for a reusability strategy. This allows the possibility for the customer to engineer-to-order the final product to some extent, but this possibility is not directly proposed in favor of ATO or MTO options in order to save costs and intend for more standardization as defined in the literature. All this configuration process must be supported by a visual user-friendly interface for the product configurator in which most of the product modules/parts are presented as 3D models with the completeness level established in the last task of phase 2 (Organize).

After the three configuration cases regarding the adaptation of the product configurator are displayed, the company should then plan the future customer's configuration process based on the advice given. For this, a TO-BE process representation with the planned future product configuration process for the user is created. Afterwards, a use case diagram is utilized to identify the stakeholders that need to be taken into account to achieve the future customer configuration process established with the TO-BE process representation Among these stakeholders, the customer or the suppliers should always be present since they are explicitly mentioned throughout the framework and are a direct input. Along with this, the objectives that the company wants to obtain with the development of this product configurator are established. This last task should be then revisited once the configurator is developed to check its effectiveness.

Once the framework has been used, the company should have the necessary information to be able to plan the development of a product configurator that can let the end user engineer-to-order the final product to some extent based on the balance of the 4 main pillars. It is important to state that the ETO possibilities are the maximum level of customization that can be achieved with this framework, but it also allows the prospect of obtaining only MTO possibilities, so that the framework can be used by a wider amount of companies. As described in phase 1, the company is aimed to always go for the maximum level of customization (up to ETO) when possible.

The product configurator to be developed varies for each company, but it can be mostly classified as an external, model-based, ATO/MTO/ETO, single-use, and interactive configurator.
External because it is used to assist the end customer in the configuration of the product and, furthermore, also covers the sales and technical stage of the product configuration process. Model-based because it uses logic, resource and constraint-based approaches to obtain the configuration knowledge. ATO/MTO/ETO because the three main business strategies in the mass customization paradigm are included in the product configurator which is then adapted according to the customer profile. Single-use because it is developed for the technical and sales-delivery process of a specific product of the company, and not for the whole product family; and interactive because it checks the configuration decisions of the customer and guides the user to create the correct

ones.

2. Theoretical background

The methods that have been mentioned throughout the framework steps are further explained here to facilitate their utilization and implementation.

AS-IS and TO-BE flowcharts

The AS-IS process representation presents a visual diagram of the current process with its associated text and metrics to determine the possible areas of improvement (Monteleone, 2010).
In this framework , the AS-IS process representation is used to represent the current configuration process that the user goes through. The different steps can sometimes be associated with their corresponding stakeholder stage and also

Table 1 (framework manual): Outcomes found across literature

OUTCOMES	References
O1. More standardized products and processes	Forza & Salvador, 2002; Kristjansdottir et al., 2017; Bredahl et al., 2021; Haug et al., 2019b; Willner et al., 2013
O2. Creation of faster sales quotes	Haug et al., 2019a; Shafiee et al., 2017; Heiskala et al., 2007; Haug et al., 2009
O3. Increased sales	Forza & Salvador, 2002; Haug et al., 2019b
O4. Higher level of customization	Zheng et al., 2017b; Kristjansdottir et al., 2017
O5. More collaboration and communication between departments and stakeholders	Willner et al., 2013; Kristjansdottir et al., 2017; Kristjansdottir et al., 2015
O6. Lead time reduction	Haug et al., 2019b; Kristjansdottir et al., 2015; Kristianto et al., 2015
O7. Better customer involvement by adapting the configuration process to the customer profile	Fuerstner et al., 2012; Weinmann et al., 2011a
O8. More efficient configuration process in ETO companies through the use of product configurators	Zheng et al., 2017b; Shamsuzzoha et al., 2011; Willner et al., 2013; Bredahl et al., 2021
O9. Accuracy increase and complexity decrease in the configuration process	Willner et al., 2013; Haug et al., 2019b; Shafiee et al., 2017

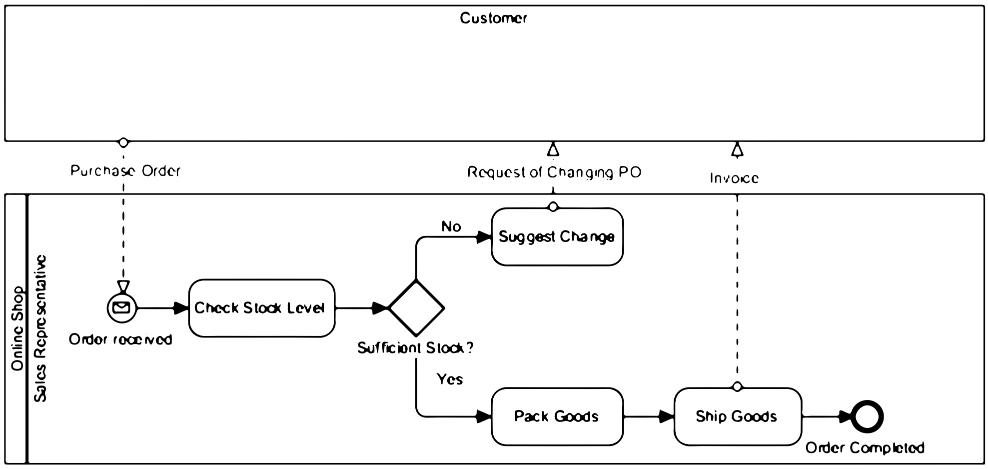

Image 9 (Framework manual): AS-IS process representation example (Visual Paradigm, 2016)

various types of flowcharts are employed to illustrate the processes. Image 9 shows a simple process example of an AS-IS process representation.

Then, based on the identified improvements, the modified diagram (TO-BE) is created with the new enhancements incorporated and an analysis is performed on how to transition to the new process (Monteleone, 2010). Image 10 shows the corresponding TO-BE process representation from the previous example in image 9.

In order to create the TO-BE process representation, the company has to take into account the level of customization that wants to be achieved with the product configurator, the organization of the modules/parts based on the business model and the customer profile (outcomes obtained from the use of the framework). Furthermore, the stakeholder requirements for the achievement of this customization (process supported by the

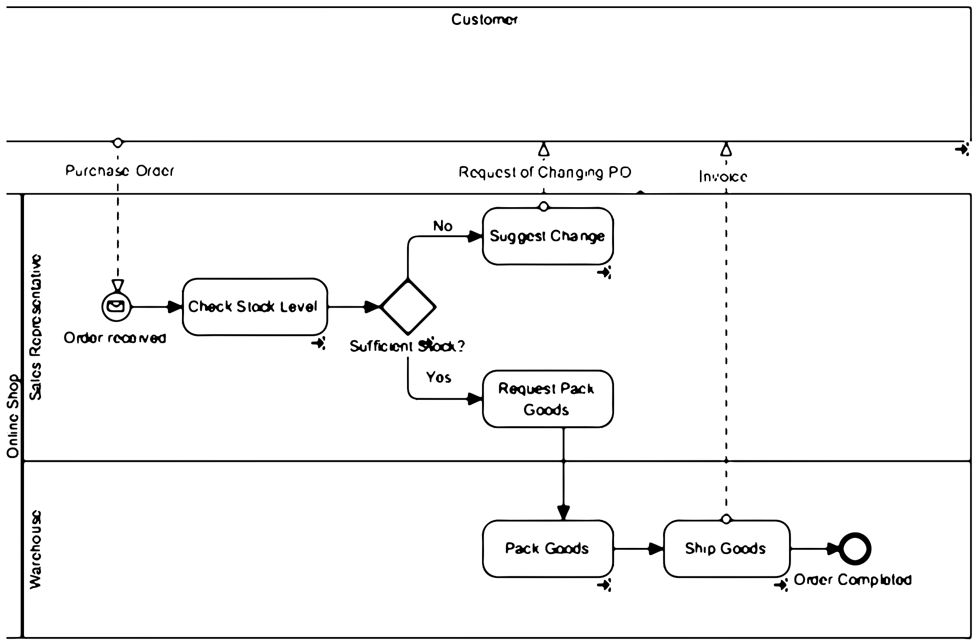

Image 10 (Framework manual): TO-BE process representation example (Visual Paradigm, 2016)

use case diagrams to be explained) also need to be taken into account to create a realistic overview of the future process.

The objectives that want to be obtained with the TO-BE process representation can be selected, as previously mentioned, from the main positive outcomes (table 5) found in the literature about the relation between product configurators and ETO processes, and product configurators and the customer knowledge. These can include, for example, a lead time reduction or a more standardized process.

Product Variant Master (PVM)

The Product Variant Master (PVM) is used to break down the components of the product into a tree structure and identify the main product variants and possible constraints for the product (Hvam et al., 2008). In this thesis, the PVM is used to classify the modules and/or parts of the product to help in the identification of which business model works best for each product module/part.

In general, the left-hand side of the PVM (also known as the "part-of"-structure) shows the components included in the product, while the right-hand side (known as the "kind-of" structure) shows the versions or variables (Hvam et al., 2008). The structures are divided into classes, which can be defined as a group of objects with the same structure or function.
In the part-of structure, a class can also contain one or more sub-classes. Each class can also contain attributes that describe the class and constraints that define the rules for how classes and their attributes can be combined. Each sub-part has cardinality describing how many sub-parts a part has.
Then, the kind-of structure describes the range of variation for a given class. Image 11 shows a simplified and generic overview of the Product Variant Master. Therefore, in this framework manual the part-of structure describes the product modules/parts by breaking them down into classes and the kind-of structure is used to define which modules/parts can and should aim for the different business models by identifying their potential

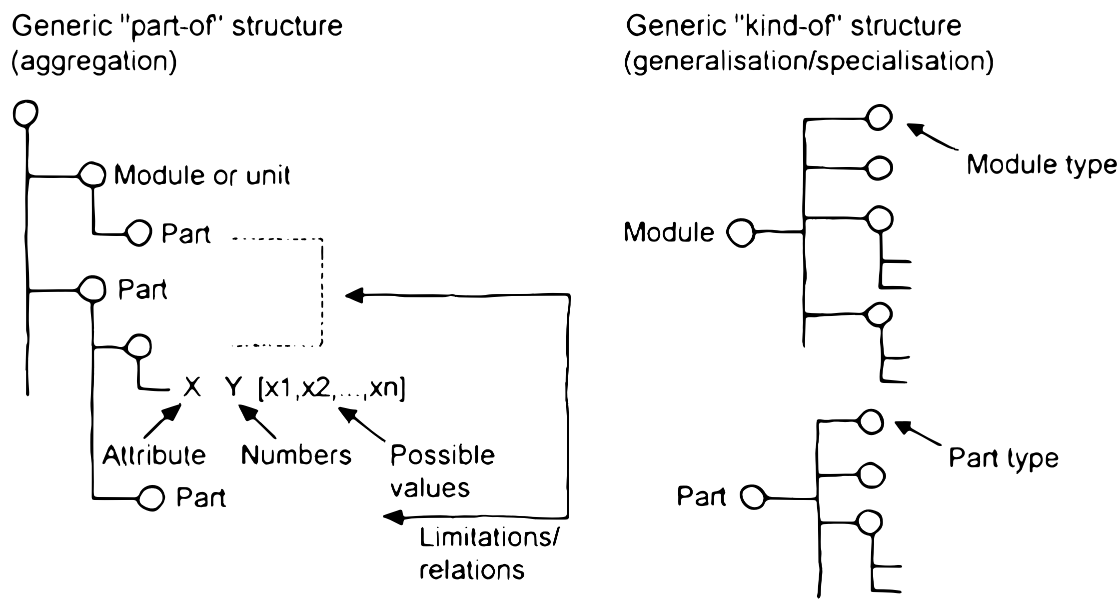

Image 11 (Framework manual): Generic principles of the Product Variant Master (Hvam et al., 2008)

versions. If a module or part is identified as a possible personalized module in some of its versions, it does not mean that it should always follow an ETO approach. In this case, depending on the customer profile (identification method to be explained in this chapter), the module/ part to be customized could follow an ATO, MTO or ETO strategy.

To describe the constraints among the different modules and parts, combination tables can be used to identify the possible relations between them. Alternatively, verbal, logical and calculation constraints can also be utilized. The Product Variant Master can be created from a customer point of view, an engineering point of view or a production point of view. This thesis focuses on the customer view which contains both functional and structural aspects of the product range. It is stated that a product configurator with ETO approaches work best with not highly complex products with a well-defined structure (Bredahl et al., 2021). The quantity of modules and parts included in the Product Variant Master is defined by the own company. It is advised to only include in the PVM modules and parts with customization potential if there are a big number of components in the product. Through this procedure, it is avoided an unnecessarily lengthy process with modules/parts that are known to not provide any further possible product variety.

Mamdany's fuzzy inferences method

The Mamdani's fuzzy inferences method is used in this framework manual to determine the customer profile based on the level of knowledge and motivation of the product configurator user (Fuerstner et al., 2012). A fuzzy analysis is utilized to solve problems that do not have a specific and certain base (Coroiu, 2015). They are used to transform an input space into an output space employing fuzzy logic.

The Mamdani's method has a simple structure of minimum and maximum operations. The fuzzy inference process is comprised of four consequent steps:

5. Evaluating the antecedents.
   First, given the provided input (always a numerical value), the membership degree, which is the degree to which an input belongs to a specific fuzzy set, is determined. The membership degree must always belong to a $0 \leq x \leq 1$ interval, based on a range from minimum (0) to maximum (1).

6. Obtaining conclusions.
   Then, for each rule resulting from the membership degree of the previous step, an implication operator is applied to obtain a new fuzzy set which is the conclusion of the rule. The operator used in this work is the product, which scales the result.

7. Aggregating all conclusions.
   Afterwards, the output of the rules obtained in step two is combined into a single fuzzy set by using an aggregation operator. In this thesis, a sum is used.

8. Defuzzifying.
   Finally, a unique numerical value is obtained as the output of the inference process. In this case, the final output is the customer profile, which is obtained after the defuzzification.

The provided input for the first step is obtained by asking a set of questions to the customer before the configuration process. In this framework, these questions, their corresponding membership degree are based on the level of knowledge and motivation of the customer. The questions, their corresponding membership degree, and the logistic variables are based on the literature and the work from the author. As described before, these values are the ones proposed in this framework manual, but the company can also adapt them to their unique situation if desired.

Regarding the level of knowledge, two questions are presented, one about the customer knowledge in the final product to be designed, and the other one about the configuration capabilities:
(1) What is your estimated knowledge about the product to be configured?
The membership degree can go from a minimum of "I have no knowledge at all about the product to be configured" (0) to a maximum of "I consider myself an expert in the field of the product" (1). This numerical answer is presented later with the letter "*x*".
(2) How would you describe your parametric or graphic design capabilities?
The minimum would be "I have no experience with parametric or graphic design" (0) to a maximum of "I can develop parametric models or graphic designs without any guidance" (1)

Regarding the level of motivation to perform the configuration process, two more questions are asked to the customer:
(3) How important is for you the customization level for the product to be configured?
In this case, the membership degree can shift from "Customization is not a priority for me " (0) to "I want to customize the product as much as possible" (1).
(4) How much time do you have for the configuration process?
The minimum would be "I have limited time for completing the configuration process" (0) to "I have enough time to complete the configuration process" (1).

Based on these answers, four logistic variables are obtained. Each variable has three resulting values that are associated with a number [*μ(x)*].
(1) Knowledge about the final product (k), with resulting values of "poor", "average" and "good".
(2) Parametric or graphic design capabilities (l), whose possible values are "low", "medium" and "high".
(3) Customer customization preference (m), with values of "irrelevant", "important" and "very important".
(4) Time for the configuration process (n), for which the values are "not enough", "average" and "enough".

Then, a fuzzy set is calculated with the membership functions for the variables. The percentages are defined by the author and are based on the literature. These functions are presented in equations 1 to 4:

Equation 1 (framework manual): Initial fuzzy set (k)

$$\mu_k(x_k) = \begin{cases} Poor\ (0{,}3) & 0 \le x_k < 0{,}3 \\ Average\ (0{,}6) & 0{,}3 \le x_k < 0{,}6 \\ Good\ (0{,}8) & 0{,}6 \le x_k \le 1 \end{cases}$$

Equation 2 (framework manual): Initial fuzzy set (l)

$$\mu_l(x_l) = \begin{cases} Low\ (0{,}2) & 0 \le x_l < 0{,}2 \\ Medium\ (0{,}6) & 0{,}2 \le x_l < 0{,}7 \\ High\ (1) & 0{,}7 \le x_l \le 1 \end{cases}$$

Equation 3 (framework manual): Initial fuzzy set (m)

$$\mu_m(x_m) = \begin{cases} Irrelevant\ (0) & 0 \le x_m < 0{,}1 \\ Important\ (0{,}7) & 0{,}1 \le x_m < 0{,}5 \\ Very\ important\ (0{,}9) & 0{,}5 \le x_m \le 1 \end{cases}$$

Equation 4 (framework manual): Initial fuzzy set (n)

$$\mu_n(x_n) = \begin{cases} Not\ enough\ (0) & 0 \leq x_n < 0{,}2 \\ Average\ (0{,}5) & 0{,}2 \leq x_n < 0{,}7 \\ Enough\ (0{,}9) & 0{,}7 \leq x_n \leq 1 \end{cases}$$

Then, for each of the rules created by the initial fuzzy sets, an implication operator (in this case a product/scale) is applied obtaining new fuzzy sets. The scale operator (β) used for each of the variables is described in equation 5. Naturally, the sum of the scale operators must equal 100%. These percentages are also defined by the author and based on the literature that establishes the level of motivation as a more important factor than the level of knowledge for the customer profile determination.

Equation 5 (framework manual): Second fuzzy set

$$\beta(y) = \begin{cases} 20\% & y = k \\ 25\% & y = l \\ 35\% & y = m \\ 20\% & y = n \end{cases}$$

The third step is the combination of all the previous fuzzy sets into a single third fuzzy set by the means of an aggregation operator, which in this case is a sum. Equation 6 represents this step:

Equation 6 (framework manual): Third fuzzy set

$$\mu_k(x_k)[\beta(k)] + \mu_l(x_l)[\beta(l)] + \mu_m(x_m)[\beta(m)] + \mu_n(x_n)[\beta(n)] = z$$

Lastly, a numerical value is obtained and based on this number, the defuzzification (equation 7) is performed obtaining the customer profile (δ) which, as previously described can be "beginner", "intermediate" or "advanced". These percentages are also defined by the author and based on the examples from the literature.

Equation 7 (framework manual): Defuzzification

$$\delta(z) = \begin{cases} Beginner & 0 \leq z < 0{,}3 \\ Intermediate & 0{,}3 \leq z < 0{,}7 \\ Advanced & 0{,}7 \leq z \leq 1 \end{cases}$$

As described in section 1, along with this explanation of the Mamdany's fuzzy inferences method for this case, an excel file that automates this process can also be utilized (Mamdani's automated excel). By using this file, the company can check, by providing different assumed answers, what the customer profile would be. Furthermore, it provides the possibility to adapt the questions or que variables of the method (Mamdani's automated excel [edit version]).

UML diagrams

This framework manual utilizes two types of behavioral diagrams from the Unified Modeling Language: use case diagrams and activity diagrams.

The UML is a general-purpose, graphically based modeling language that has its origin in the field of object-oriented programming and is usually intended to describe and create software systems (Kleidermacher & Kleidermacher, 2012). Behavioral diagrams are those that capture the varieties of interaction and instantaneous states within a model as it executes over time, tracking how the system will act in a real-world environment, and observing the effects of an operation or event, including its results (Kleidermacher & Kleidermacher, 2012).

Use case diagrams

The use case diagrams are used to model user/system interactions (Kleidermacher & Kleidermacher, 2012). They give a graphic overview of the actors involved

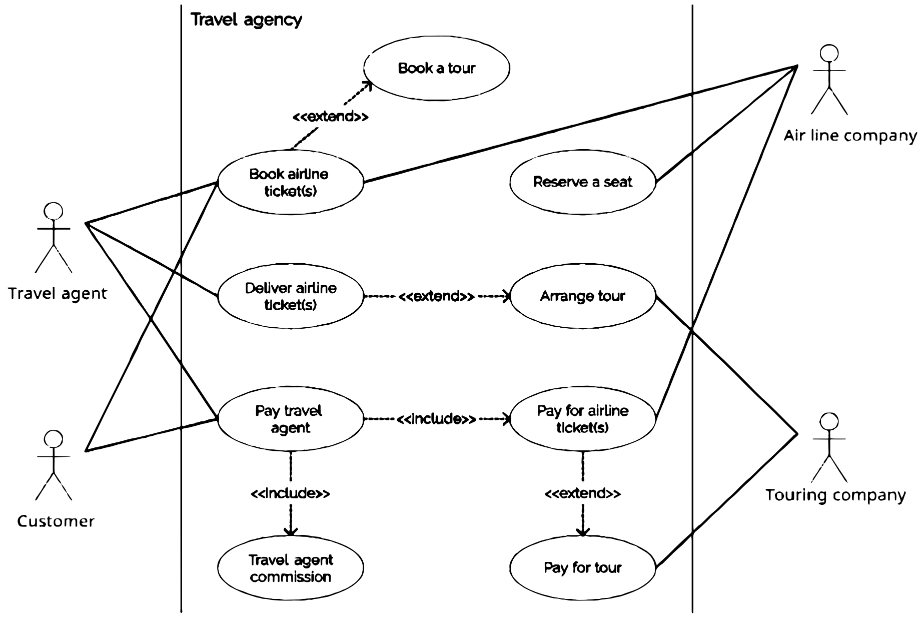

Image 12 (Framework manual): Example of a use case diagram (Creately, 2021)

in a system, different functions needed by those actors and how these different functions interact (Creately, 2021). The main relationship type in the use case diagrams is the association between an actor and a use case. Nevertheless, there are also others like the "extend" between two use cases or the "include" between two use case. In the case of "include", one of the use cases is conditioned by another one to be performed, it denotes a full dependency to another use case. In the case of "extend", the association is an addition to a use case, not always dependent on the other every time the use case is performed.

In this framework manual the use case diagram is utilized to identify the relevant stakeholders in the configuration process that the user goes through when using the product configurator. Image 12 shows an example of a use case diagram for a travel agency.

Activity diagrams

The activity diagrams are used to represent interactions between processes. These diagrams show how the system entities, usually components, run in parallel with each other and the synchronization points between them (Kleidermacher & Kleidermacher, 2012).

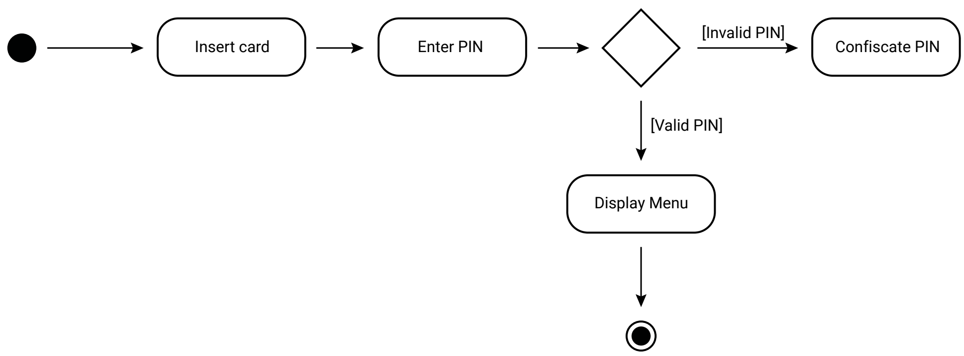

Image 13 (Framework manual): Example of an activity diagram (Creately, 2021)

Basically, activity diagrams graphically represent workflows. They can be used to describe the business workflow or the operational workflow of any component in a system (Creately, 2021). Image 13 shows an example of a simple activity diagram for the SIM process menu in a phone.

This type of behavioral diagram from the Unified Modeling Language is chosen to organize the different phases of the framework, since it offers a visual and standard method to visualize the framework's workflow, and helps to provide an intuitive way to understand the decision-support framework. It is also utilized to represent the information of the AS-IS and TO-BE process representations previously described, in order to use similar approaches in terms of workflows.

The main elements to develop an activity diagram are the following (Lucidchart, n.d; Creately, 2021) (described graphically in image 14):

1. Start symbol. It represents the beginning of a process or workflow in an activity diagram. It can be used by itself or with a note symbol that explains the starting point. When a letter is included it represents the continuation of the diagram.

2. Activity symbol. It indicates the activities that make up a modeled process.

3. Connector symbol. It shows the directional flow, or control flow, of the activity.

4. Decision symbol. It represents a decision and always has at least two paths branching out with condition text to allow users to view options.

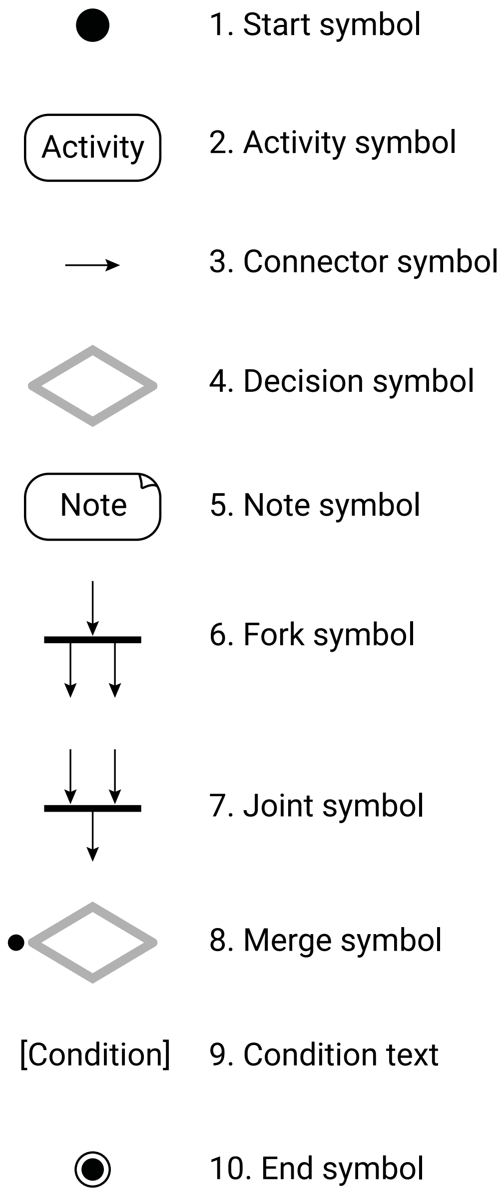

Image 14 (Framework manual): Framework activity diagram elements

5. Note symbol. It allows for the communication of additional messages that don't fit within the diagram itself.

6. Fork symbol. It splits a single activity flow into two or more concurrent activities.

7. Joint symbol. Combines two or more concurrent activities and re-introduces them to a flow where only one activity

occurs at a time. The process can not continue until both concurrent activities are performed.

8. Merge symbol. It brings together multiple flows that are not concurrent. It has several inputs, but one output.

9. Condition text. It is placed next to a decision marker to let know under what condition an activity flow should split off in that direction.

10. End symbol. It marks the end state of an activity and represents the completion of all flows of a process. It can also be used with a note symbol explaining the ending point.

Appendix B: Reference correspondence

REFERENCE CORRESPONDENCE

Appendix

B

In this appendix, the correspondence between the references in the literature and the numbers in the reference and impact models is displayed.

Table 7: Reference correspondence

Nº in the reference/ impact model	REFERENCE IN THE LITERATURE
1	Forza & Salvador (2002)
2	Blecker et al. (2004)
3	Zhang (2014)
4	Hicks & Mcgovern (2009)
5	Vollmar & Gepp (2015)
6	Olhager (2003)
7	Pandit & Zhu (2007)
8	Zheng et al. (2017b)
9	Kristjansdottir et al. (2017)
10	Fuerstner et al. (2012)
11	Haug et al. (2019b)
12	Willner et al. (2013)
13	Shafiee et al. (2014)
14	Du et al. (2005)
15	Weinmann et al. (2011a)
16	Hvam et al. (2008)
17	Kristjansdottir et al. (2016)
18	Bredahl et al. (2021)
19	Zheng et al. (2017a)
20	Haug et al. (2019a)
21	Kristianto et al. (2015)
22	Kristjansdottir et al. (2015)
23	Brière-Côté et al. (2010)