Aalto University
School of Engineering

Imaad Shaik

Utilising a Modern Quality Function Deployment Process in Ship Modularisation

Master's Thesis submitted for examination for the degree of
Master of Science in Technology

Espoo 29.04.2019
Supervisor: Prof. Kevin Otto
Advisor: M.Sc. Pasi Laakeristo

This page is intentionally left blank

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Imaad Shaik

Title of thesis Utilising a Modern Quality Function Deployment Process in Ship Modularisation

Master programme Mechanical Engineering **Code** ENG25

Thesis supervisor Prof. Kevin Otto

Thesis advisor(s) M.Sc. Pasi Laakeristo

Date 29.04.2019 **Number of pages** 98 + 4 **Language** English

Abstract

Rising passenger numbers in the leisure cruise industry has resulted in cruise ships sailing in full capacity. This trend is estimated to grow further by 42% until 2027 causing the cruise companies to order around 120 new ships to be delivered by 2027. The increasing order numbers have put most of the shipyards around the world that build cruise ships to run in full capacity. However, to increase their productivity while staying competitive, the shipyards have to take a different approach to build ships. One such approach is building modularly designed ships.

This thesis study forms a part of the case company's efforts to explore the modular ship design process by utilising a tailor-made Quality Function Deployment approach. Specifically, the study looks into finding a robust approach of generating product requirements by incorporating customers' desires and wishes with the help of the QFD process recommended by the newly standardised ISO 16355 series of standards.

Study of the modular design process, the case company's internal design process along with the QFD approach recommended by the ISO standard, the author creates a draft QFD process, which is tested out in the shipyard along with the technical experts to get insights on the draft approach. The study also analyses the suggestions to the classical QFD by the ISO documents and recommends the better alternative since not many case studies have been made using the ISO recommended QFD approach.

The feedback obtained along with the observations made helped to create a robust tailored QFD approach for the case company to incorporate in their modular product development efforts. Further, the author recommends solutions to eliminate or reduce the impact of the challenges the case company might face while implementing the recommended QFD approach in the new modular design process.

Keywords Quality Function Deployment, Modular Ship Design, ISO 16355 standard

This page is intentionally left blank

Acknowledgement

It has been a fantastic time learning, growing, making new friends and gathering unforgettable experiences at Aalto. Getting introduced to Aalto Design Factory was one of the best things that happened in my life. It’s there that I learned the true meaning of inter-disciplinary collaboration, got out of my comfort zone and started thinking in an entirely new way. I am grateful to all the Aalto University community members who directly or indirectly have made an impact on my life.

I am also grateful to my supervisor Prof. Kevin Otto who not only made sure that I was on track, but also encouraged me to explore new directions in my thesis study. I would like to thank Meyer Turku Oy for trusting in my abilities and giving me this thesis opportunity. Thanks also go to my thesis advisor, Pasi Laakeristo, for guiding me through this complex world of shipbuilding and not forgetting Juha Tomberg and Mika Mäkinen for always providing me guidance and tools to carry out my thesis successfully. Thanks to all the technical experts of Meyer Turku Oy who made time to participate in this study and gave fruitful data for and insights about the study. I would also like to thank my friends who have supported me both directly or indirectly during this period.

Finally, I would like to thank my mum, dad, brother and my sister for their unconditional love and support, without whom I would have never been in the place that I am today.

Imaad Shaik

Espoo, 29.04.2019

This page is intentionally left blank

Table of Content

Glossary

QFD	Quality Function Deployment
MFD™	Modular Function Deployment™
ISO	International Organization for Standardization
RTD	Robust Tolerance design
SS	Steam Ship
CLIA	Cruise Lines International Association
CIN	Cruise Industry News
P&O	Peninsular and Oriental cruises
MPD	Modular Product Development
DSM	Design Structure Matrix
FSH	Function Structure Heuristics
SH	Similarity Heuristics
HoQ	House of Quality
MIM™	Module Indication Matrix™
MD	Module Driver™
Md	Module
TS	Technical Solution
ASI	American Suppliers Institute
QFD-ID	QFD Instituts Deutschland
VoC	Voice of Customer
VoE	Voice of Engineer
VoS	Voice of Stakeholder
VoB	Voice of Business
AHP	Analytic Hierarchy Process
L-Matrix	An L shaped Matrix
MECE	Mutually Exclusive and Collectively Exhaustive
ANP	Analytic Neural Process
QPT	Quality Planning Table
MVT	Maximum Value table
DPT	Design Planning Table
TRIZ	теория решения изобретательских зада *(Theory of Inventive Problem Solving)*

List of Figures

List of Tables

This page is intentionally left blank

1 Introduction

To be successful in today's competitive market, businesses not only should be innovative in their product offerings but also make sure the product solves the customers' problems. This is evident from a survey conducted by McKinsey & Company were 84% of the executives agreed that the innovation is critical to their growth; however, most of them also agreed that the majority of innovations fell far short of their ambitions (Christenses, et al., 2016). Many a time's large companies develop products that are superior in technology to their previous versions but fail to satisfy the customers. One of the main reasons for the failure is the product designer's belief that they know what the customer wants better than anyone does, even the customers (Baker, 2010). To avoid this, the product designer's should start by understanding what the customer really wants from the customer's own words, prioritise the most critical needs and translate the identified needs into the requirements that shall be incorporated in the finished product while also considering the business aspect of the product. However, as this process is carried out, some of the information gets biased or changed due to the conflicts in the needs and requirements of the different stakeholders involved in the project (Bendjenna, et al., 2012). Moreover, when we consider a global organisation, these conflicts can also emerge from the misunderstandings or the lack of communication between different groups of people, such as departments within the company, customers or suppliers, each with their own linguistic or cultural identities. These differences play a significant role in the final quality of the product.

Having a systematic approach to the product development process helps the organisation to understand their customers' needs better and translate them into a list of relevant technical specifications, which results in an organisation having better control of the quality, costs and engineering aspects of the product (Maritan, 2015). One such approach is *Quality Function Deployment (QFD)* introduced in Japan in 1966 (Akao, 1972).

The overall aim of this thesis is to utilise the newly standardised QFD approach, *i.e., ISO 16355 — Application of statistical and related methods to new technology and product development process,* to propose a tailored QFD process for identifying the customer needs and translating them into product requirements such that the product requirements are used as the input for the subsequent processes in the modular ship development process. This thesis study forms a small, yet crucial part of a more extensive process used by the case company, *i.e., Modular Function Deployment*™. The advantage of utilising modular design is to create a strategically flexible product design, which allows variation in products without requiring the redesign of products every time a new product variant is required. Moreover, the flexibility of modular architecture design not only helps to reduce product development lead-time but also helps in parallel development of the products that in turn leads to less capital tied in production due to shortened production lead-time, easier service and upgrading and overall improved quality (Ericsson & Erixon, 1999). Dahmus, et al., in their journal mentioned that Volkswagen saved $1.7 Billion annually on development and production costs through effective product architecture and use of standard components among its four brands, *i.e., VW, Audi, Skoda and Seat* (Dahmus, et al., 2001). Therefore, having a well-defined QFD process is necessary to obtain relevant data to feed the subsequent processes for the modular product development of the ship.

The primary objective of this thesis is to propose:

> *A tailored QFD approach to help the case company successfully carry out the ship modularisation process.*

To achieve the set objective, it is crucial to understand the way the case company currently works and finding an appropriate QFD flow to integrate into the case company's current workflow without requiring many changes. This required the QFD process to be carried out in realtime. However, to ease the execution of the QFD process, a list of questions are put forth forming research questions for this thesis, *i.e.,*

i. *What are the steps that can be both beneficial and economical while implementing the QFD process in the case company?*
ii. *How to have a seamless transition from the QFD process to the subsequent processes of modular product development?*
iii. *What are the challenges one might face while implementing the QFD process in ship modularisation and how to overcome these challenges?*

The study is carried out in three phases: *Literature review, process implementation and result analysis*. Figure 1.1 summarises the path of the study used to answer the research questions.

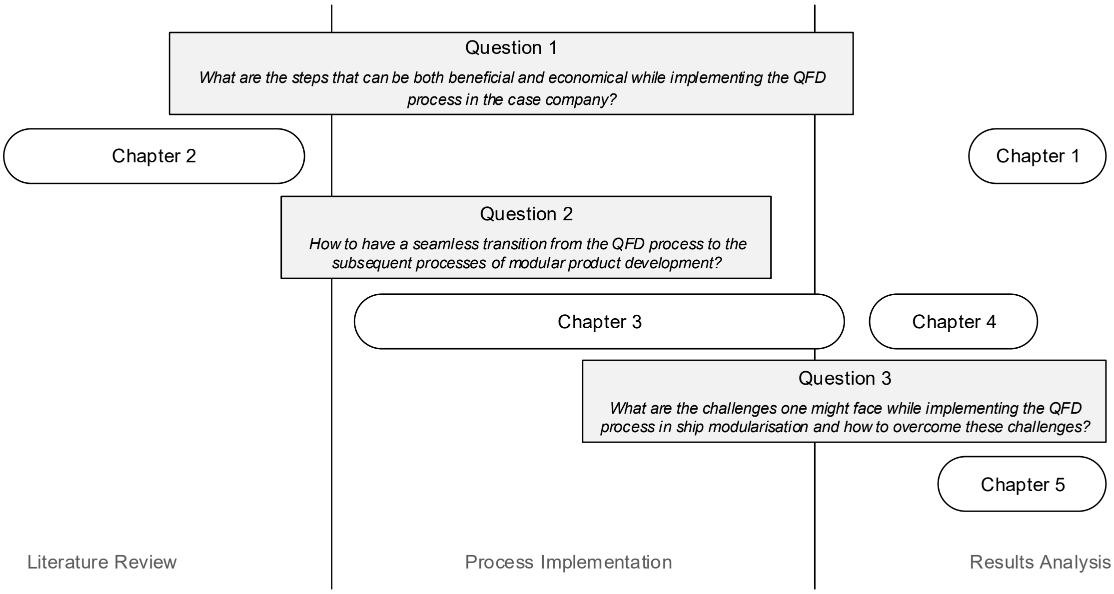


Figure 1.1 Division of the thesis study and the chapter covered in each phase

Literature Review phase:

In this phase, the first question is answered by studying the ISO 16355 series documents thoroughly to understand the ISO recommended QFD approach and the tools helpful to carry out the QFD process. Simultaneously, the Modular Function Deployment™ *(MFD™)* process is investigated briefly to understand the nature of the output required from the QFD process to be used as the input for the MFD™ process, which not only helps to get an idea of how to approach the second question but also to define the scope of the QFD process.

Process Implementation Phase:
This phase starts by developing an initial draft of the QFD approach based on their advantages and disadvantages in the context of ship modularisation. This is followed by piloting the draft QFD approach along with the stakeholders in the shipyard, which helps to understand whether the process is suitable for implementation in the case company and gives a chance to understand the challenges associated with the implementation answering the third question.

Result Analysis phase:
Finally, in this phase, the results and findings of the case study are analysed, and a tailored QFD approach is recommended to successfully integrate the QFD process in the shipyards modular ship development process.

The structure of this thesis is according to the following five chapters: *Introduction, Background, Methodology, Results and Discussion,* and *Conclusion*. Chapter 2, *Background*, dives deep into the existing literature about the QFD process, MFD™ process and more precisely the ISO recommended QFD approach. Chapter 3, *Methodology*, focuses on answering the fundamental questions required to achieve the objective successfully and the processes carried out. Chapter 4, *Results and discussion,* analyses the obtained results from the case study to understand the usefulness of the results to answer the research questions, concluding the chapter by recommending a tailored QFD process for the case company and the limitations of this thesis. Finally, chapter 5, *Conclusion,* reflects on the key findings on arriving at the tailored QFD approach.

1.1 ISO 16355 series

1.1.1 About ISO

The International Organization for Standardization or ISO, is a non-governmental, independent international organisation founded in 1947 to *"Facilitate the international coordination and unification of industrial standards"* and to answer a fundamental question – *"What is the best way of doing this?"*. Currently, ISO is composed of members from 164 national standard bodies and 786 technical committees and subcommittees who are responsible for the standards development (ISO, 2019a).

ISO develops standards for products, systems and services to ensure quality, safety, reliability and efficiency for almost all of the industries ranging from manufacturing to technology, food safety, electronics, healthcare, agriculture and aerospace. Academic and industrial researchers, along with industry experts, consumer associations, NGO's and the regulatory bodies of various countries together make the standards, which makes it a reliable source of information (ISO, 2019b).

1.1.2 Role of ISO 16355

ISO 16355 series demonstrates the dynamic nature of a customer-driven approach by describing the QFD process, its purpose, users, and tools. This standard series is written to satisfy a wide variety of stakeholder from different industries with diverse background, goals and product offering, thus employing the comprehensive QFD approach. Therefore, ISO 16355 standard functions as a guide to the users that describes and discusses the current best practice of QFD rather than forcing the users to follow all the procedure and tools described in the standard. This gives users the freedom to choose the tools and methods based on their project requirement (ISO 16355-1:2015, 2015). The ISO 16355 series is divided into the following seven parts:

Part 1: General Principle and Perspective of QFD Method (ISO 16355-1:2015, 2015)
Part 2: Non-quantitative approaches for the acquisition of VOC and VOS (ISO 16355-2:2017, 2017)
Part 3: Quantitative approaches for the acquisition of VOC and VOS (ISO 16355-3:2019, 2019)
Part 4: Analysis of non-quantitative and quantitative VOC and VOS (ISO 16355-4:2017, 2017)
Part 5: Solution Strategy (ISO 16355-5:2017, 2017)
Part 6 [Under Development]: QFD related approaches to optimization (ISO 16355-6)
Part 8: Guidelines for commercialization and life cycle (ISO/TR 16355-8:2017, 2017)

NOTE: *Part 7 replaced with ISO/CD 16337 – Robust Tolerance Design (RTD)*

Below is a list of questions Mazur (2016) has compiled that a product developer may have while developing a product and linked it to the appropriate parts of the ISO 16355 standard that would be helpful to answer these questions.

- Which customer voices are critical to hear? (ISO 16355-2:2017, 2017)
- Which activities of those customers most concern them? (ISO 16355-2:2017, 2017)
- What are the customers saying, doing, thinking during these activities? (ISO 16355-2:2017, 2017)
- What problems *(undesired negatives)*, opportunities *(unfulfilled positives)* and image *(look and feel good)* issues are customer facing? (ISO 16355-4:2017, 2017)
- Which of these are most important for us to address first? (ISO 16355-3:2019, 2019; ISO 16355-4:2017, 2017)
- What competitive alternatives does the customer have? (ISO 16355-4:2017, 2017)
- What must our new product, service, software or process be or do to solve the customers most important problems, opportunities or image issues? (ISO 16355-5:2017, 2017)
- What are the optimal targets of function and performance must the new product, service, software or process achieve to sufficiently solve and be robust to the most critical problems, opportunities or image issues? (ISO 16355-6; ISO/CD 16337)
- What activities are essential to delivering these function and performance targets to the customer? (ISO/TR 16355-8:2017, 2017)
- How can we assure these activities are carried out with sufficient quality and carried into the next generation product? (ISO/TR 16355-8:2017, 2017)

2 Background

Humans have been sailing across the waterbodies for millenniums in search of fertile lands, expansion of their civilisation, fishing, trade, transport and warfare. It is believed that the first humans arrived in Australia presumably by some type of raft or boat about 45,000 – 60,000 years ago (Laidlaw, 1984). However, the earliest evidence of the existence of a ship is a painted disc found in Kuwait dating back to 5000 – 5500 BC (Carter, 2006).

During the 19th century, the rising inter-continental trade and the industrial revolution fuelled the development of transportation on water, and by 1807, Robert Fulton successfully built the first commercially successful steamboat to transport passenger across the Hudson River (Hunter, 1985). In 1819, SS Savannah became the first steam-powered ship to cross the Atlantic Ocean, which took her around 29 days to complete (Smithsonian, 1819). However, the industry of leisure cruising began when the Peninsular & Oriental Steam Navigation Company *(currently P&O Cruises)* started offering tours to Malta and Athens in 1844 (Cable, 1937). In the meantime, the trend of transatlantic travel in ocean liners continued as the migration to the Americas increased, and in 1858, Isambard Brunel designed the world's largest ship of the time, SS Great Eastern, which held her title until the early 1900s with a passenger carrying capacity of 4000 (Mars & Jubelin, 2001). During World War I and World War II, many of the ocean liners were converted into hospital or troop transporting vessels and some even converted into warships (Le Goff, 1998; Gérard, 2009).

The leisure cruising did not have a significant share of the market until the early part of 1960s, when the demand for Ocean liners declined as it could not compete with the jetliners, which travelled the transatlantic route in under 1/12th the time it took for the ocean liners to complete the same journey and could effectively carry much more passengers over the same period of time. This forced the ship owners to convert their ocean liners into cruise ships, and by 1986, the passenger ocean liners ceased their operations and concentrated on cruise ships instead (Mars & Jubelin, 2001).

Today, the cruise industry has seen an increase of 37% in the passenger numbers compared to 2011 and is estimated to grow even further about 42% until 2027. Currently, there are 386 cruise ships in service carrying around 28.2M passengers and approximately 120 new cruise ships on order through 2027 (CLIA, 2019; CIN, 2019). To fulfil these orders in a fiercely competitive industry, shipyards must offer not only competitive pricing and shorter delivery times but also be innovative on how they approach their shipbuilding process (Bertram, 2005).

The following sections explain the current shipbuilding process and the benefits of a modular approach to building ships along with QFD helping the shipyards to tackle the problems mentioned above.

2.1 Ship design process

As the cruising industry progressed, the end-users became more demanding, which led to the design of cruise ships become much more sophisticated. At present, the process of ship design consists of four stages, *i.e., concept design, preliminary design and contract design,* followed by a *detail design* phase. This highly iterative approach of ship design is called the design spiral and is illustrated in figure 2.1.

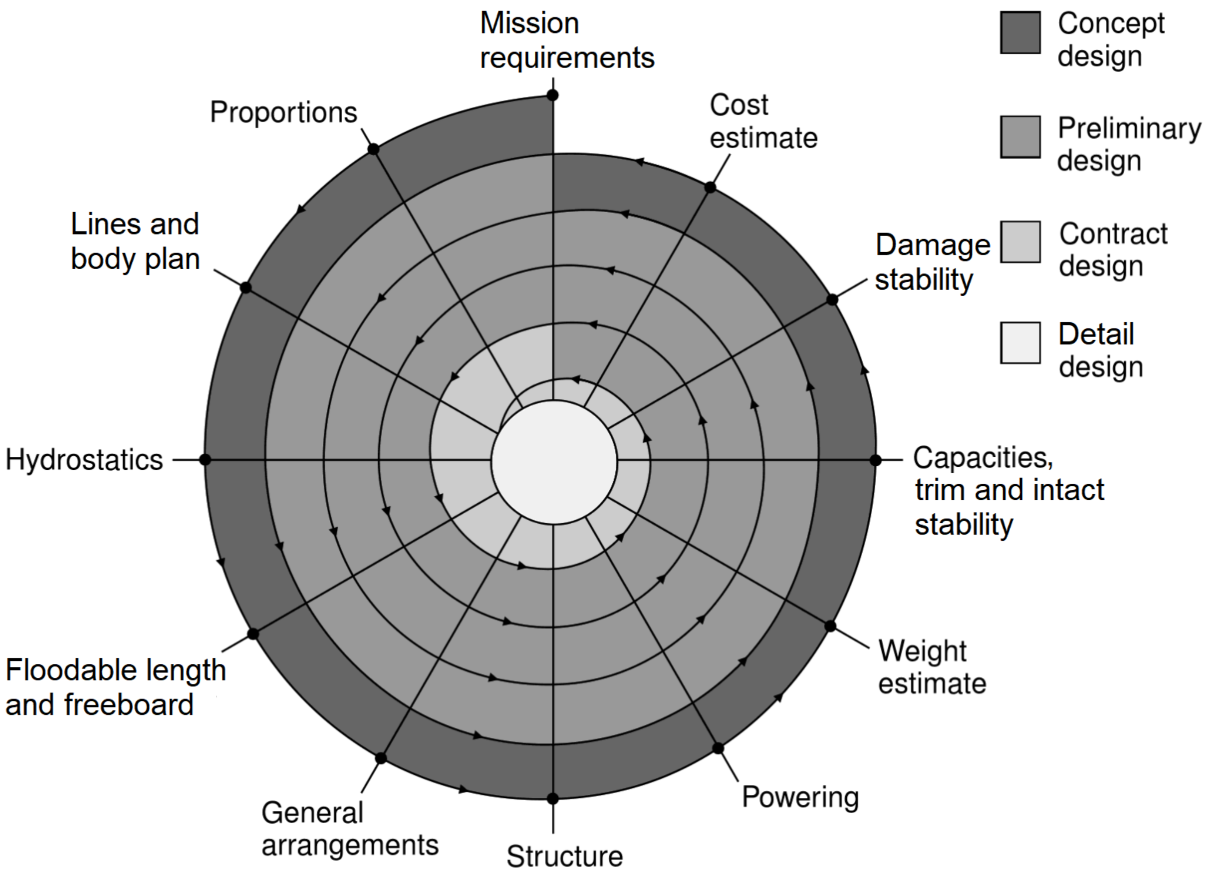


Figure 2.1 Design Spiral – Adapted from Evans (1959) & Eyres (2006)

Concept design phase is the starting point of the ship design were the objectives, or the mission requirements of the ship design is translated into the fundamental engineering characteristics of the ship such as power estimation, preliminary hull shape, cost estimation and preliminary hydrostatic and hydrodynamic calculation (Vossen, et al., 2013). Further, this phase helps to provide sufficient information for the assessment of the basic techno-economic alternatives for the design. The economic criteria used to measure profitability for commercial ship design are the net present value, discounted cash flow or required freight rate (Eyres, 2006).

Preliminary design phase is used to find the most efficient overall design by analysing and refining the evaluated concept designs in close cooperation with the customer. The refined concept is helpful to fill out the general arrangement and to optimise service performance. At this stage, the builder has sufficient information to prepare the tender (Eyres, 2006).

Contract design phase is carried out after a successful tender process to finalise the details of the contract such as the general characteristics, the general arrangement and the ship's primary systems or equipment's, which are annexed in the contract with the agreement of the shipyard and the customer (Eyres, 2006).

Detail design phase comprises of detailed drawing and plans for manufacturing, prefabrication and installation of the blocks and machinery elements. Usually, the major parts of the detailed design are outsourced to the sub-contractors.

Once the design process is completed, a work plan helps to keep track of the following processes and better allocate the machinery slots. Next, the drawings are handed over for manufacturing where the ship structures and equipment are built in-house or by the suppliers and delivered to the shipyard. These manufactured ship structures are assembled on land to form mega structures called blocks, and the blocks are assembled to other blocks on the dry dock. Assembly of the manufactured equipment's may happen before assembling the blocks on land or after on land or in dry docks depending on the manufacturing plan. After all the blocks and equipment are assembled, the ship is tested rigorously and approved by the regulatory bodies as well as the shipowner. If any problems are found, the shipyard has to fix the problem before the delivery of the vessel. After completing all the checks, the ship is handed over to the shipowner.

With this approach, usually, the whole process from ship design to delivery takes between 2-3 years. However, once the design is fixed, it is expensive and time-consuming to make any changes to the designs or systems, as it would affect other systems as well. Therefore, a modular product development approach will help to design and define ship systems and their interfaces beforehand resulting in a faster ship design process, while also being able to accommodate changes arising later in the project without requiring to put too much effort and resources.

2.2 Modular Product Development

Modular products refer to components, assemblies or systems that fulfil various functions through the combination of distinct building blocks *(modules)* (Pahl, et al., 2007). The process of developing modular products is called modularisation. In general term, modularisation is a set of principles for managing complexity (Langlois, 2002). Ericsson and Erixon (1999) define modularisation as *"Decomposition of a product into building blocks [... or modules] with specified interfaces, driven by company-specific strategies"*.

Modular Product Development *(MPD)*, in general, helps to shorten the development time and reduce the cost by reusing the physical parts or the module designs. If done right, the product can have a large amount of configuration since the interaction between the modules is at a minimum. Due to this reason, it is easier to modify the product when there are changes in the market or the technology since the changes would influence only a small amount of the parts of the module. Moreover, the modules can be produced independently*, i.e., in-house or subcontracted,* making it possible to have a parallel manufacturing process (Ericsson & Erixon, 1999).

Apart from the benefits gained during product design and manufacturing stage, MPD approach helps to improve quality of the product by testing the individual modules outside the system, reducing feedback link and allowing for easier adjustments (Ericsson & Erixon, 1999). Since the individual modules are tested outside the ship, the safety in the shipyard is also improved. There are several methods proposed by the researchers for Modular Product Development. Börjesson and Hölttä-Otto (2014) in their paper have categorised some of the modularity methods like the Design Structure Matrix (Steward, 1981), Function Structure Heuristics (Stone, et al., 2000), Modular Function Deployment™ (Erixon, 1998) and Similarity Heuristics (Zamirowski & Otto, 1999) based on the approach used for the data, *i.e., matrix-based approach or function network-based approach, with a further categorisation based on the coupling or similarity-based approach.* Table 2.1 depicts the classification of these modularity methods.

Table 2.1 Classification of modularity methods (Börjesson & Hölttä-Otto, 2014)

	Matrix-based	**Functional Model-based**
Coupling based	Design Structure Matrix *(DSM)*	Function Structure Heuristics *(FSH)*
Similarity-based	Modular Function Deployment™ *(MFD™)*	Similarity Heuristics *(SH)*

As per table 2.1, DSM and FSH follow the coupling-based approach where the elements are typically clustered into modules by following the principle of maximising the connectivity *within* the modules and minimising the connectivity *between* the modules were the former uses matrix-based approach, and the latter uses the functional decomposition based approach. Similarly, MFD™ and SH follow the similarity-based approach where the modules are defined based on the level of similarity between the strategic module drivers and the product properties (Börjesson & Hölttä-Otto, 2014).

2.2.1 Modular Function Deployment™

The method followed in this thesis is Modular Function Deployment™ *(MFD™),* developed by Erixon (Ericsson & Erixon, 1999). According to them, *"MFD™ is a structured, company-supportive method with the objective of finding an optimal modular product design, taking into consideration the companies specific needs".* It consists of five major phases:

i. Define product requirements
ii. Derive functions and select a technical solution
iii. Generate module concepts
iv. Evaluate module concepts
v. Prepare module cards

2.2.1.1 Define product requirements

This thesis mainly concentrates on the product requirement definition phase of the MFD™ process, which uses QFD. Section 2.3 provides an extensive explanation of the QFD approach. In brief, the QFD process helps in understanding the customer or the end users perspective about their likes and wishes of the product. Based on these needs, the design team can define the requirements of the products that satisfy the customer's needs while fulfilling business goals. Even though QFD has been proven as a robust tool for product development, academics have criticised QFD method on the opinion that the workload to populate the matrix is enormous and the result seldom leads to any conclusion (Short, et al., 2009). However, MFD™ proposes the use of the HoQ, and it is not mandatory to use the roof of the house, which results in a reduction of workload and time. Further, QFD is needed to derive the functions using the product requirements, therefore, closing the loop and making QFD more conclusive (Börjesson, 2012).

2.2.1.2 Derive functions and select a technical solution

The product requirements collected from the previous phase focuses strongly on the market and the users. To develop a product, these market-focused requirements have to be converted into a technical-focused requirement, which is achieved by looking at the requirements from a functional point of view with the help of function trees. Section 2.3.3.4.3.a.2 provides explanation for the function tree method. This process of breaking down the product into functions and their corresponding technical solution is called as functional decomposition (Ericsson & Erixon, 1999). Once the functions are derived, there can be many technical solutions to satisfy a function, giving the team multiple alternatives to choose from. In such cases, a Pugh matrix is useful to compare the alternatives against a set of criteria (Burge, 2009).

Table 2.2 Pugh matrix – Adapted from Pugh (1981, 1991)

Alternatives for technical solution X	**Evaluation Criteria**				Sum +	Sum -
	Datum	Criteria 1	Criteria 2	…		
Alternative A	Datum	+	+		2	0
Alternative B	Datum	-	+		1	1
…						

2.2.1.3 Generate module concepts

Module concepts are generated by assessing the Module Drivers™ with the technical solutions obtained from the previous phase. Module drivers are the driving force used to indicate the strategic reason for the creation of the module in the first place. These strategic reasons are meant to capture voices of all the stakeholders involved such that it covers a broad spectrum of the product's lifecycle (Lange & Imsdahl, 2014). Once the module drivers are defined, these are transferred to a new matrix called Module Indication Matrix™ or MIM™, which is the core of the MFD™ method. In this matrix, the technical solutions are compared against the module drivers according to their importance, and corresponding values are assigned as shown in table 2.3 (Ericsson & Erixon, 1999).

Table 2.3 Module Indication Matrix™ – Adapted from Ericsson & Erixon (1999); MD = Module Drivers™; Md = Module; TS = Technical Solution; Scoring scale – ● = Strong (9), ◑ = Medium (3), ○ = Weak (1)

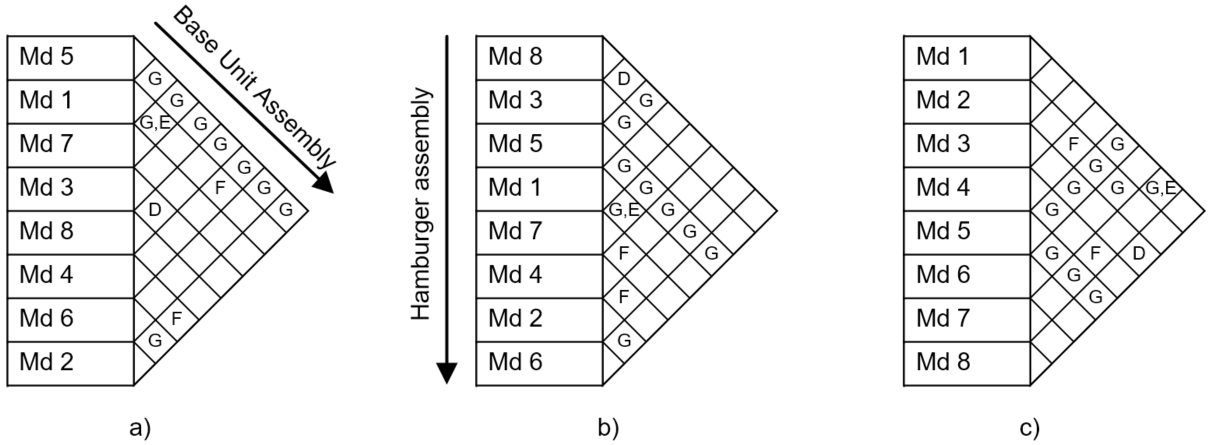
	Technical Solutions							
Module Drivers™	**TS 1**	**TS 2**	**TS 3**	**TS 4**	**TS 5**	**TS 6**	**…**	**Sum**
MD 1	●	○			○	●		**20**
MD 2				●		◑		**12**
MD 3		◑	◑	○	◑	○		**11**
MD 4	●	○	●	◑		◑		**25**
…								
Sum	18	5	12	13	4	16		
	Md 1	**Md 2**		**Md 1**	**Md 2**	**Md 1**		

Next, a suitable number of the technical solutions with the highest scores are picked, and the lower scored technical solutions are evaluated for the possibility of integration with the higher scored technical solutions through pattern recognition in the MIM™. Using this analogy for the product in table 2.3, the *TS 1, TS 4* and *TS 6* form one of the module concept namely *Md 1*, and *TS 2* and *TS 5* form another concept module namely *Md 2*. However, according to Ericsson & Erixon (1999), an ideal number of modules a product shall have is approximately equal to the square root of a number of parts currently required to assemble the product. This estimate is based on the optimisation of assembly lead-time. Therefore, the ideal number of modules for the product in table 2.3 shall be equal to $\sqrt{6} = 2.45 \sim 2$ Modules. In practice, a much larger and broader range of module concepts are proposed based on the MIM™ matrix, which is evaluated in the next phase.

2.2.1.4 Evaluate module concepts

Evaluation of the identified modular concepts is crucial to know the relationship between the interfaces of the different modules since these interfaces have a strong influence on the flexibility of the final product. The modules may have fixed interface *(e.g. to connect or transmit forces)*, moving interface *(e.g. to transmit rotational energy or alternating stresses)* or have an interface as a medium for transmission *(e.g. transmit data, fluids or electricity).* A matrix similar to the roof of HoQ called interface matrix is the recommended tool to evaluate the identified module concepts. As shown in table 2.4, the identified modules are entered in the matrix according to their predetermined assembly order, and the interrelation between the module concepts are noted in their respective intersecting cells. The need to enter the module concepts according to their expected assembly order is to know if it follows any one of the ideal principles of interface assembly, *i.e., base unit assembly (Table 2.4a) or hamburger assembly (Table 2.4b)*. The advantage of having the result of interface matrix follow one of the principles is that it gives an overall picture of the assembly order of the modules and facilitates simultaneous development and easier process planning with greater flexibility in the workshop organisation. If the results of the interface matrix deviate from the principles of interface assembly, then assembly order shall be reconsidered (Ericsson & Erixon, 1999).

Table 2.4 Interface matrix – a) Base unit assembly principle; b) Hamburger assembly principle; C) Assembly order to reconsider – Adapted from Ericsson & Erixon (1999)
Abbreviation for interface types: G = Geometric; E = Electric; F = Fluidic; D = Data



2.2.1.5 Prepare Module card

As the name suggests, this step mainly consists of writing the specification for the modules in the form of a module card. The module card usually consists of module description, technical information, interfaces, cost targets, planned development and description of variants, thus, forming an essential output of the modularisation process. Once these specifications are established, the detailed design of the specific module based on the module card is developed. The module specification shall be improved over time to optimise the modules or incorporate any changes in the product platform (Ericsson & Erixon, 1999). Table 2.5 shows an outline of a basic module card.

Table 2.5 Outline of a Module Card – Adapted from Ericsson & Erixon (1999)

Module Owner: **XXX** Department: **YYY**	Module Name: **Md 1**
Technical Solutions: **TS1** **TS4** **TS6**	Module Driver: **MD 1** **MD 4**
Interface: **MD 2** **MD 7** **MD 4**	Type: **Geometric** **Geometric; Electric** **Fluidic**
Other information:	

2.2.2 Advantages and disadvantages of MFD™

For well over two-decades, academics and industrial experts have researched and used MFD™ process for practical purposes. This has given people time to praise and criticise this approach of modular product development. Table 2.6 is a compilation of the advantages and disadvantages of MPD from the studies conducted by Erixon (1998), Marshall (1998) and Börjesson (2009).

Table 2.6 Advantages and disadvantages of Modular Product Development (Erixon, 1998; Marshall, 1998;Börjesson, 2009)

	Advantage	Disadvantage
MPD	• Re-use of module design can reduce cycle time to the market • Allows parallel development and manufacturing of the modules reducing lead time • Use of matrices for statistical generation of modules • Incorporates customer, engineers and business strategic needs • Increased capacity for variation due to simpler interfaces • Increased quality by pre-testing modules • Increases safety since modules are manufactured and assembled in the factory floor • Reduces inventory holding which in turn frees up the operation capital • Increased customer satisfaction	• An uncommon way of working which requires additional training • Managing the changes in the new way of working • Problems may occur during the interface definition • Quality and results are highly dependent on good requirement definition and consistent scoring which requires an experienced team • May get the wrong level of module resolution if there are an insufficient number of product requirements • Increased initial product development time • Re-use of common modules in some cases may result in loss of brand identity

2.3 Quality Function Deployment

2.3.1 History

A journey to find a process that could assure the quality of the products based on customer satisfaction lead Prof. Yoji Akao to develop the concept of Quality Function Deployment *(QFD)* in Japan in 1966 under the name – *henshitsu tenkai,* which means *Quality Deployment* (Akao, 1972). In 1972, one of Akao's fellow researchers, L. T. Fan, from Kansas State University suggested him to name the process as – *henshitsu kino tenkai*, which translates to *Quality Function Evolution*. The name *Quality Function Deployment* was not formed until 1983 when the sponsor for Akao's seminar suggested him to change the word *Evolution* to *Deployment* (Akao & Mazur, 2003).

However, Akao's initial approach alone was inadequate regarding setting the design qualities (Akao & Mazur, 2003). It was not until 1972 did the QFD gained traction in Japan when the Kobe Shipyard – a part of Mitsubishi Heavy Industries, introduced the Quality Charts – later named as *House of Quality*, in the design of an oil tanker (Hauser & Clausing, 1988; Akao, 1990). Meanwhile, Katsuyoshi Ishihara introduced a value engineering *(VE)* concept into QFD that helped to define the functions of a product (Mizuno & Akao, 1978). Combining the earlier QFD concept proposed by Akao with the Quality Chart (Nishimura, 1972; Takayanagi, 1972) and the value engineering concepts formed the QFD process known today (Akao & Mazur, 2003).

In 1983, the QFD process was introduced to the USA and Europe when American Society of Quality Control published one of Akao's article in the Quality Progress journal (Akao, et al., 1983). It further gained traction due to the efforts of Prof. Don Clausing *(by education and publication)* and Robert M. Adams *(by launching the North American QFD Symposium in 1989)*. The late '80s to mid-'90s saw a rise in usage of the QFD process not only in the USA but also in Brazil, China, India, South Korea, Sweden, Taiwan, and the UK (Akao & Mazur, 2003). Carnevalli & Carpinetti (2002) compiled their work based on the surveys that focused on the application of QFD in Brazil (Cauchick & Carpinetti, 1999), Japan (Christiano, et al., 2000), Sweden (Ekdahl & Gustafsson, 1997), the UK (Martins & Aspinwall, 2001) and the USA (Christiano, et al., 2000) based on the usage, benefit and difficulty in employing QFD process. They summarised that the majority of the organisations who employed QFD were large companies that aimed at increasing customer satisfaction and improving their product development process. It was also noted that the companies from Sweden, The UK and the USA primarily use the House of Quality when compared the companies in Brazil and Japan who used other matrices as well.

Until the late '80s, much of the QFD usage was seen in the manufacturing and electronics space. However, usage of QFD in the software development space has been increased in recent years due to the modification made to the previously proposed QFD models to better suit the fast-paced software development world.

2.3.2 Definition

After integrating the initial QFD proposal with the quality charts and value engineering concepts, Akao defined QFD as:

> *"QFD converts user demands into substitute quality characteristics, determines the design quality of the finished good, and systematically deploys this quality into component quality, individual part quality and process elements and their relationships."*
>
> (Akao & Ohfuji, 1989)

In the meantime, the American Supplier Institute defined QFD around the automotive industry as:

> *"A system for translating customer requirements into appropriate company requirements at every stage, from research through production design and development, to manufacture, distribution, installation and marketing, sales and services."*
>
> (ASI, 1989)

Later, in his book Akao generalised QFD as:

> *"QFD is [a] method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demand into design targets and major quality assurance points to be used throughout the production phase."*
>
> (Akao, 1990)

Lillrank, a Finnish researcher defined QFD as:

> *"QFD is a methodology that concentrates on taking account of quality and its different dimensions during the product design process, integrating quality to a product from the beginning."*
>
> (Lillrank, 1990)

In the first European conference on QFD, Hill described QFD as:

> *"QFD translates the subjective quality criteria and product requirements stated in the customer's own words into objective, viable product requirements, stated in parameters that can be quantified & measured and then used to design and manufacture the product."*
>
> (Hill, 1992)

Cohen mentions the use of QFD as a tool for communication in his book as:

> *"QFD is a structured approach for translating customer requirements into design specifications. It is a powerful tool that ensures proper communication between the client and [the] design team."*
>
> (Cohen, 1995)

ISO 16355:1-2015 defines QFD as:

> *"QFD is an approach to ensuring quality throughout but not necessarily at each stage of the product development process, starting with the initial product concept […and] managing of all organisational functions and activities to assure product quality."*
>
> (ISO 16355-1:2015, 2015)

2.3.3 QFD approaches over the years

QFD is a versatile tool employed in not only the automobile, electronics, manufacturing and software industries but also the marketing, service and supply chain industries. As the research in QFD advanced, researchers came up with different approaches of utilising QFD, starting from Akao with his Comprehensive QFD approach (Akao, 1990), followed by American Suppliers Institute who took only the required matrices from the comprehensive QFD and proposed a Four-phase QFD approach (ASI, 1992). These two approaches *(now called as Classical QFD)* were well used by the design and manufacturing industries but were not embraced by the fast-changing technology projects often found in the IT and software development space because these approaches consumed a significant amount of resources. To tackle these issues, Modern QFD researcher Zultner proposed Blitz QFD® approach in 1995 that was mainly build to support the QFD process in software industries. Following sections briefly mention the different QFD approaches.

2.3.3.1 Comprehensive QFD

Section 2.3.3.4.3 provides an extensive explanation of the comprehensive QFD approach.

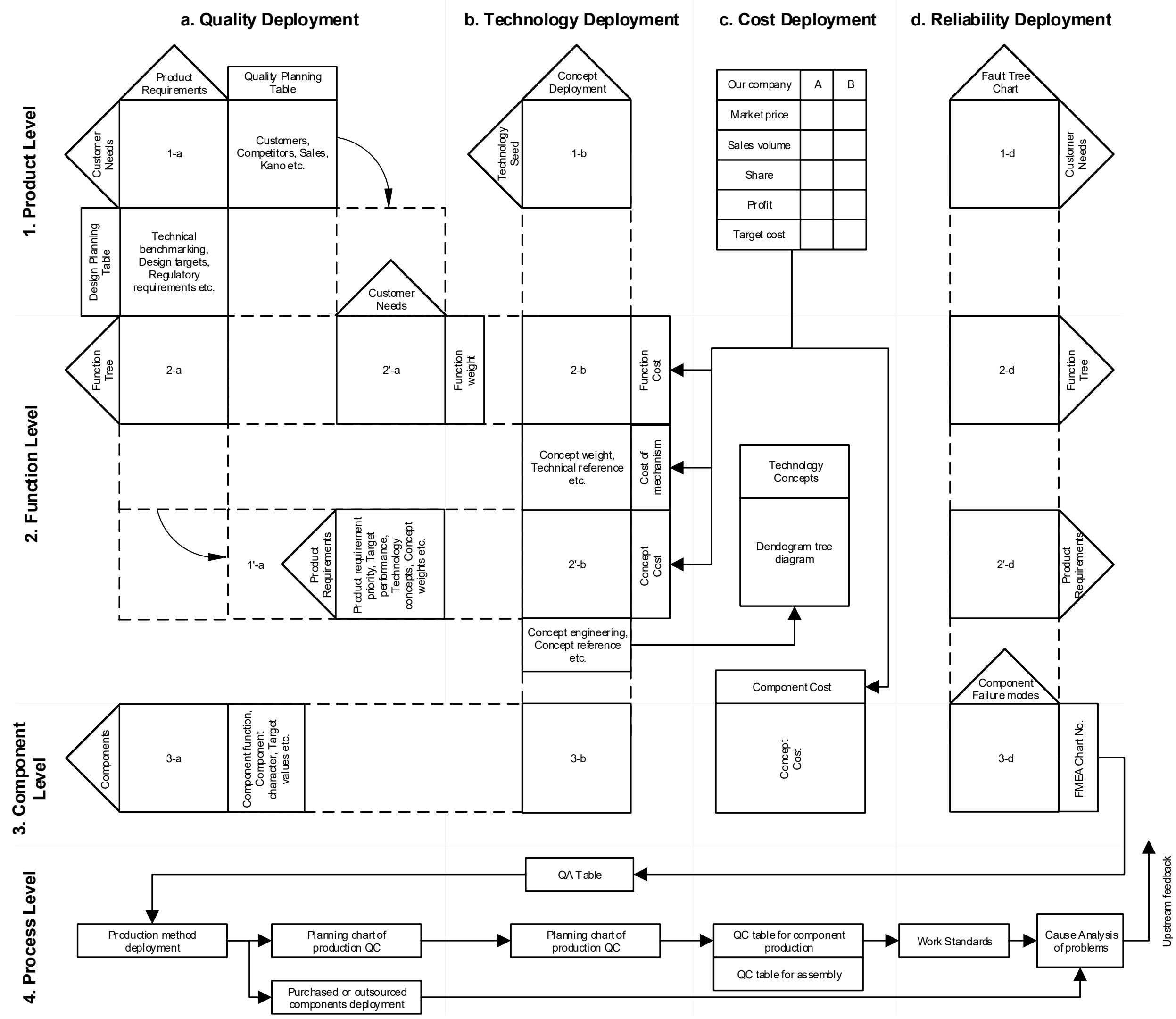


Figure 2.2 Comprehensive QFD approach – Adapted from Akao (1990)

2.3.3.2 Four-phase QFD

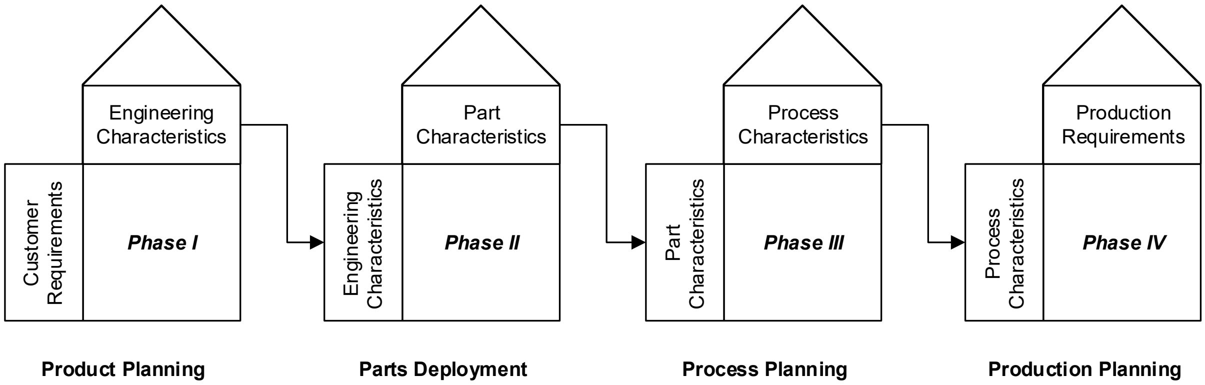


Figure 2.3 Four-phase QFD approach – Adapted from the American Supplier Institute (ASI, 1992)

The comprehensive QFD had a large number of matrices to work with, which resulted in difficulties for the beginners to learn the process. Moreover, the matrices other than that mentioned in figure 2.3 where not required by the U.S. automotive suppliers. Therefore, ASI proposed a four-phase QFD approach based on a study conducted by Fuji-Xerox, which addressed common reliability concerns in the usage of QFD and include the following phases,

a. Product Planning *(Customer needs-Engineering characteristics matrix),*
b. Part Deployment *(Engineering characteristics-Part characteristics matrix),*
c. Process Deployment *(Part characteristics- Process characteristics matrix)*
d. Production planning *(Key process operations- Process characteristics matrix).*

The U.S. auto-part industry dubbed this model as *"Kindergarten QFD"* due to its simple yet non-flexible approach, which limited its adoption (Andersson, 1991; Mazur, 2007). This approach resulted in widespread use of 4-phase QFD throughout the U.S. and other parts of the world (Mazur, 2012).

The product planning phase is carried out to define and prioritise the customer needs, benchmark competitors and input critical target values for the engineering characteristics. The part deployment phase consists of identifying critical parts, assemblies or concepts that can satisfy the engineering characteristics, and translate them into critical part characteristics and their target values. In the process deployment stage, the critical process flow and their characteristics are identified that can fulfil the critical part characteristics, and establish critical process parameters which are useful to develop production equipment characteristics. In the final phase, process/quality control methods, maintenance schedule, operating instruction are identified (Christiano, et al., 2000).

2.3.3.3 Blitz QFD®

As mentioned earlier, the Comprehensive QFD approach was too broad and resource consuming, and the 4-phase QFD approach was focused only on automotive suppliers. Moreover, the classical QFD approaches lacked the need for analysing the business and the project goals and customer/market segments. This lead Zultner (1995) to develop a faster and lean approach to gather customer needs in QFD called Blitz QFD®, which initially was designed to serve the software industries and further suggests the use of Maximum Value Table *(MVT)* to derive product requirements and rank them instead of the HoQ matrix when the customer needs dataset is small in number (Mazur, 2012).

Figure 2.4 shows a process flow diagram for the Blitz QFD® approach. It first starts with the definition of the project goals and identification of the stakeholders to get the customer needs. Next, the customer needs data is collected by meeting the stakeholders at their workplace along with observing their surroundings to get unspoken needs. Structuring the needs helps the team to avoid double counting and to fill in the gaps in the structure. Finally, the structured needs are prioritised, and the high priority needs are analysed further to obtain the product requirements with the help of MVT. In some cases, classical QFD matrices like HoQ is used if there are a lot of high priority customer needs instead of MVT.

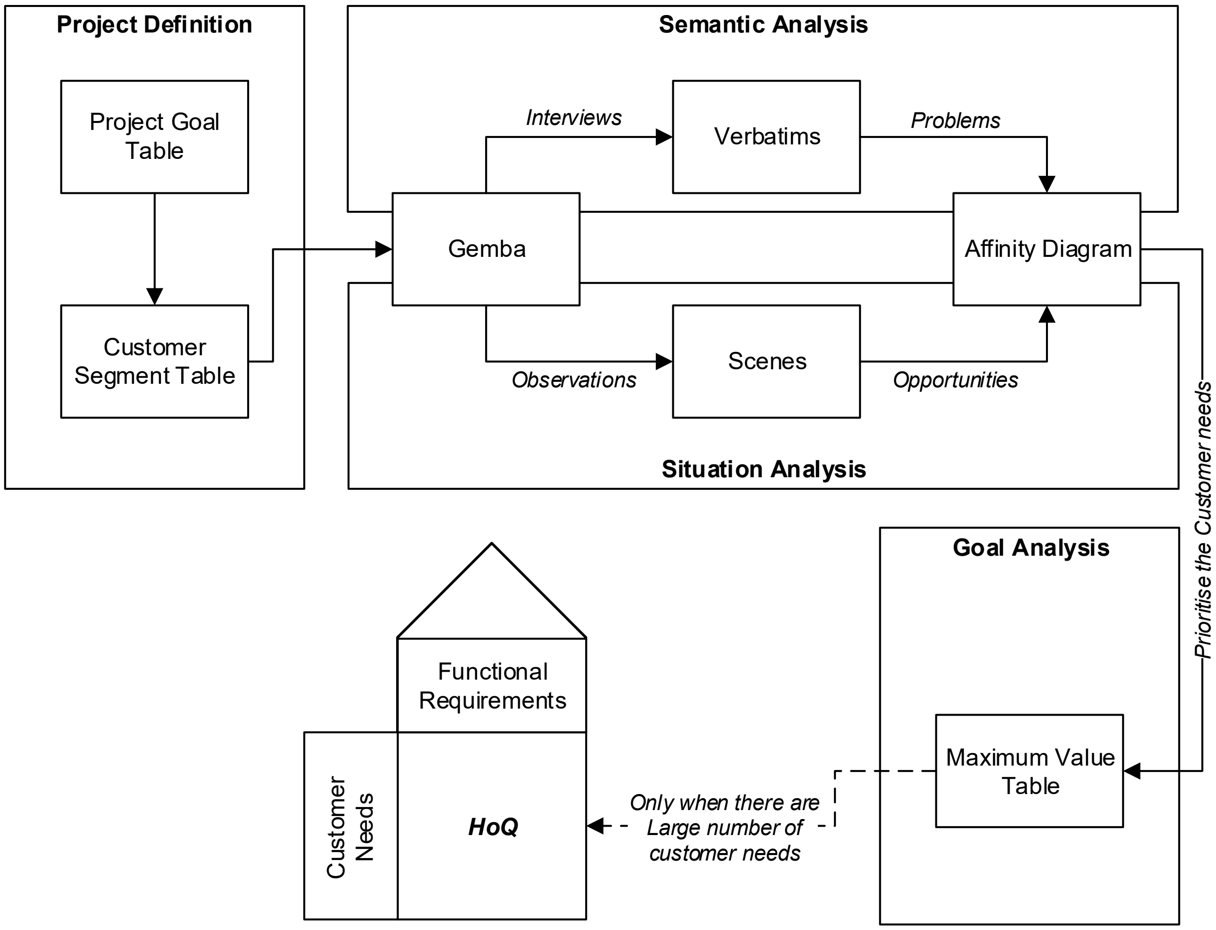


Figure 2.4 Modern Blitz QFD® approach – Adapted from Mazur (2012)

2.3.3.4 QFD approach recommended by ISO 16355 standard

This thesis focuses on building the QFD process based on ISO 16355 standard. ISO 16355 standard is based mostly on the Comprehensive QFD approach with reference to additional tools and processes from the modern QFD approaches to enhance the Comprehensive QFD process *(figure 2.5)*. Therefore, the steps presented in this section revolves around the Comprehensive QFD concepts recommended by the standard with the additional categorisation of processes into different phases based on their deployment status. The author recommends the division of the QFD process into there phases, an approach similar to that used by Davide Maritan (2015). The primary purpose of the division is to differentiate the purpose and the timeline of the processes such that it will be easier to understand the process. The phases are as follows,

i. Strategy development Phase
ii. Customer Analysis Phase
iii. Deployment Phase

Strategy development phase:
Strategy development phase or the business strategy phase mainly consists of defining business or project goals and prioritising them such that the goals will help the team to identify and focus on the stakeholders who are essential to achieving the set goals *(2.3.3.4.1)*. Further, the identified business goals can assist an organisation in prioritising projects when they have limited resources as explained in section 2.3.3.4.1a, Project Prioritization Phase *(a sub-phase of Business development phase)*. Figures 2.6 and 2.7 illustrate the process flow of these phases.

Customer analysis phase:
Customer analysis phase focuses on identifying the customers and gathering the data required in the Quality deployment stage. Variety of data acquisition tools can be used based on the criteria's mentioned in section 2.3.3.4.2.3. Translation of the acquired data becomes an integral part of this phase since the data provided by the customer might include statements that are not exactly the customer needs as explained in section 2.3.3.4.2.4. Data regarding customer satisfaction level and competitors analysis are also gathered in this phase. Figures 2.8, 2.9 and 2.10 illustrate the process flow of this phase.

Deployment phase:
The primary function of the deployment phase is to convert one data set into another while progressing through different levels and phases of the Comprehensive QFD model *(2.3.3.4.3)*. However, for this thesis, the explanation of the process is only limited until obtaining the functions as specified in section 2.3.3.4.3.a.1. Figure 2.11 illustrates the process flow and the relation this phase has with the MFD™ process.

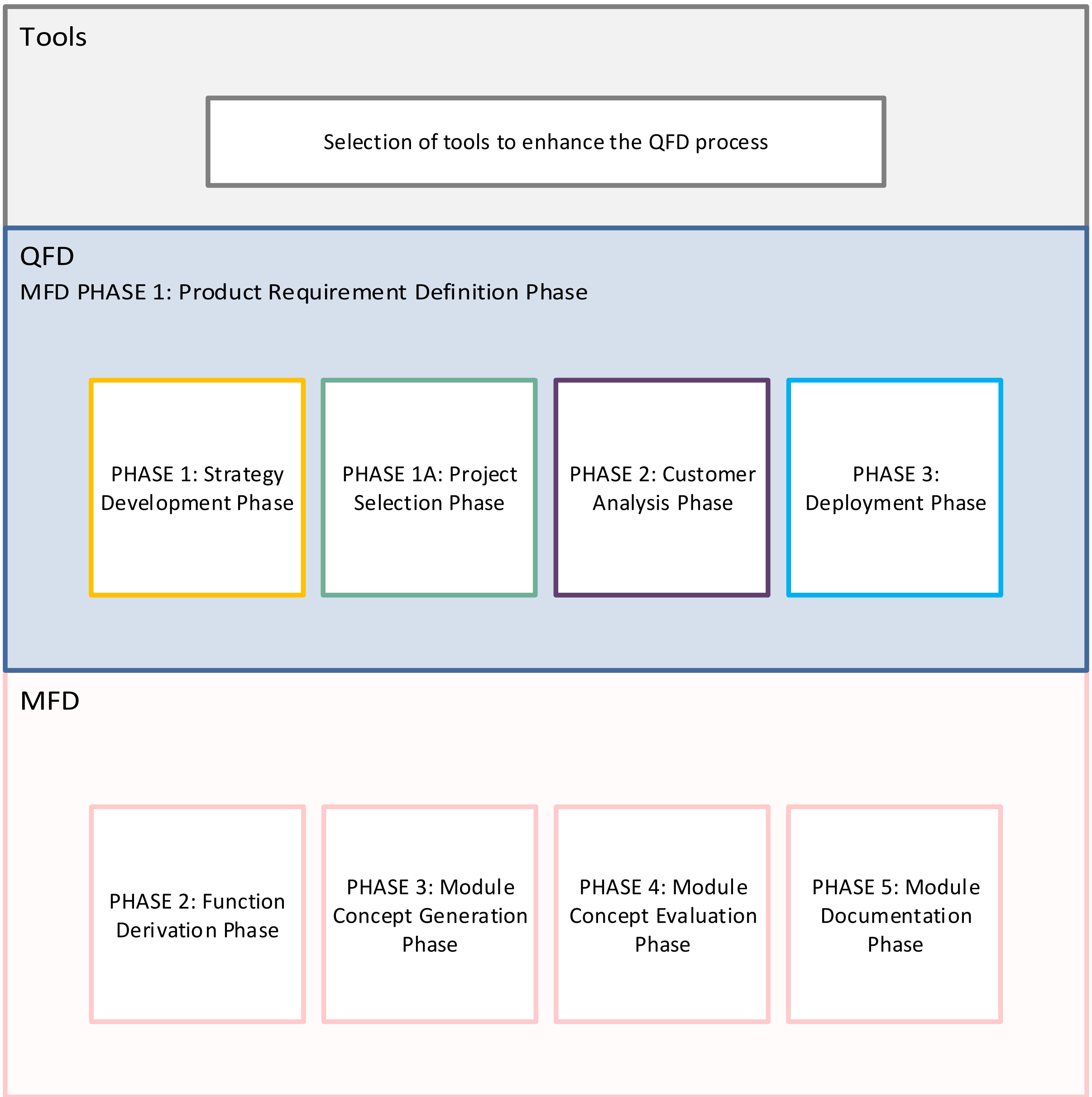


Figure 2.5 Block diagram of the Modular Product Design approach studied in this thesis

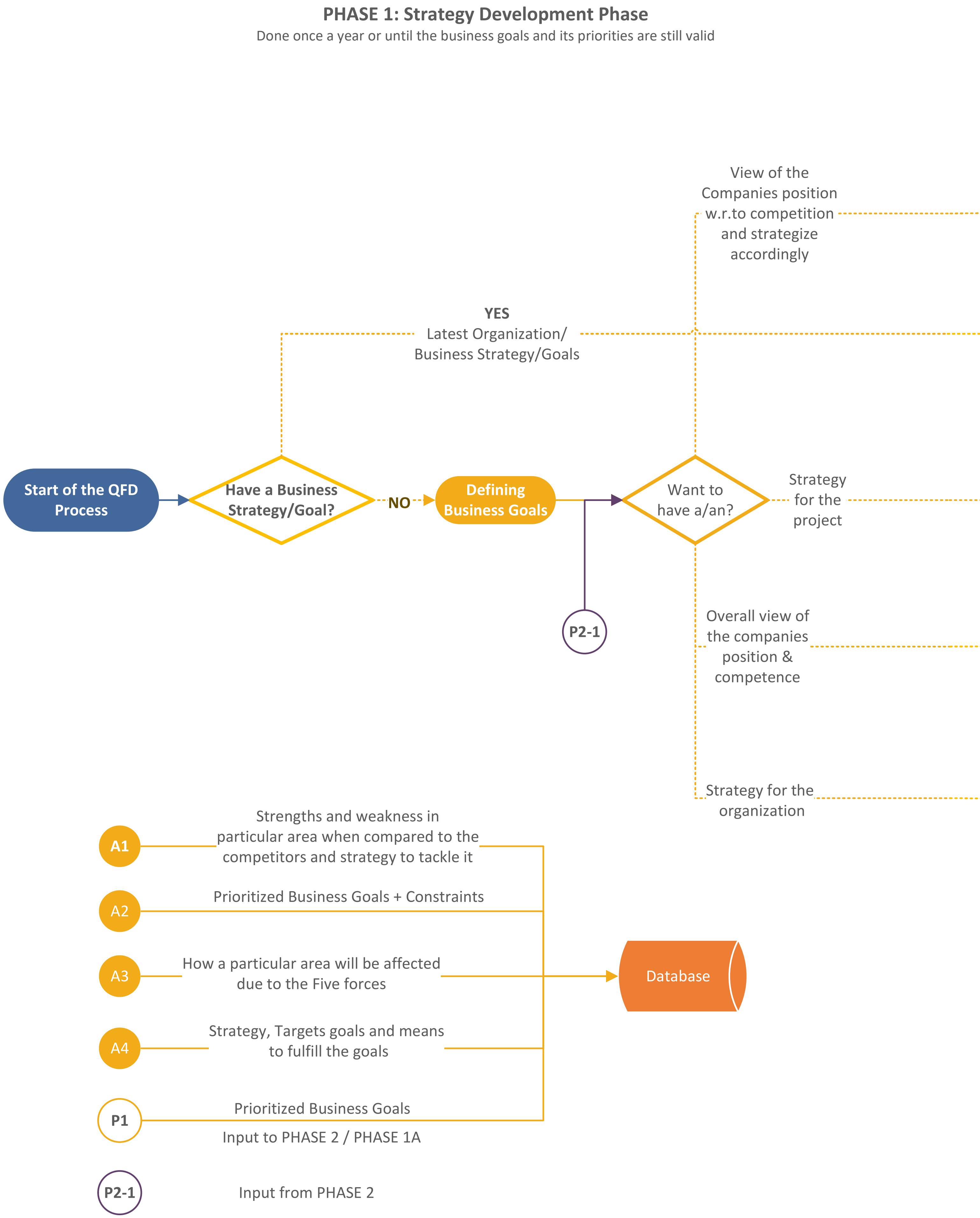
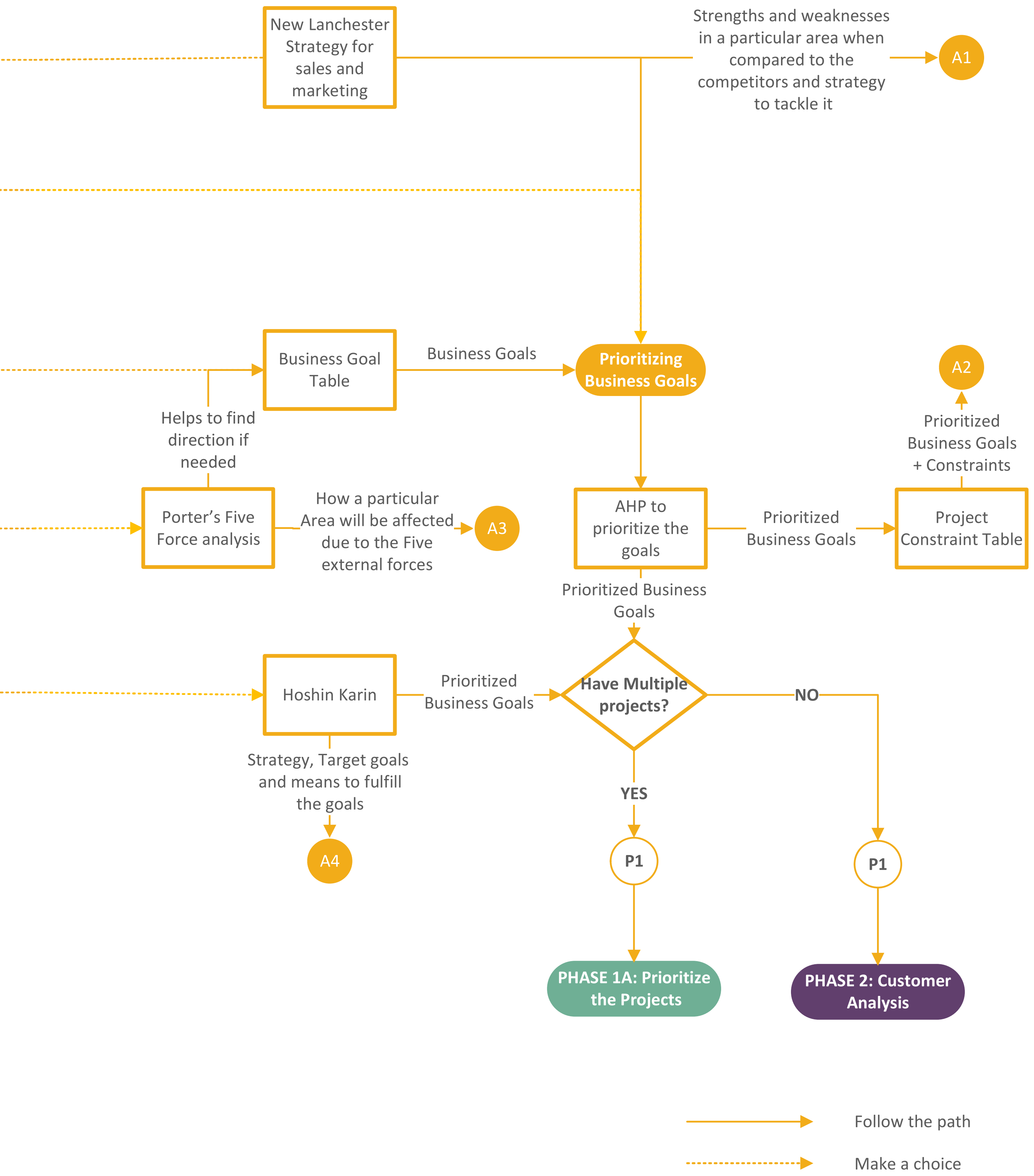


Figure 2.6 Strategy Deployment Phase



New Lanchester Strategy for sales and marketing
Strengths and weaknesses in a particular area when compared to the competitors and strategy to tackle it
A1
Business Goal Table
Business Goals
Prioritizing Business Goals
A2
Prioritized Business Goals + Constraints
Helps to find direction if needed
Porter's Five Force analysis
How a particular Area will be affected due to the Five external forces
A3
AHP to prioritize the goals
Prioritized Business Goals
Project Constraint Table
Prioritized Business Goals
Hoshin Karin
Prioritized Business Goals
Have Multiple projects?
NO
YES
Strategy, Target goals and means to fulfill the goals
A4
P1
P1
PHASE 1A: Prioritize the Projects
PHASE 2: Customer Analysis
Follow the path
Make a choice

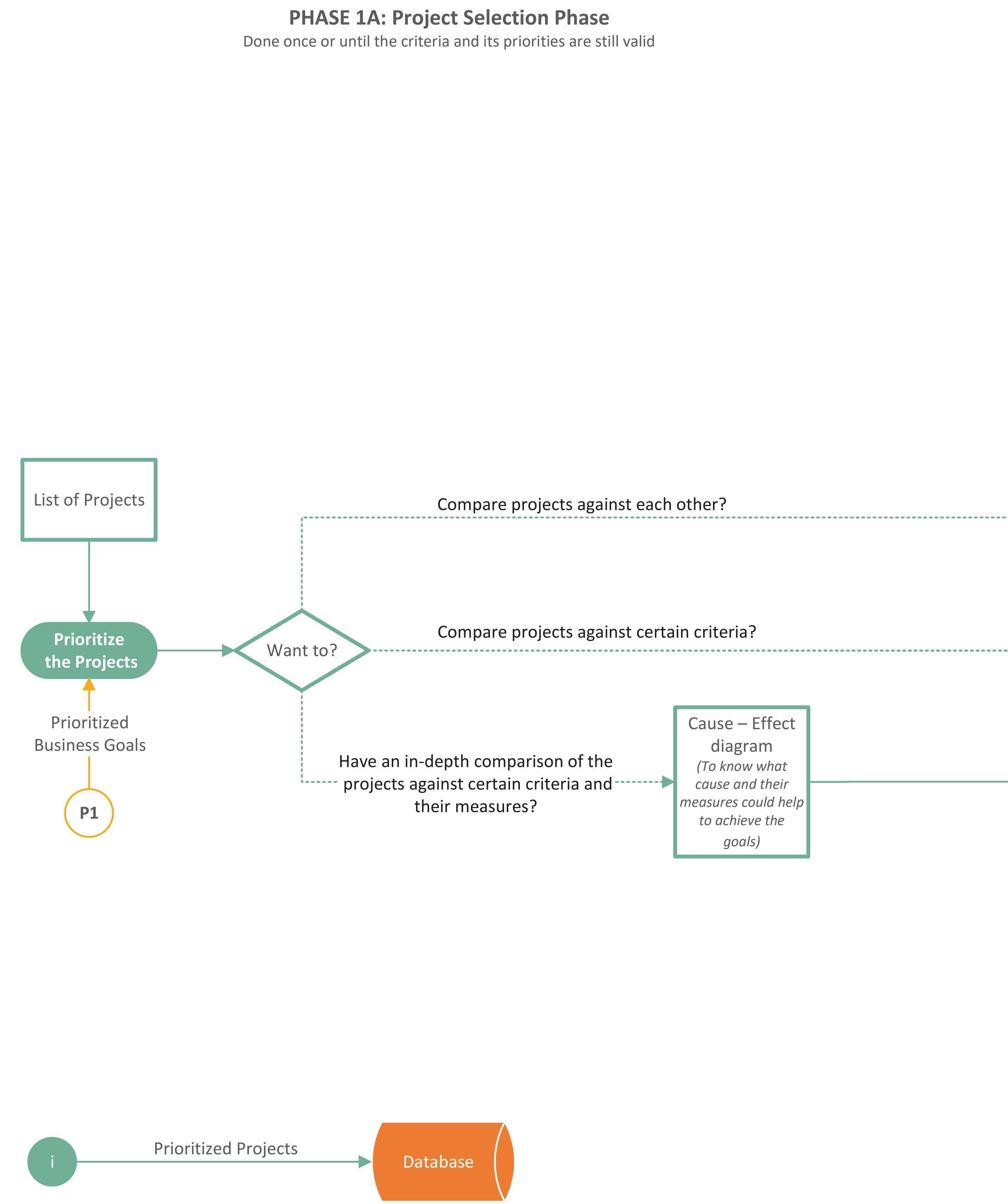
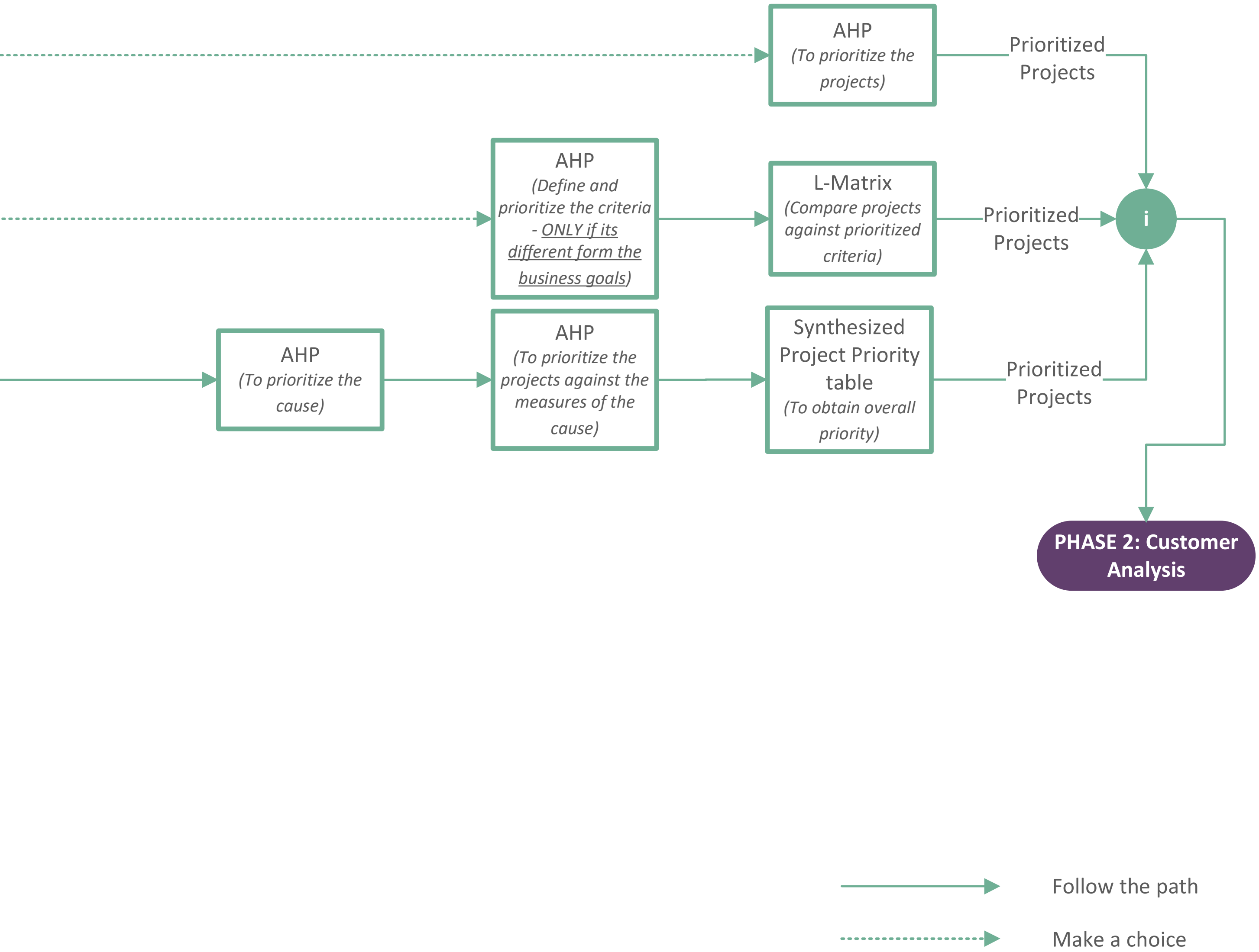


Figure 2.7 Project Selection Phase


AHP
(To prioritize the projects)
Prioritized Projects
AHP
(Define and prioritize the criteria - ONLY if its different form the business goals)
L-Matrix
(Compare projects against prioritized criteria)
Prioritized Projects
i
AHP
(To prioritize the cause)
AHP
(To prioritize the projects against the measures of the cause)
Synthesized Project Priority table
(To obtain overall priority)
Prioritized Projects
PHASE 2: Customer Analysis
Follow the path
Make a choice

PHASE 2: Customer Analysis Phase

VOC/VOS: Done every time. Requires also input from Phase 1

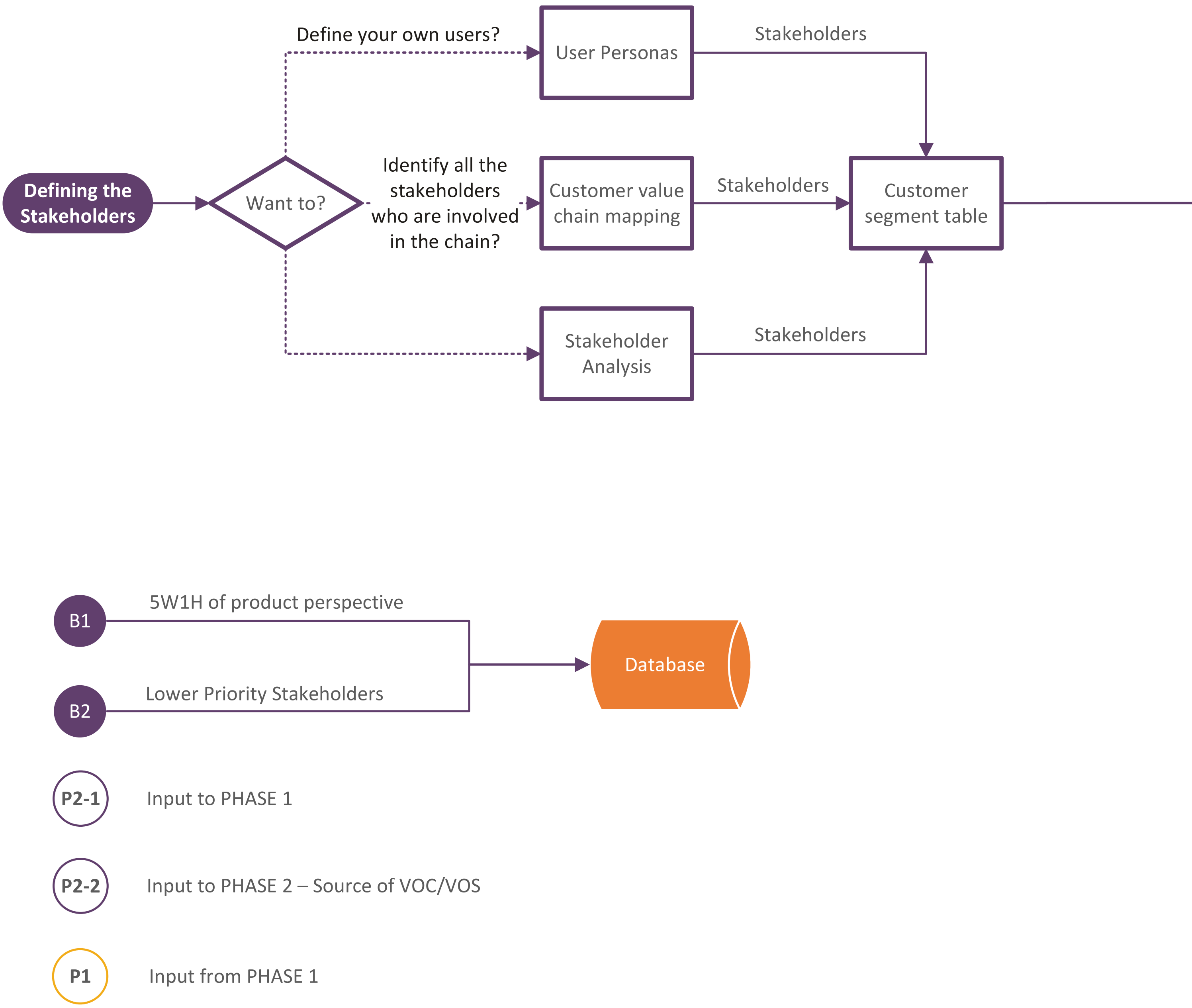
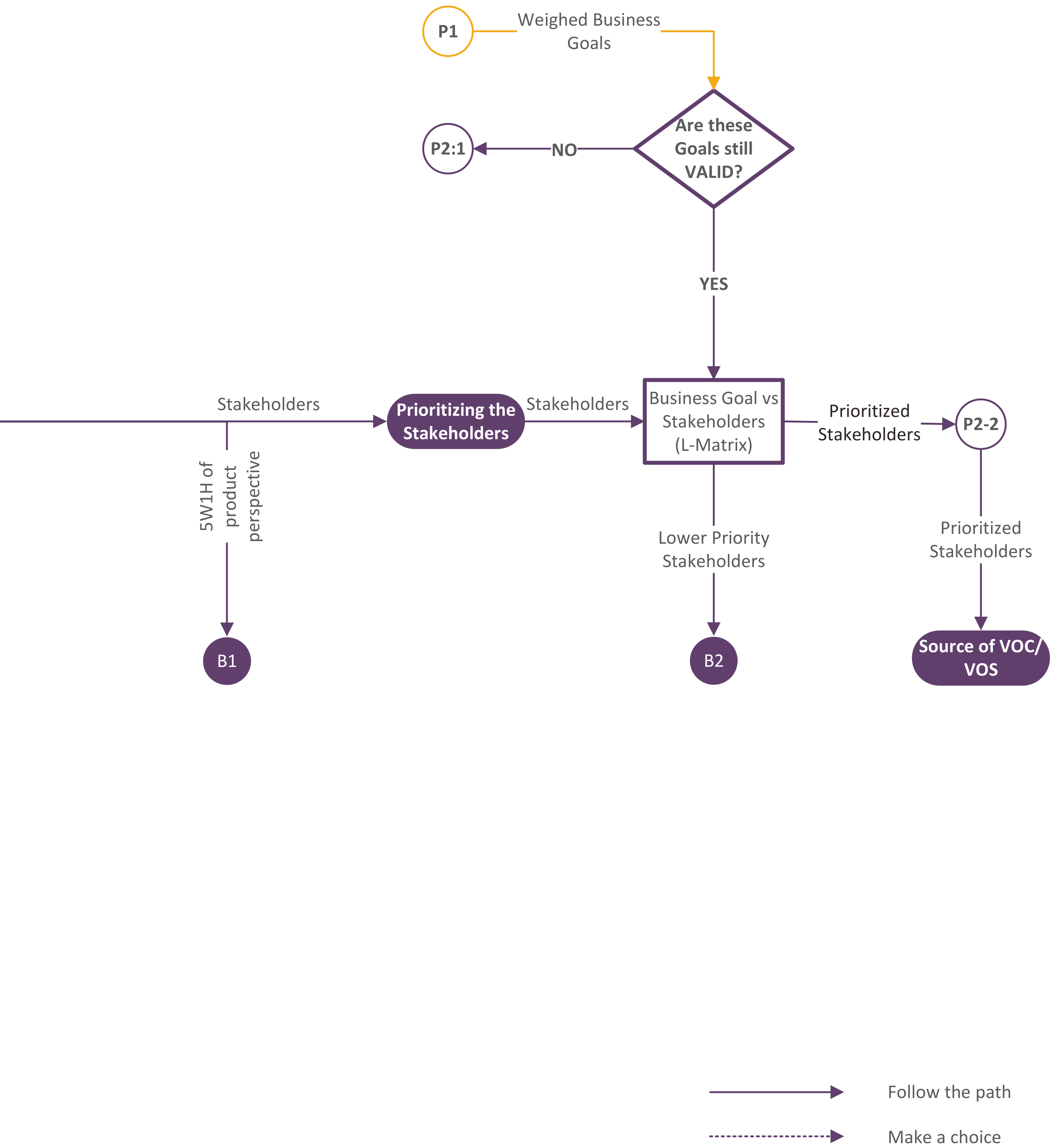


Figure 2.8 Customer Analysis Phase


P1
Weighed Business Goals
Are these Goals still VALID?
NO
P2:1
YES
Stakeholders
Prioritizing the Stakeholders
Stakeholders
Business Goal vs Stakeholders (L-Matrix)
Prioritized Stakeholders
P2-2
5W1H of product perspective
Lower Priority Stakeholders
Prioritized Stakeholders
B1
B2
Source of VOC/ VOS
Follow the path
Make a choice

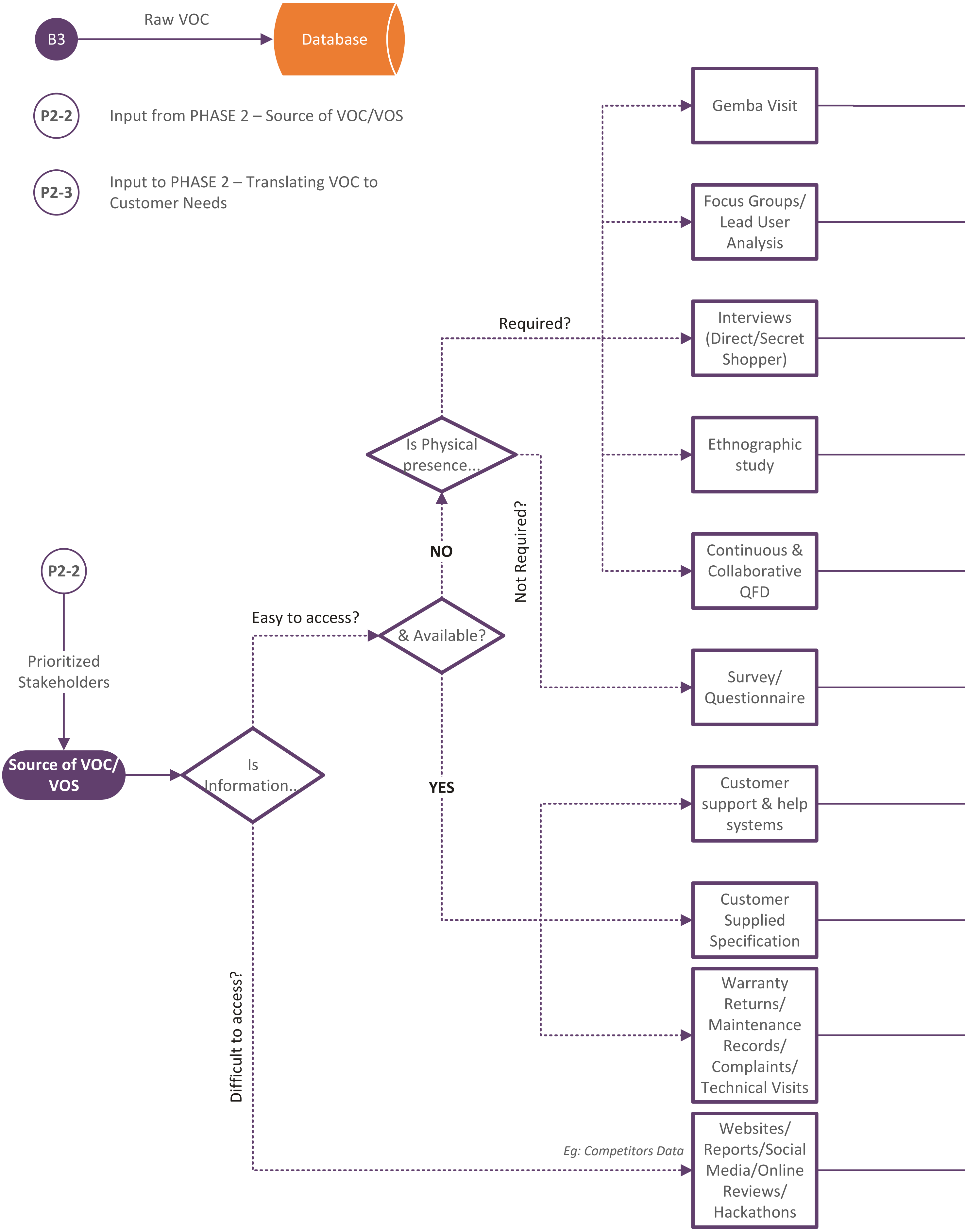
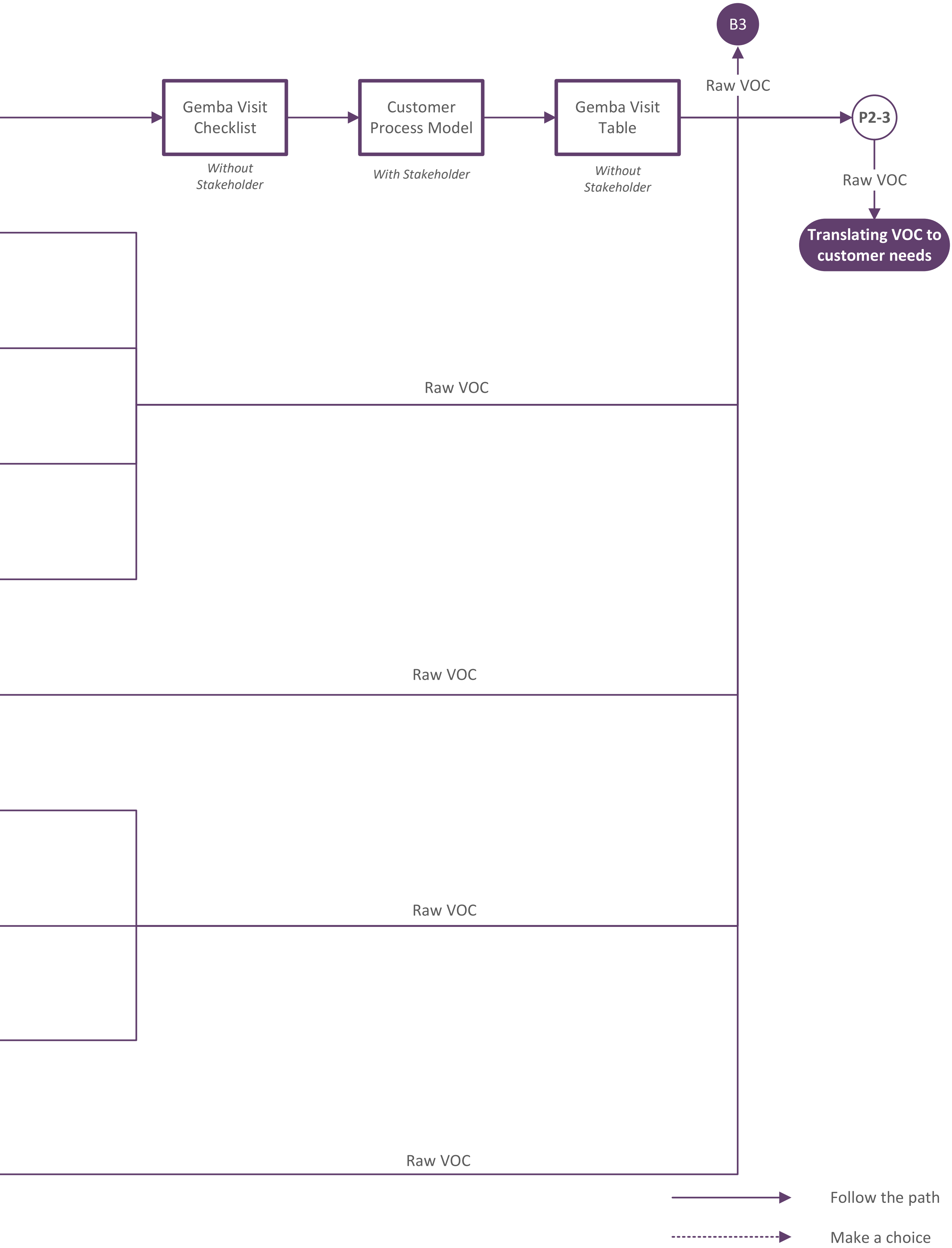


Figure 2.9 Customer Analysis Phase


B3
Raw VOC
Gemba Visit Checklist
Without Stakeholder
Customer Process Model
With Stakeholder
Gemba Visit Table
Without Stakeholder
P2-3
Raw VOC
Translating VOC to customer needs
Raw VOC
Raw VOC
Raw VOC
Raw VOC
Follow the path
Make a choice

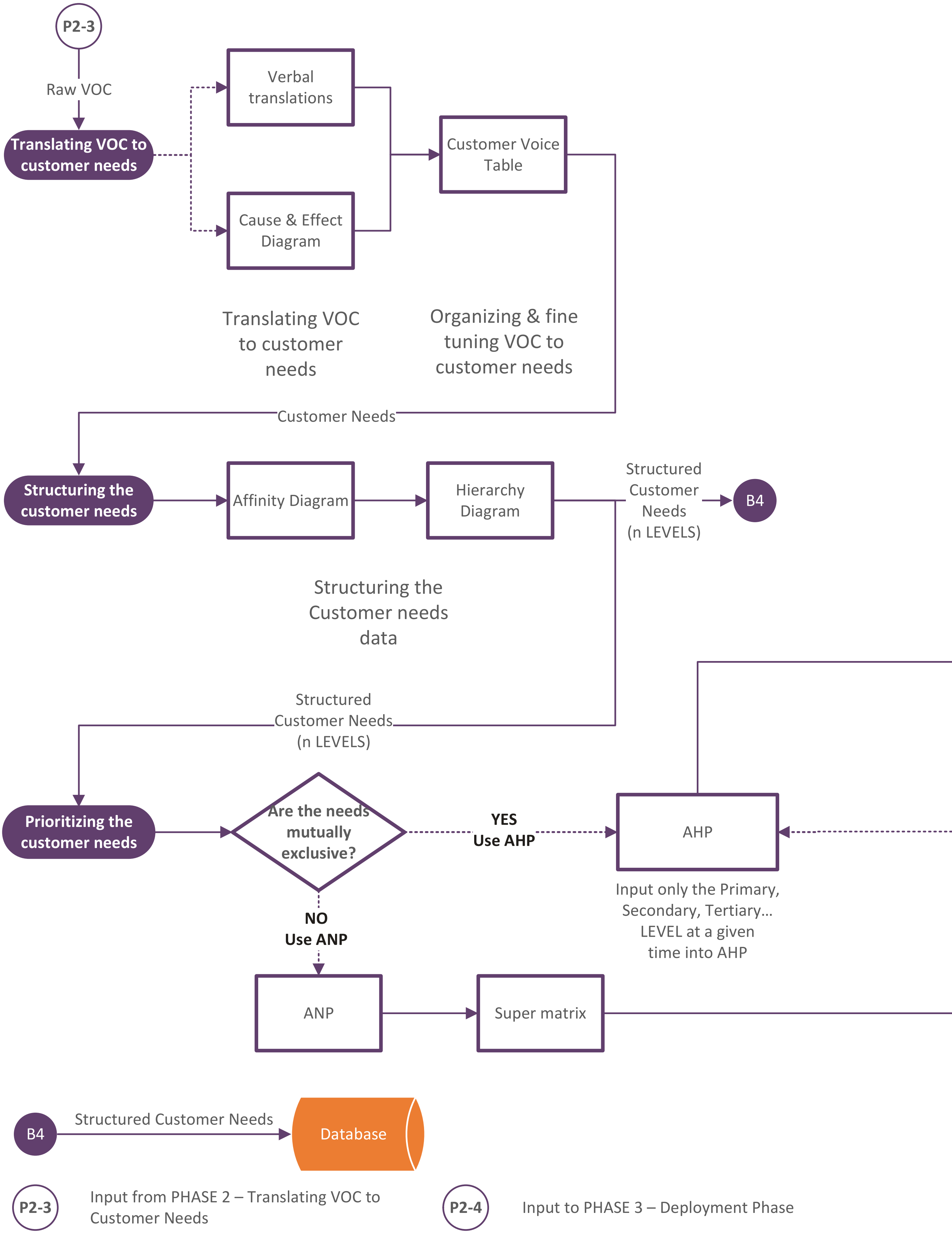
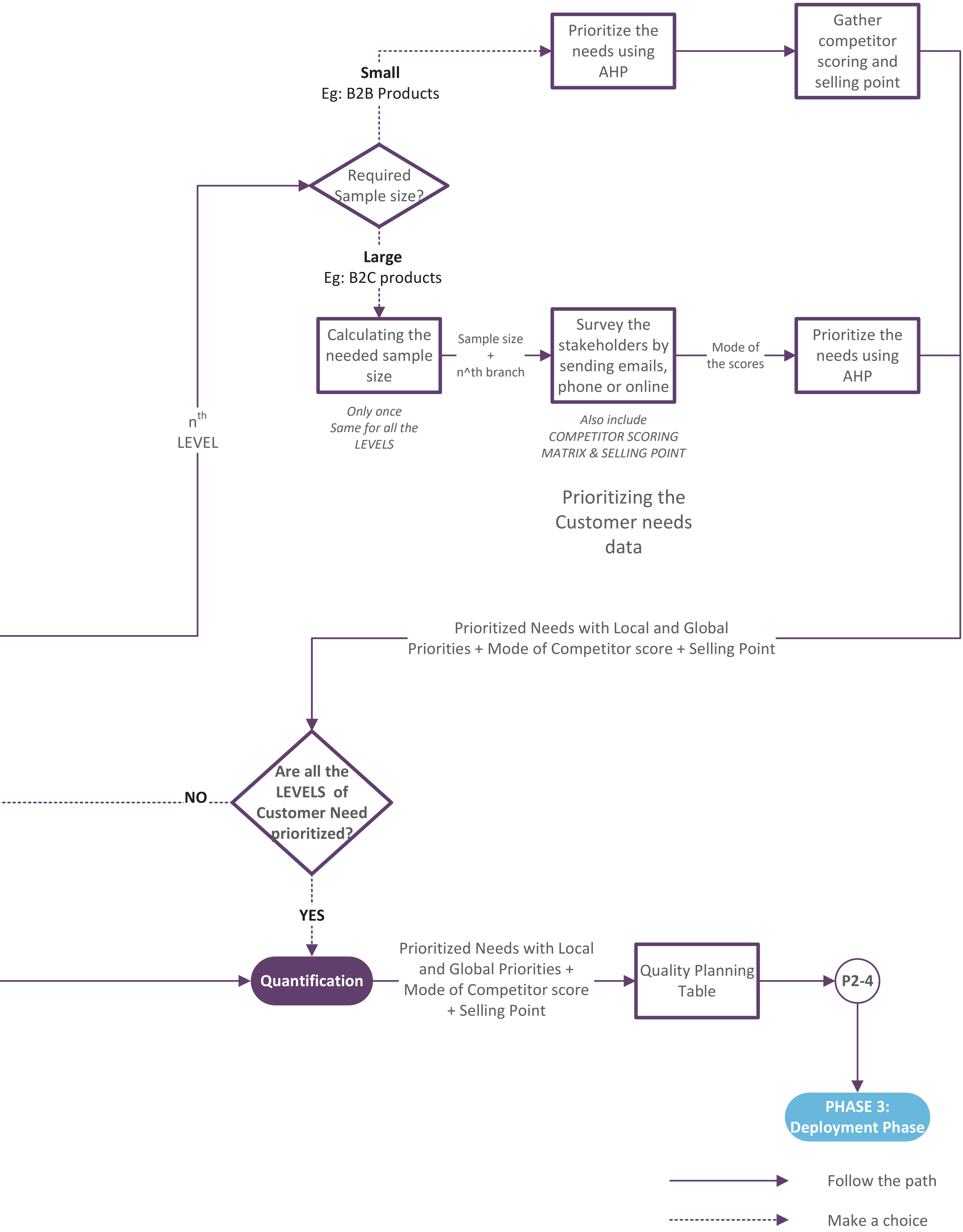
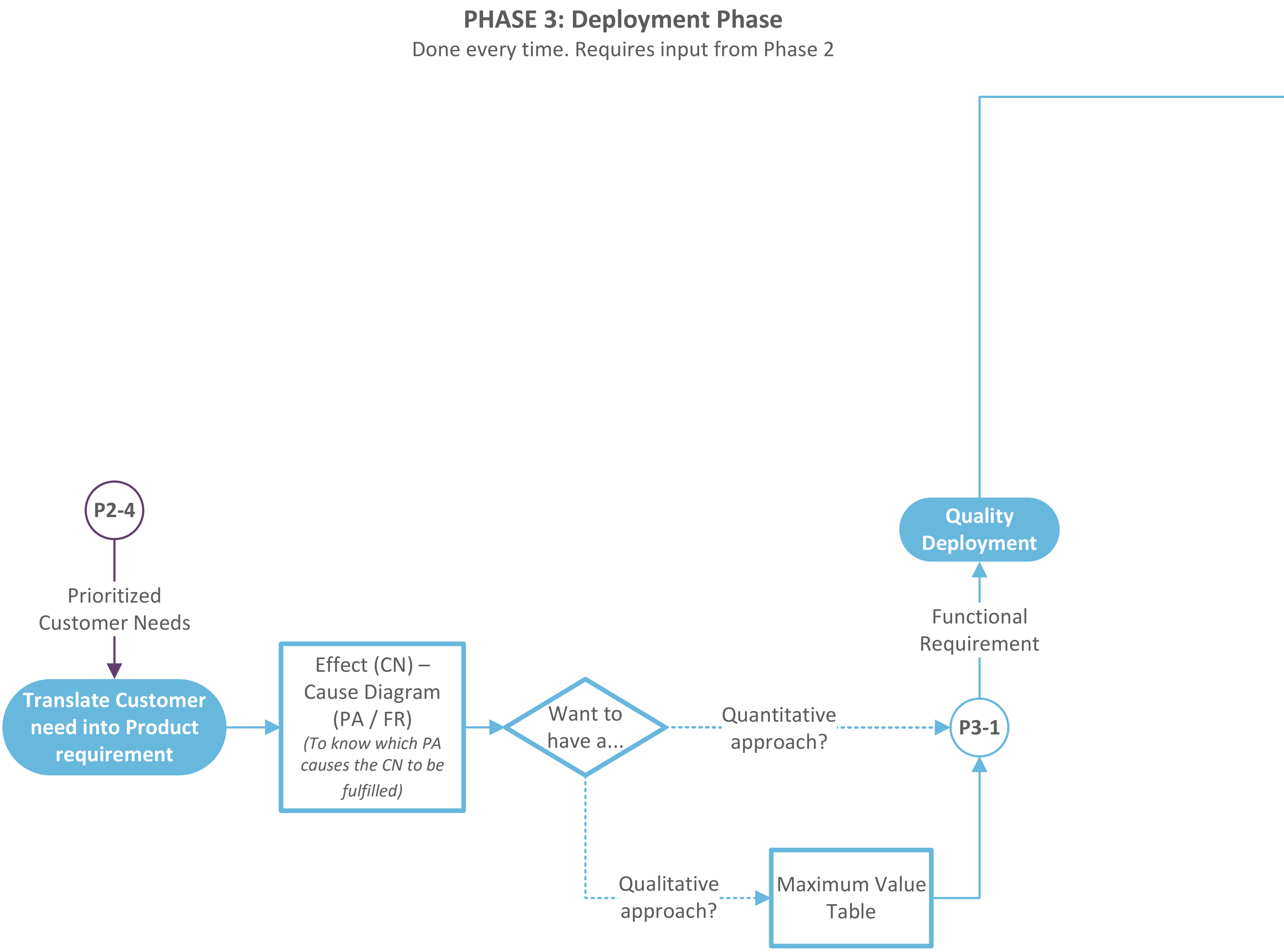


Figure 2.10 Customer Analysis Phase



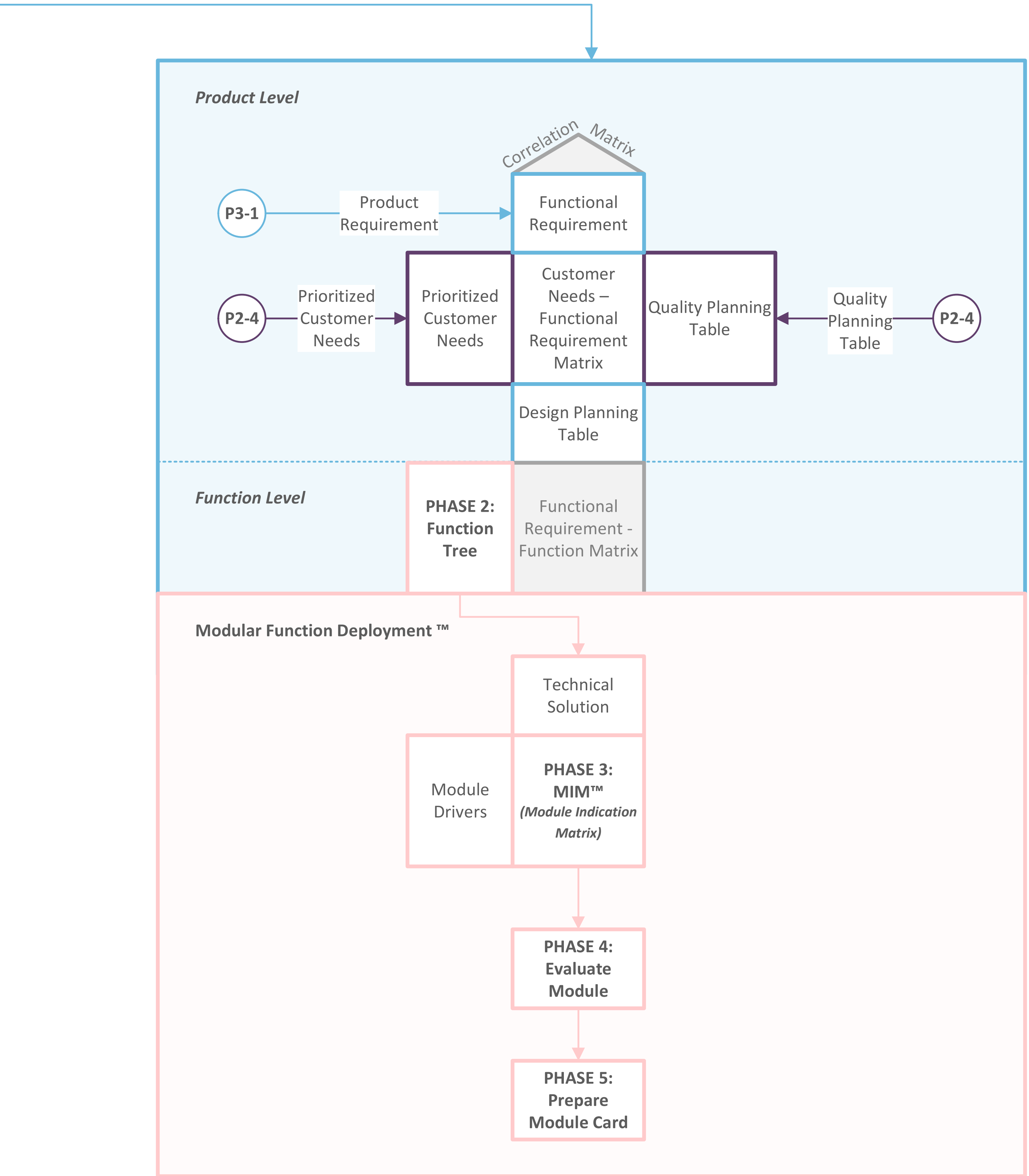
Prioritize the needs using AHP
Gather competitor scoring and selling point
Small
Eg: B2B Products
Required Sample size?
Large
Eg: B2C products
Calculating the needed sample size
Sample size + n^th branch
Survey the stakeholders by sending emails, phone or online
Mode of the scores
Prioritize the needs using AHP
nth LEVEL
Only once Same for all the LEVELS
Also include COMPETITOR SCORING MATRIX & SELLING POINT
Prioritizing the Customer needs data
Prioritized Needs with Local and Global Priorities + Mode of Competitor score + Selling Point
NO
Are all the LEVELS of Customer Need prioritized?
YES
Quantification
Prioritized Needs with Local and Global Priorities + Mode of Competitor score + Selling Point
Quality Planning Table
P2-4
PHASE 3: Deployment Phase
Follow the path
Make a choice



ABBREVIATION USED:

CN	Customer Needs
PA / FR	Product Attribute / Functional Requirement
QA	Quality Assurance
QC	Quality Control
P2-4	Input from PHASE 2 – Quantification
P3-1	Input to PHASE 3 – Quality Deployment

Figure 2.11 Deployment Phase



Product Level
Correlation Matrix
P3-1
Product Requirement
Functional Requirement
P2-4
Prioritized Customer Needs
Prioritized Customer Needs
Customer Needs – Functional Requirement Matrix
Quality Planning Table
Quality Planning Table
P2-4
Design Planning Table
Function Level
PHASE 2: Function Tree
Functional Requirement - Function Matrix
Modular Function Deployment ™
Technical Solution
Module Drivers
PHASE 3: MIM™ (Module Indication Matrix)
PHASE 4: Evaluate Module
PHASE 5: Prepare Module Card

2.3.3.4.1 Phase 1: Strategy Development phase

Business strategy helps the organisation to set short-term or long-term goals, policies and guides the organisation to achieve those goals. It also helps the organisations to focus their effort in the right direction and allocate the resources efficiently (Chandler, 1962). Therefore, the strategy development phase forms a crucial part for a successful deployment of the QFD process. The output of this phase, *i.e., prioritised business goals,* will guide the rest of the QFD process by enabling product managers, process managers, designers and developers to comprehend and prioritise both organisational goals and project-specific goals (ISO 16355-2:2017, 2017). The first step consists of gathering or defining the business goals by listening to the Voice of Business *(VoB)* followed by prioritisation of the business goals. Figure 2.6 illustrates the process flow of this phase.

2.3.3.4.1.1 Step 1: Define Business Goals

Business goals can be an organisational level or project level. Accordingly, the decision makers or the people heading the project define business goals once in a year or for every project. As mentioned, business goals are required not only to keep the teams focused on the company strategy, but also to determine which project or who among the stakeholders will benefit most while achieving the business goals (ISO 16355-2:2017, 2017).

Due to the dynamic nature of the businesses, these goals can change intermediately. If so, the QFD process allows the team to realign the previous goals to match the new business goals. ISO 16355-2:2017 suggests the tools and best practices used to implement in this phase. There are multiple approaches to define business goals. Therefore, the selection criteria for the process is based on the intended use *(Use Case)* and the type of output needed *(Output).* Table 2.7 shows the process selection matrix to define business goals.

Table 2.7 Process selection matrix for the definition of business goals

		Process			
		Business Goal Table	Porter's Five Force Analysis	Hoshin Karin	New Lanchester Strategy
Use Case	Strategy for the company	x	x	x	x
	Strategy for the project	x			
	Competitor Comparison		x		x
Output	Business Goals	x		x	x
	Targets			x	

Key Takeaways:

- A clear **business goal/strategy** will guide the development process of the product in the right direction.
- The basis for the process selection should depend on the **use case** and the **output** required from the process.
- The **Decision Makers** or **people heading the project** carry out this step.
- Prioritisation of these **Business goals** will take place in the next step.

2.3.3.4.1.2 Step 2: Prioritise Business Goals

Every project can be unique and have different needs. However, fulfilling the needs that do not provide much value to the business and the stakeholders can deplete the resources allocated to the project. Hence, prioritising the business goals help the project team to separate the high priority goals from the lower priority goals and assist the team in allocating the resources efficiently (Saaty & Saaty, 2016).

The decision makers or the people heading the project who defined the business goals in the previous step prioritise the goals. Additionally, any constraints for the project are noted down in a table called the project constraint table. ISO 16355-2:2017 suggests the use of a multi-criteria decision-making tool called *Analytic Hierarchy Process* or *AHP* as one of the prioritisation tools. AHP is a powerful tool that helps to facilitate the decision-making process when a judgment on individual criteria is required *(which may be relative or absolute)*, thus allowing the construction of a cardinal group decision, which is compatible with the individual preferences (Saaty & Saaty, 2016). Initially, the list of goals/items are categorised using an affinity diagram to form primary criteria's, and the respective goals/items are assigned to one of the corresponding primary criteria. Then, each criterion is compared with every other criterion on a similar level of affinity diagram, followed by the comparison of goals/items of the criteria's among themselves. The obtained priorities give much more accurate results when compared to the regular ranking methods. Further, it has an inbuilt way to measure the consistency of the judgements made, which makes AHP a robust decision-making tool. Appendix A.1 provides more information about AHP.

Key Takeaways:

- **Prioritised business goals** help the team focus on the projects and their needs that bring value to the business as well as the customers.
- It is necessary to organise the business goals using an **affinity diagram** before using **AHP** to prioritise the business goals.
- The **Decision Makers** or **people heading the project** carry out this step.
- The **prioritised business goals** are used as the input to prioritise the projects and the stakeholders later in the QFD process.

2.3.3.4.1a Phase 1 A: Project Prioritization phase

When there are multiple projects and limited resources, prioritising the projects will help the team to determine which project brings the most value to the organisation by fulfilling the business goals. Prioritising the projects is an optional phase in QFD and carried out when the organisation has multiple project or project ideas and no sufficient resources to carry them out. The decision makers or the people heading the project determine the importance of each project based on specific criteria. Prioritised business goals and a list of the projects are the input for this process.

The selection of a process to prioritise projects depends on the use case, *i.e., whether the projects are compared against each other or different criteria,* and the depth of detail the team wants to extract. Table 2.8 and figure 2.7 shows the process selection matrix and flow diagram for Project Prioritisation. Appendix A.2 and section 2.3.3.4.2.2 provide more information about the L-matrix and section 2.3.3.4.2.4 provides more information about Cause-Effect diagram.

Table 2.8 Process selection matrix for Project Prioritisation

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">Process</th></tr>
<tr><th>AHP</th><th>Cause-Effect Diagram</th><th>L-Matrix</th></tr>
<tr><td rowspan="3">Use Case</td><td>Compare projects against each other</td><td>x</td><td></td><td></td></tr>
<tr><td>Compare projects against other criteria</td><td></td><td></td><td>x</td></tr>
<tr><td>An in-depth comparison of projects against multiple criteria's</td><td colspan="2">x</td><td></td></tr>
</table>

Key Takeaways:

- **Prioritising projects** help the team to determine which project brings the **most value** to the organisation by fulfilling the **business goals**.
- The basis for the process selection should depend on the use case and the level of detail.
- The **Decision Makers** or **people heading the project** carry out this step.

2.3.3.4.2 Phase 2: Customer Analysis Phase

As much as the product shall be built economically and be competitive, once launched it shall be able to solve the customer problems. If not they move to the competitor's product, which makes customers one of the crucial elements for the success of the product (Bonchek & Cornfield, 2016). Gallois (1993) explains that *"The market has taken power over from industrial companies, which are now time-driven and customer-driven"*. Therefore, knowing the customer's desires is very crucial to be successful in a competitive market. Moreover, knowledge of the customer's needs helps to focus the attention on the critical issues and limits *(or eliminates)* the focus on the issues which are not crucial for the customers. QFD helps to achieve this by having a systematic approach to collect the required customer data and convert it into useful technical data.

According to Akao (1990), Quality Function Deployment is a process used to – "*Develop design qualities (attributes/requirements - What's) aimed at satisfying the customer needs (Why's) and converting the qualities into design targets and major quality assurance points that would be used throughout the production stage"*. Therefore, this phase of the QFD process focusses on definition or identification of the customers influenced by the project or the product in step 1 *(2.3.3.4.2.1)*, followed by prioritisation of these customers based on how much they would help to fulfil the business goals set by the organisation in step 2 *(2.3.3.4.2.2)*. Once the most important customers are identified, the voice of these customers is gathered in step 3 *(2.3.3.4.2.3)*. Typically, the collected voice of customer data will be raw information *(also known as Voice of Customer or VoC)* and often include complaints, needs, functional requirements, performance specifications and targets, solutions, components, materials and other customer statements. Analysis and translation of these VoC into customer needs takes place in step 4 *(2.3.3.4.2.4)* of this phase.

The structuring of the customer needs in step 5 *(2.3.3.4.2.5)* will help the team to find the unspoken or missing customer needs to improve the accuracy of the priorities and increase the efficiency of the prioritisation process (Ronney, et al., 2000; ISO 16355-4:2017, 2017). These structured customer needs are then prioritised in step 6 *(2.3.3.4.2.6)* of this phase. The prioritisation of the customer need helps the QFD team to focus on the needs that provide maximum benefit to the customer or the stakeholder. In the final step of phase 2 *(2.3.3.4.2.7)*, the quantification of the customer need takes place. Quantification of customer needs includes customers current and hoped-for satisfaction levels, customer scoring of the magnitude of existing product and benchmarking competitive alternatives, and other factors that are necessary during the quality deployment process (ISO 16355-4:2017, 2017). The output of phase 2, *i.e. prioritised customer needs*, will help in prioritising the product requirements *(product attributes)* in phase 3 of the QFD process.

2.3.3.4.2.1 Step 1: Identify the stakeholders

To get the customer needs, the QFD team first has to identify the stakeholders* whom the product benefits the most. Identifying these stakeholders will help the QFD team to determine the relationship between stakeholders and the value they add to achieve the defined business goals. The stakeholders involved in the project consists of a combination of external stakeholders *(i.e., end-users, client/owner, suppliers, architects, sub-contractors, legislators/ regulators, insurance providers)* or internal stakeholders *(i.e., sales, R&D, design, planning, procurement, HR, production, assembly)*. Therefore, the process for identification of the stakeholders depends on the existence of the stakeholder in real life and the amount of detail required. Table 2.9 and figure 2.8 show the process selection matrix and a flow diagram for the identification of the stakeholder.

Table 2.9 Process selection matrix for Stakeholder identification

		Process		
		User Persona	**Customer Value Chain Analysis**	**Stakeholder analysis**
Stakeholder Existence	**Stakeholder exist**		x	x
	Stakeholder does not exist *(Fictional)*	x		
Details about the Stakeholder	**The relationship between the stakeholders**		x	x
	In-depth analysis			x

Key Takeaways:

- **Identifying the stakeholders** helps to determine the **relationship** between stakeholders and the **value** they add to achieve the defined business goals.
- The basis for process selection should be the existence of the stakeholder and the level of detail.
- **QFD team** will carry out this step

** Stakeholders = Customer or Stakeholder*

2.3.3.4.2.2 Step 2: Prioritise the stakeholders

As mentioned previously, a project might consist of multiple internal or external stakeholders depending on the nature of the project. However, focusing on all the identified stakeholders will be laborious considering the time and cost involved in engaging them when compared to the value they add to fulfil the business goals. Prioritising the stakeholders will help the QFD team to focus on the high priority stakeholders who are critical to achieving the business goals (ISO 16355-2:2017, 2017).

This step requires the evaluation of two different data sets*, i.e., stakeholders and business goals.* ISO 16355-2:2017 suggests the use of L-matrix. The business goals and their weights obtained from Step 2 of Phase 1: Strategy Development Phase *(2.3.3.4.1.2)*, are entered in the rows and the identified customers in the columns. QFD team, led by the product owner and the marketing team judge the importance of each customer segment in achieving the business goals, row by row.

ISO recommends the used of 5-level ratio scale *(3.1.3)* to carry out this process. Judging the strength of the relationship between the customer and the business goal is subjective. Therefore, using at least five or nine levels of judgement when making subjective decisions optimises human decision-making capabilities, *i.e., weak (W), moderate (M), strong (S), very strong (VS), or extremely strong (ES), and if necessary, intermediate intervals such as weak-to-moderate (W-M), and so forth* (Fehlmann & Glenn, 2016). This approach aligns with the Miller's Law proposed by the psychologist George A. Miller (1956), which states that – *"The limits in absolute judgement and short-term memory are optimised at seven 'chunks' of information with ± 2 for memory processing"*.

Table 2.10 Ratio scale to judge the strength of subjective relationships (5-interval)

	Extremely Strong	**Very Strong**	**Strong**	**Moderate**	**Weak**	**None**
Score	0,503	0,26	0,134	0,068	0,035	0
Symbol	●	◕	◑	◔	○	.
	ES	VS	S	M	W	.
	5	4	3	2	1	0

Key Takeaways:

- **Prioritising** the stakeholder is essential **to achieve the business goals** by focusing on the high priority stakeholders
- Reduces the **time** and **cost** associated with stakeholder engagement
- **AHP** is the suggested method for the prioritisation

2.3.3.4.2.3 Step 3: Source of VoC or VoS

VoC or Voice of the Customer is a process to capture the customer's wants and needs, which are later structured *(2.3.3.4.2.5)* and prioritised *(2.3.3.4.2.6)* (Hauser, et al., 2010). This step involves acquiring relevant information from the previously prioritised customer segment while thinking broadly about the project issues (Brodie & Burchill, 2005). It is a crucial step in the QFD process since it mainly consists of gathering the customer or stakeholder inputs by various means. This step is also the most time consuming, yet if done right it can be a rewarding one.

There are various processes available while sourcing the VoC or VoS. The selection of the process depends on the ease of information access, availability of the VoC or VoS data and requirement of physical presence of the team and the stakeholder. Since there are multiple stakeholders involved in the project, the process to source the VoC or VoS may vary for each stakeholder depending on the selection criteria mentioned above. Table 2.11 and figure 2.9 shows the process selection matrix and the flow diagram to source the VoC or VoS.

Table 2.11 Process selection matrix for sourcing the VoC or VoS

Information	Available	Physical Presence	Process/Tool
Easy to Access	No	Required	Gemba Visit
			Focus Group
			Lead User Analysis
			Contextual Analysis
			Interviews *(Direct/Secret shopper)*
			Ethnographic study
			Continuous & Collaborative QFD
		Not Required	Survey
			Questionnaire
	Yes	Required	Customer Supplied Information
			Technical Visits
		Not Required	Customer Support
			Warranty Information
			Maintenance Record
Difficult to Access		Required	Hackathons
			Conference
			Product Launch
		Not Required	Websites
			Annual Reports
			Social Media

Key Takeaways:

- Consists of **gathering** the customer or stakeholder **inputs** using a variety of tools
- Carried out by the **QFD team** along with the **customer** or **stakeholder**
- Selection of the process depends on the **ease** of information access, **availability** of the VoC or VoS data and requirement of **physical presence**.

2.3.3.4.2.4 Step 4: Translate VoC to Customer Needs

Hauser & Griffin (1993) defined customer needs as – *"A customer need is a description, in the customer's own words, of the benefits to be fulfilled by the product or service"*. Timoshenko & Hauser (2018) further explained that the knowledge of customer's needs would help in identifying opportunities (Herrmann, et al., 2000) or improvements for new products (Krishnan & Ulrich, 2001; Sullivan, 1986; Ulrich & Eppinger, 2016), managing product portfolios (Stone, et al., 2008) and improve existing products and service (Matzler & Hinterhuber, 1998). However, the VoC data collected will often include complaints, customer needs, functional requirements, performance specifications and targets, solutions, components, materials and other customer statements. Therefore, to derive true customer needs, QFD team along with the area experts must identify and separate customer needs from other data and translate the separated data into customer needs that ultimately leads to more flexibility and innovativeness in finding appropriate solutions to satisfy the stakeholders (ISO 16355-4:2017, 2017)

There are two process recommendations to translate raw VoC to customer need, *i.e., Verbal translations and Cause-to-Effect diagram.* The verbal translation process is simple and straightforward. The raw VoC statements are quickly analysed to check if they contain data other than customer needs and translate them to customer needs. However, this method may result in the omission of data, which are closely related. On the other hand, Cause-to-Effect diagram helps to identify the Effect *(Customer Need)* occurring due to some Cause *(VoC)*. Figure 2.12 illustrates the Cause-to-Effect model. Also, a *Customer Voice Table (CVT)* can be helpful to organise and store the data (ISO 16355-4:2017, 2017).

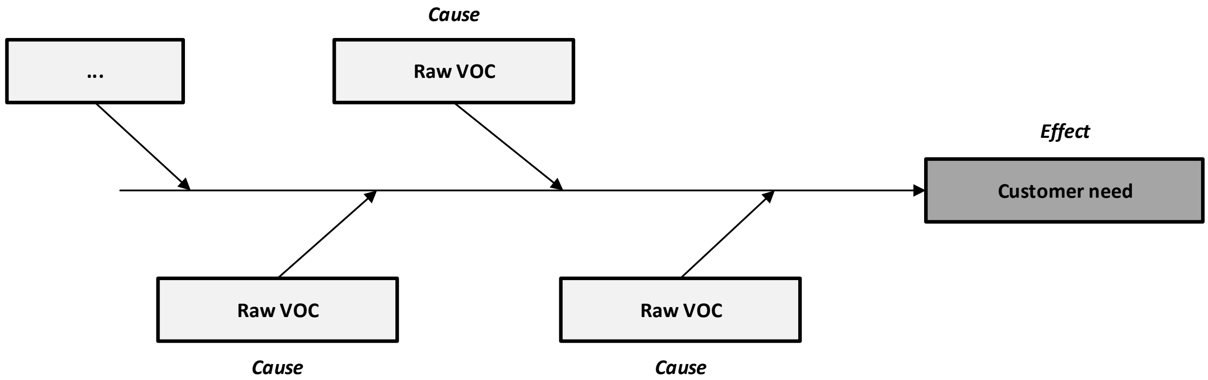


Figure 2.12 Cause-to-Effect diagram illustration – Adapted from Ishikawa (1985)

Key Takeaways:

- **Raw VoC** data collected will often include complaints, customer needs, functional requirements, performance specifications and targets, solutions and suggestions
- Carried out by the **QFD team** along with the **domain area experts**
- Depending on the intricacy needed the team can opt for **Verbal Translation process** or **Cause-to-Effect diagram**.

2.3.3.4.2.5 Step 5: Structure the Customer Needs

Structuring the customer need data is a vital part to organise and reduce the time needed while prioritising the customer needs. Further, well-structured data should be Mutually Exclusive and Collectively Exhaustive *(MECE)*, which will help to avoid double counting and missing choices. To obtain data that is MECE, ideally, the stakeholder who provided that dataset will be required to structure it and make appropriate adjustments to the data so that it exhibits MECE characteristics (Fehlmann & Glenn, 2016).

Use of Affinity diagram is the suggested process to structure the customer needs data. It starts by writing each need on a sticky note and requesting the stakeholder to organise them from the bottom up by first grouping the needs, assigning them into a common category and finally building the groups of these categories (Beyer, 2010). Next, the structured data will be turned 90° counterclockwise to visualise it as a hierarchy diagram as shown in figure 2.13. This arrangement will help to address any structural issues with the organised data, specifically to check if the categories are Mutually Exclusive *(ME)*. Further, it also helps to find unspoken or missing customer needs, which improves the accuracy and reduces the work required during the prioritising process forming a Collectively Exhaustive *(CE)* list (ISO 16355-4:2017, 2017).

The significance of structuring the needs is crucial before prioritisation process because of the time required to prioritise the needs if the dataset is only a single level. Equation 1 shows the formula required to calculate the time needed for prioritisation.

$$t_t = \left(\frac{n^2-n}{2}\right) \times t_{pd} \tag{1}$$

Where,

$t_t = Total\ time\ (sec)$

$n = Number\ of\ customer\ need\ data$

$t_{pd} = Estimated\ time\ per\ customer\ need\ comparison\ (sec)$

Key Takeaways:

- A well-structured data is **Mutually Exclusive** and **Collectively Exhaustive**
- Structuring **improves accuracy** and **reduces the work** during prioritisation
- **Affinity diagrams** and **Hierarchy diagrams** are used to structure the information
- The **stakeholders** who provided the dataset carry out the process

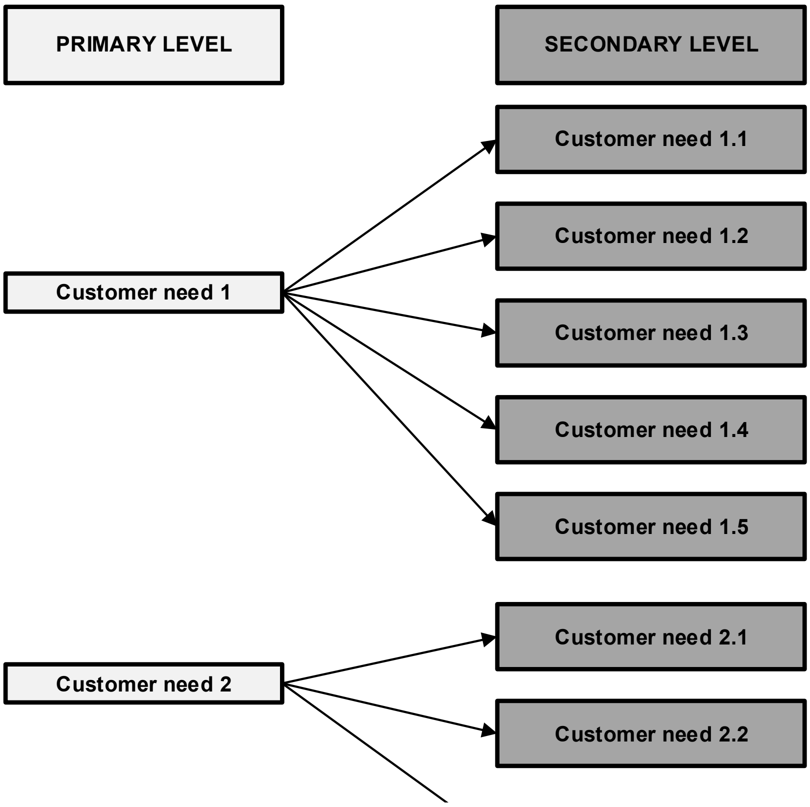


Figure 2.13 Hierarchy diagram of the customer need – Adapted from Fehlmann & Glenn (2016)

2.3.3.4.2.6 Step 6: Prioritise the Customer Needs

After the preceding processes, the QFD team may have collected a large number of customer need data. Satisfying all the customer needs is practically impossible even for large corporations due to the constraints in the technology and the limitation on the resources (Cook, 1997). Therefore, prioritising these needs helps the team to focus only on the needs which when fulfilled will add maximum benefit to the customer with minimum effort from the team (Fehlmann & Glenn, 2016). Further, the priorities assigned should be accurate, unbiased and unambiguous as possible since they are later used to allocate cost and resources (ISO 16355-4:2017, 2017). This can be achieved if the prioritisation is carried out by the stakeholder group who provided that data and with the use of the ratio scale as discussed in section 3.1.3.

The process for prioritisation of customer needs depends on whether the needs are mutually exclusive. Table 2.12 shows an overview of the selection table of the process to prioritise customer needs.

Table 2.12 Process selection table to prioritise customer needs

Interaction between needs	Process
Mutually exclusive	AHP
Not mutually exclusive	ANP

Yüksel and Dağdeviren (2007) mentioned that the AHP is based on a framework that incorporates unidirectional hierarchical relationship *(figure 2.14a)* while the Analytic Neural Process *(ANP)* accepts complex interrelationships among hierarchy levels and alternatives *(figure 2.14b)*.

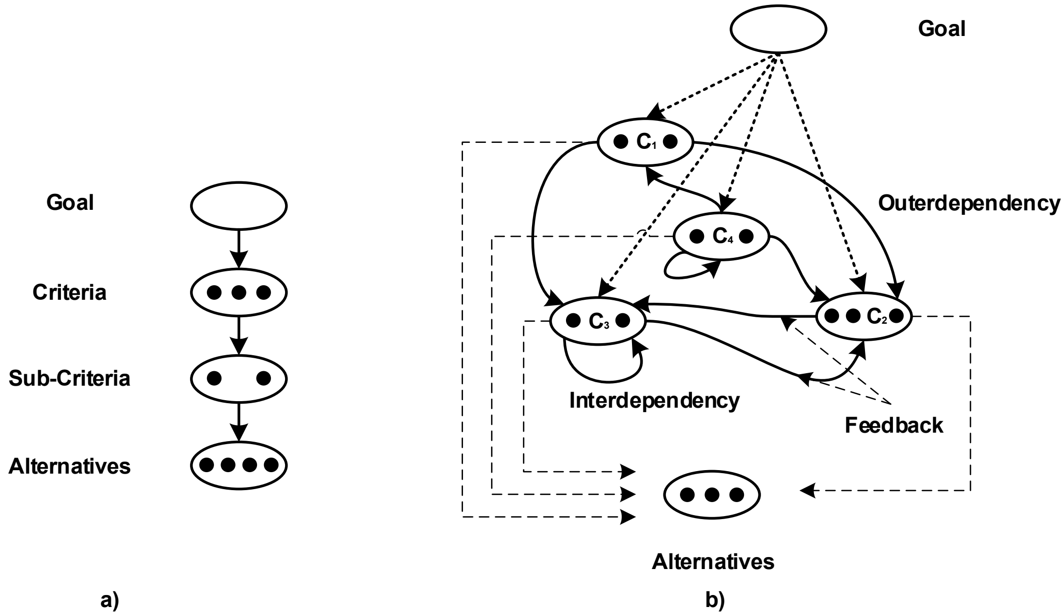


Figure 2.14 The structural difference between a) AHP and b) ANP (Görener, 2012)

When the data is mutually exclusive, *i.e., no overlaps*, AHP can carry out the pairwise comparison to give accurate results when a quantitative measure is required from a qualitative customer needs data. The prioritisation process is similar to the stakeholder prioritisation but carried out in stages. First prioritising the highest level needs *(abstract)* followed by prioritisation of the next level needs *(more detailed)* which forms the branch of the same higher-level need to obtain local priority of that branch. The global priorities of a level are obtained by multiplying the priorities *(global priorities)* of their higher-level need with their local priorities (Fehlmann & Glenn, 2016). Figure 2.15 shows the hierarchy of the needs after prioritisation with higher-level need *(abstract)* on the left side and detailed needs on the right side with their local and global priorities. On the other hand, when the data are not mutually exclusive, ANP is used.

Key Takeaways:

- **Prioritised customer needs** help the team to **focus** on the needs that benefits most to the customers
- Process selection depends on the **mutual exclusivity** of the criteria's, *i.e., If the data is mutually exclusive use **AHP**, if not use **ANP***
- Depending on the level of information, multiple **AHP/ANP** process is used
- The **stakeholder's** group who provided the dataset carries out the process

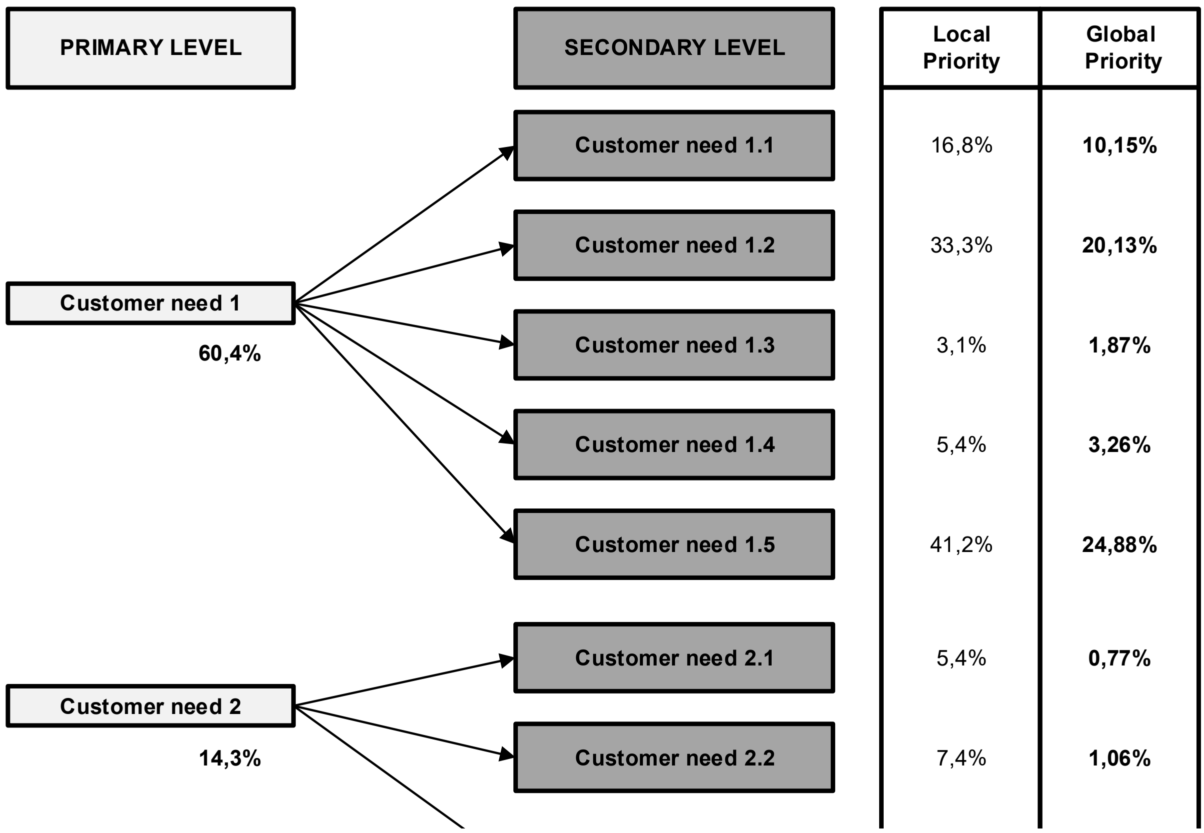


Figure 2.15 Hierarchy diagram of the customer needs with their priorities – Adapted from Fehlmann & Glenn (2016)

2.3.3.4.2.7 Step 7: Quantification

Quantifying the customer needs gives an overview of the product's current and expected performance level that includes the minimum acceptable level *(below which there is no real benefit)* and the maximum thresholds *(beyond which there is no additional benefit).* It also includes the competitor's performance levels (ISO 16355-4:2017, 2017). Terninko (1997) suggest the use of Quality Planning Table *(QPT)* for the quantification process. However, the quantities used were in the ordinal scale. Therefore, ISO 16355-4:2017 (2017) suggest the use of Likert verbal scale when possible as it is easy to comprehend by the stakeholder.

First, the factors and their elements affecting the needs are identified as shown in figure 2.16 *(Customer satisfaction level, competitor's performance levels, and factor 3).* The scales *(Likert verbal scale or ordinal scale)* to be used for the factors are identified, and its elements are judged using AHP, to obtain the prioritised weight of the scale elements. With the help of an unweighted QPT, the customer needs, and the elements of the factors are compared, and weights are assigned using Likert verbal scale or ordinal scale. Substitution of these weights with the ratio scale weights obtained from the AHP helps to get the local priorities of the needs. The global priority of each customer need in a factor is obtained by multiplying the local priorities of the selected customer needs with the global priority of that factor. Finally, the global priorities of all the factors for each need are added to get the adjusted priority of that customer need.

Table 2.13 shows a weighed quality planning table with global priorities for the customer needs *(figure 2.15)* and their adjusted priority with weights assigned for the identified factors. One of the drawbacks of this step is that it will take a considerable amount of effort to acquire these preferences. Therefore, it is recommended to obtain the data only for the high priority customer need.

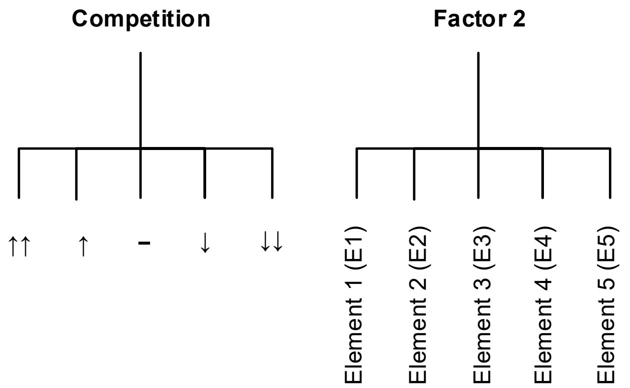


Figure 2.16 Identification of the factors and their elements

Table 2.13 Weighed Quality Planning table (ISO 16355-4:2017, 2017)

Customer needs	Customer			Competition							Factor 2				Adjusted Priority %
	Priority %	Local Priority %	Global Priority %	Current	Competitor	Target	Improvement Level	Priority %	Local Priority %	Global Priority %	Factor 2 element	Priority %	Local Priority %	Global Priority %	
	Customer		52,50	Survey			Competition			14,30	Factor 2			33,30	
Customer need 1.1	10,15	16,83	8,84	3	3	4	↑	26,30	20,82	2,98	E5	50,30	55,83	18,59	30,40
Customer need 1.2	20,13	33,39	17,53	1	4	5	↑↑	55,80	44,18	6,32	E2	6,80	7,55	2,51	26,36
Customer need 1.3	1,87	3,11	1,63	3	2	3	–	12,20	9,66	1,38	E1	3,50	3,88	1,29	4,31
Customer need 1.4	3,26	5,41	2,84	5	1	2	↓	5,70	4,51	0,65	E1	3,50	3,88	1,29	4,78
Customer need 1.5	24,88	41,27	21,67	2	3	5	↑	26,30	20,82	2,98	E4	26,00	28,86	9,61	34,15

Key Takeaways:

- Gives an overview of the product's **current** and **expected performance level, competitors performance level** from the customer's point of view
- **Quality Planning Table** along with **AHP** is used to quantify the customer needs
- The **stakeholders** who provided the dataset carry out the process

2.3.3.4.3 Phase 3: Deployment Phase

Deployment phase mainly consists of translating one information set into another and assigning priorities to them. As mentioned in section 2.3.3.4, ISO 16355 QFD approach is based on the comprehensive QFD *(figure 2.2)*. Comprehensive QFD has multiple deployment stages *(dimensions of design a, b, c, and d – vertical processes in figure 2.2)* with various level of design in each deployment stage *(levels of design – 1, 2, 3 and 4 – horizontal processes in figure 2.2), i.e.,*

Dimensions of Design

a. Quality Deployment
b. Technology Deployment
c. Cost Deployment
d. Reliability Deployment

Levels of Design

1. Product level
2. Function level
3. Component level
4. Process level

This type of division of stages and levels gives the team greater flexibility to choose an approach according to their requirement (ISO 16355-8:2017, 2017). Similar to the Classical comprehensive QFD, the ISO recommended QFD approach also uses the output of the previous deployment stage as the input for the subsequent deployment stages.

2.3.3.4.3.a Quality Deployment

According to Hauser (1993), if the product has to fulfil customer's needs, it must meet the measurable requirements, *i.e., product requirements.* Quality deployment focuses on the translation of the prioritised customer needs into product requirements structured at the product level, functional level, component level or process level and to find the relationship between them (ISO 16355-5:2017, 2017). Therefore, different matrices and tools are used at different levels, *i.e.,*

1. Product level *(Customer needs-Product requirements matrix or HoQ)*
2. Function level *(Customer needs-Functions matrix & Product requirements-Functions matrix)*
3. Component level *(Product requirements-Components matrix)*
4. Process level *(Process charts)*

NOTE: *For this thesis, only the first two levels of the Quality deployment stage are explained in detail, and other stages are summarised.*

2.3.3.4.3.a.1 Product level: Customer needs-Product requirements matrix (HoQ)

The House of Quality matrix serves as a tool to translate customer needs into product requirements and capture the relationship between them. The primary purpose of this matrix is to help the QFD team determine which of the products functional and the performance levels can help to achieve the customer's desired wishes *(Customer needs).*

As shown in figure 2.17, the input for this stage is the prioritised customer needs and quantified customer scoring both obtained from phase 2. The essential part of this process is the product requirements obtained by converting the customer needs *(Why's)* into product requirements (*What's)* using Effect-to-Cause diagram in step 1. Further, a Maximum Value table *(MVT)* is helpful to capture everything important to the customer and the means to fulfil them. This helps to document and identify where to apply the efforts to provide maximum value to the customer. However, MVT does not capture the priorities of the product requirement. Instead, employing the L-matrix helps in overcoming the shortcoming of MVT. Once the priorities for the product requirements are obtained from the L-matrix in the product level, it is used as the input for the Functional level *(Second level of Quality deployment)*, in which comparison of product requirement and functions takes place.

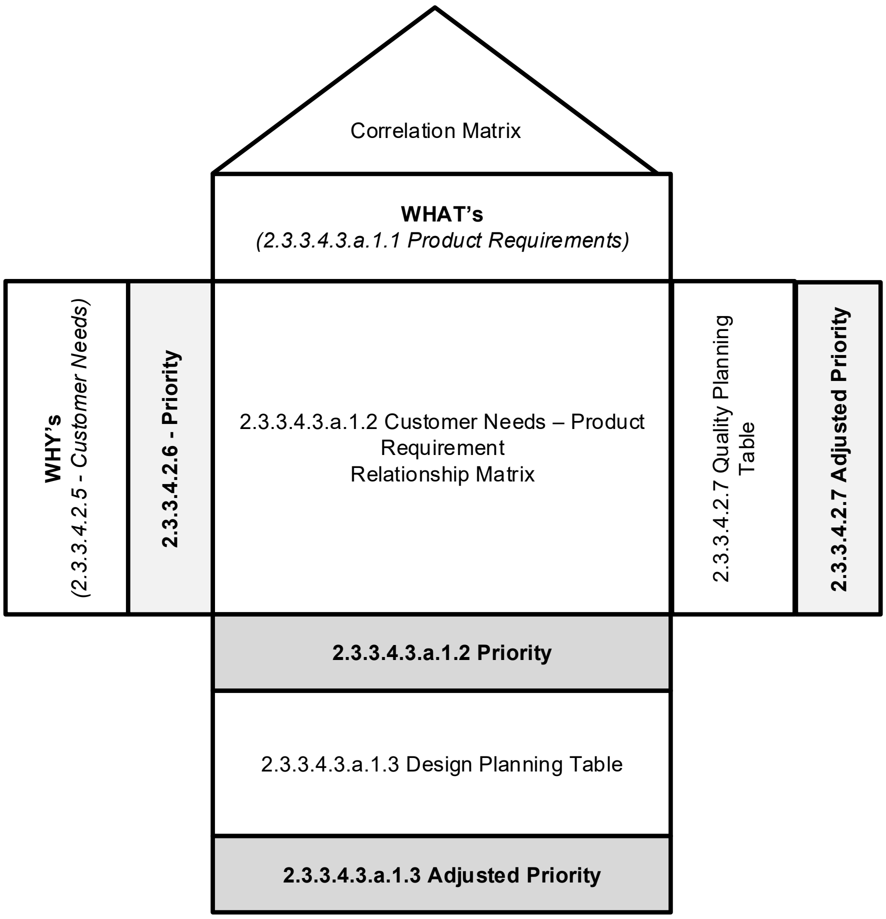


Figure 2.17 Overview of Customer needs–Product Requirement Matrix – Adapted from Chan & Wu (2002)

2.3.3.4.3.a.1.1 Step 1: Translate Customer Needs into Product Requirements

The primary purpose of carrying out the translation process is to understand what a product shall have or do such that it fulfils the customers desired needs. This will help the technical team to know the quantities they have to consider while designing. The recommended process to translate customer need to product requirement is the Effect-to-Cause diagram. It is similar to the Cause-to-Effect diagram as mentioned in Phase 2: Step 4 *(2.3.3.4.2.4)* but in the opposite direction. Here the QFD team determines for each customer need *(Effect)* during development through commercialisation what product requirements *(Cause)* are essential to deliver a quality product. Care should be taken while translation to avoid inclusion of any technical solutions which would restrict innovation. Figure 2.18 illustrates an Effect-to-Cause diagram.

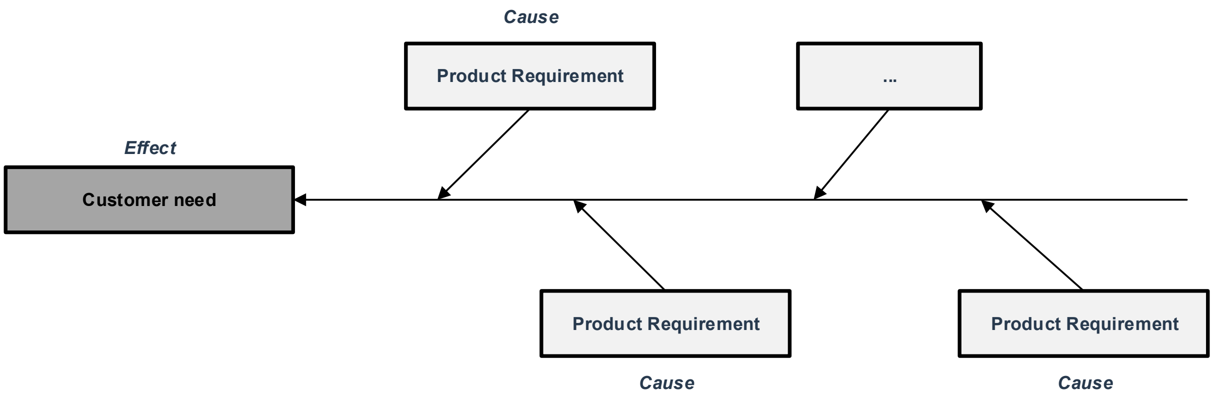


Figure 2.18 Effect-to-Cause diagram illustration - Adapted from Ishikawa (1985)

2.3.3.4.3.a.1.2 Step 2: Quantifying matrix relationships

Figure 2.17 shows the Quality Deployment stage at a product level. The combined shape of the matrices looks like a house. Therefore, this deployment matrix is nicknamed as the *House of Quality* or *HoQ*. L-matrix is used to determine the relationship between the two information sets and examine the goals and means to achieve them. As shown in table 2.14, the customer need *(Effect)* along with their priorities are placed in the rows of the matrix and product requirements *(Cause)* in the columns of the matrix.

Row-by-row, each customer need is compared to the product requirements to obtain their relationship and noted down in the intersecting cell. Similar to the Phase 2: Step 2, the judgment level used in the L-matrix is a verbal scale *(weak (W), moderate (M), strong (S), very strong (VS), or extremely strong (ES), and if necessary, intermediate intervals such as weak-to-moderate (W-M), and so forth)*. Conversion of these judgment levels using AHP help to obtain the ratio scale as shown in table 2.10. Next, the absolute priority of the product requirement is obtained by multiplying each customer need with its respective intersecting cell and adding all the elements of that product requirement *(column).* Once, the absolute priorities for all the product requirements are obtained, they are added up and divided by the absolute priorities of each of the product requirement to get the priority for the product requirement. Appendix A.2 provide more information about the calculation using L-matrix.

Table 2.14 Quantified Customer Needs-Product Requirements matrix

Product requirements / Customer Needs	Priority (%)	Product Requirement 1	Product Requirement 2	Product Requirement 3	Product Requirement 4	Product Requirement 5	Product Requirement 6
Customer need 1.1	30,40	M	VS	ES	S	W	M
		0,021	0,079	0,153	0,041	0,011	0,021
Customer need 1.2	26,36		W	ES		M	S
		0,000	0,009	0,133	0,000	0,018	0,035
Customer need 1.3	4,31	ES	M	S	ES	W	VS
		0,022	0,003	0,006	0,022	0,002	0,011
Customer need 1.4	4,78	S		M	VS	W	ES
		0,006	0,000	0,003	0,012	0,000	0,024
Customer need 1.5	34,15	S	S	M	W	W	ES
		0,046	0,046	0,023	0,012	0,012	0,172
Absolute priority		0,095	0,137	0,318	0,087	0,042	0,263
Product Requirement Priority (%)		10,0	14,6	33,8	9,2	4,5	27,9

Key Takeaways:

- **L-matrix** is employed to determine the relationship between **customer needs** and **product requirements** *(or any two dataset)*
- **Row-by-row comparison** of each customer needs to the product requirements to obtain their relationship
- **Prioritised Product Requirements** are obtained at the end of this step
- Carried out by the **QFD team** with the help of **technical experts**

2.3.3.4.3.a.1.3 Step 3: Design Planning Table *(DPT)*

DPT helps the QFD team to set the design target needed for the product requirement to fulfil the high priority customer needs. Similar to the QPT, a DPT can be unweighted or weighted depending on the project. However, the drawback of the QPT *(time-consuming)* does not apply to the DPT since the QFD team carries it out and only allocates the target values for high priority product requirements. The process of building the DPT is the same as that of QPT mentioned in Phase 2: Step 7 *(2.3.3.4.2.7)*. Table 2.15 shows a weighed Design planning table with global priorities for the product requirements of each of the factors and the adjusted priority of the product requirement.

Table 2.15 Weighed Design Planning table (ISO 16355-5:2017, 2017)

			Product Requirement 1	Product Requirement 2	Product Requirement 3	Product Requirement 4	Product Requirement 5	Product Requirement 6
Customer	Priority %	Weight	10	14,6	33,8	9,2	4,5	27,9
	Local Priority %		10	14,6	33,8	9,2	4,5	27,9
	Global Priority %	65,50	6,55	9,56	22,14	6,03	2,95	18,27
Technical Evaluation	Current	Performance	5	20 kW	25 %	1	3	1
	Competitor		4	20kW	30 %	3	1	2
	Target		5	22kW	35 %	4	1	2
Competition	Judgement	Weight	Equal	Better	Much Better	Much Better	Worse	Equal
	Priority %		12,2	26,3	55,8	55,8	5,7	12,2
	Local Priority %		7,26	15,65	33,21	33,21	3,39	7,26
	Global Priority %	21,50	1,56	3,37	7,14	7,14	0,73	1,56
Technical Challenges	Judgement	Weight	Major	Minor	Minor	None	Major	Minor
	Priority %		63,3	26	26	10,6	63,3	26
	Local Priority %		29,41	12,08	12,08	4,93	29,41	12,08
	Global Priority %	13,00	3,82	1,57	1,57	0,64	3,82	1,57
	Adjusted Priority (%)		11,94	14,50	30,85	13,81	7,50	21,41

Key Takeaways:

- Helps to set **target** needed to fulfil the high priority customer needs
- It can include other factors which reflect the design values
- **AHP** is used to convert judgements into a ratio scale
- The **design team** along with the **technical experts** carry out the process

2.3.3.4.3.a.1.4 Step 4: Assembling the HoQ matrix

One of the reasons for building the tables separately and assembling them at the end is for the ease of information management since it is possible to have a 1000 row by 1200 column HoQ for a complex project (ISO 16355-5:2017, 2017). Moreover, separating the tables from the matrices gives us the flexibility to choose the tools according to the project needs. As shown in table 2.16, the Customer needs-Product requirements matrix is placed in the leftmost position. The QPT from Phase 2: step 7 *(2.3.3.4.2.7)* is placed at the right side of this matrix, and a Design Planning table *(DPT)* from step 3 *(2.3.3.4.3.a.1.3)* at the bottom of this matrix. Since all the information is present at a single place, it will help the design team to quickly glance the info in future without incorrectly interpreting any of the quantities.

2.3.3.4.3.a.1.5 Correlation matrix

The correlation matrix is a triangular shaped matrix placed at the top of the Customer needs-Product requirements matrix and thus named as the *"Roof"* of the HoQ. It is helpful while identifying positive and negative correlations among the product requirements. Traditionally, this matrix was suggested to be used in the HoQ (Akao, 1990). However, due to its inherent dependence on the technology, the ISO 16355-5:2017 (2017) recommends not to use this matrix in the Quality deployment stage, instead suggests to use it in the Technology deployment stage.

2.3.3.4.3.a.2 Functional level: Product requirements-Functions matrix

ISO 16355-1:2015 (2015) defines the term function as – *"Function is what the product must do in order for the product to be acceptable by the customer".* Therefore, the functional level of Quality deployment stage is useful to identify and prioritise the functions that have a strong relationship with the product requirements. If the team identifies high priority product requirement without substantial relation with a function, it implies that there can be a possible gap in the product concept, which can result in under-performance or missing feature. On the contrary, if the identified functions do not have a strong relationship with the product requirement, there can be a potential of overdesign or unnecessary feature in the product that may drive up the cost (Shillito, 1994; 1997). Figure 2.19 shows the Quality deployment stage at the function level. Regarding modular product development, identification of the functions is necessary to find a technical solution and group them to form a module in a way that it performs a specific task and ideally will not interfere with or depend on another module (Ericsson & Erixon, 1999).

However, as shown in figure 2.11, for the phase 2 of MFD™, it is sufficient to gather only the functions from this stage, since these functions play a crucial part while identifying the technical solution, which will be the input to generate the module concept in the Module Indication Matrix ™ (Ericsson & Erixon, 1999). The new information set; *i.e., Functions,* are identified with the help of a function tree.

Table 2.16 Assembled Customer needs-Product requirements matrix (HoQ) (ISO 16355-5:2017, 2017)

Customer Needs \ Product requirements	Priority (%)	Product Requirement 1	Product Requirement 2	Product Requirement 3	Product Requirement 4	Product Requirement 5	Product Requirement 6	Quality Planning Table: Customer % — Priority %	Customer % — Local Priority %	Customer % (52,50) — Global Priority %	Survey — Current	Survey — Competitor	Survey — Target	Improvement Level	Competition % — Priority %	Competition % — Local Priority %	Competition % (14,30) — Global Priority %	Factor 3 element	Factor 3 % — Priority %	Factor 3 % — Local Priority %	Factor 3 % (33,30) — Global Priority %	Adjusted Priority %
Customer need 1.1	30,40	◔ 0,021	◕ 0,079	● 0,153	◑ 0,041	○ 0,011	◔ 0,021	10,15	16,83	8,84	3	3	4	↑	26,30	20,82	2,98	5	50,30	55,83	18,59	30,40
Customer need 1.2	26,36	. 0,000	○ 0,009	● 0,133	. 0,000	◔ 0,018	◑ 0,035	20,13	33,39	17,53	1	4	5	↑↑	55,80	44,18	6,32	2	6,80	7,55	2,51	26,36
Customer need 1.3	4,31	● 0,022	◔ 0,003	◑ 0,006	● 0,022	○ 0,002	◕ 0,011	1,87	3,11	1,63	3	2	3	–	12,20	9,66	1,38	1	3,50	3,88	1,29	4,31
Customer need 1.4	4,78	◑ 0,006	. 0,000	◔ 0,003	◕ 0,012	○ 0,000	● 0,024	3,26	5,41	2,84	5	1	2	↓	5,70	4,51	0,65	1	3,50	3,88	1,29	4,78
Customer need 1.5	34,15	◑ 0,046	◑ 0,046	◔ 0,023	○ 0,012	○ 0,012	● 0,172	24,88	41,27	21,67	2	3	5	↑	26,30	20,82	2,98	4	26,00	28,86	9,61	34,15
Absolute priority		0,095	0,137	0,318	0,087	0,042	0,263															
Product Requirement Priority (%)		10,0	14,6	33,8	9,2	4,5	27,9															

Design Planning Table			Product Requirement 1	Product Requirement 2	Product Requirement 3	Product Requirement 4	Product Requirement 5	Product Requirement 6
Customer	Priority %	Weight	10	14,6	33,8	9,2	4,5	27,9
	Local Priority %		10	14,6	33,8	9,2	4,5	27,9
	Global Priority %	65,50	6,55	9,56	22,14	6,03	2,95	18,27
Technical Evaluation	Current	Performance	5	20 kW	25 %	1	3	1
	Competitor		4	20kW	30 %	3	1	2
	Target		5	22kW	35 %	4	1	2
Competition	Judgement	Weight	Equal	Better	Much Better	Much Better	Worse	Equal
	Priority %		12,2	26,3	55,8	55,8	5,7	12,2
	Local Priority %		7,26	15,65	33,21	33,21	3,39	7,26
	Global Priority %	21,50	1,56	3,37	7,14	7,14	0,73	1,56
Technical Challenges	Judgement	Weight	Major	Minor	Minor	None	Major	Minor
	Priority %		63,3	26	26	10,6	63,3	26
	Local Priority %		29,41	12,08	12,08	4,93	29,41	12,08
	Global Priority %	13,00	3,82	1,57	1,57	0,64	3,82	1,57
	Adjusted Product Requirement Priority (%)		11,94	14,50	30,85	13,81	7,50	21,41

2.3.3.4.3.a.2.1 Step 1: Identifying functions

The product requirement obtained from the product level of the Quality deployment stage *(2.3.3.4.3.a.1.1)* has a strong focus on the customers. A broader technical view is required while designing a product. Looking at a product from a functional point of view will assist in identifying technical solutions (Ericsson & Erixon, 1999). Identification of the functions takes place by employing an engineering design tool called function-means tree *(or function tree)* which is a method of overall decomposing function of a device, system, or a process into sub-functions such that when completed it will satisfy the overall function (Otto & Wood, 2001). Figure 2.19 shows the concept of a function tree where the function is decomposed into sub-functions and the means to fulfil them.

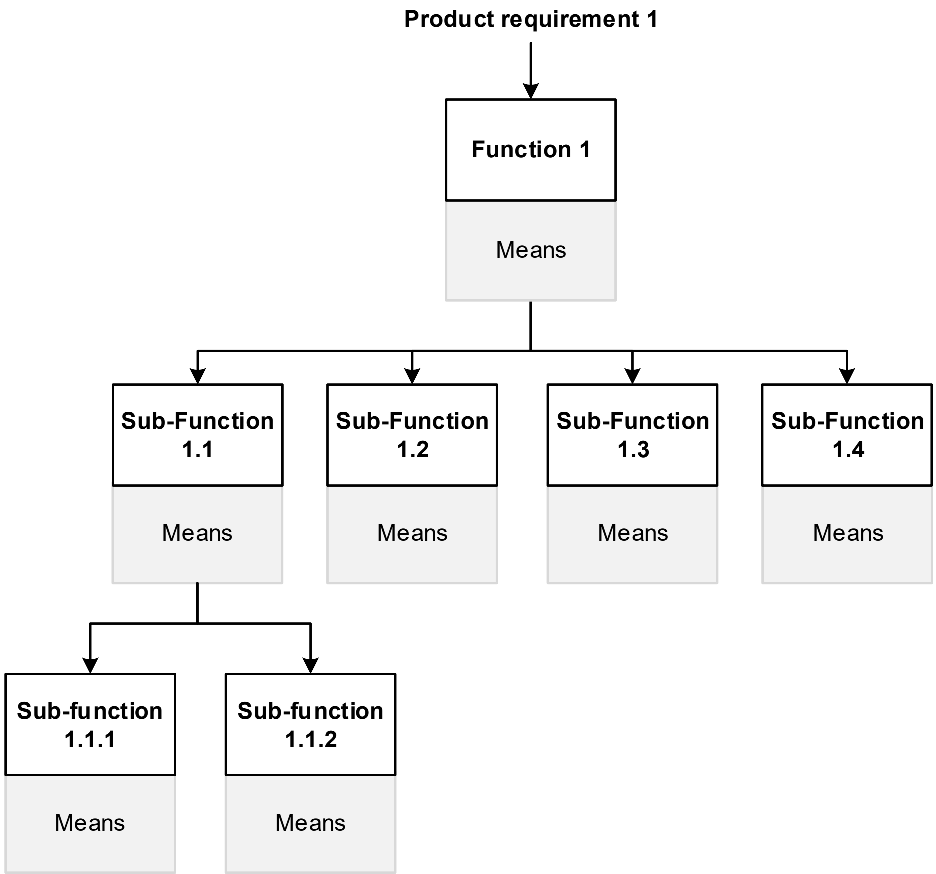


Figure 2.19 Function-mean tree (Function tree) – Adapted from Ericsson & Erixon (1999)

Key Takeaways:

- **Function tree** is used to **decompose** the overall function of a device, system, or a process into sub-functions such that when completed it will satisfy the overall function
- The **design team** along with the **technical experts** carry out the process

2.3.3.4.3.a.2.2 Step 2: Quantifying matrix relationships

Since the MIM ™ in the MFD ™ process requires only the function, this step can be skipped for the MFD ™ process. The process involved in quantifying product requirements-functions matrix is similar to the prioritisation process of customer needs-product requirement matrix *(HoQ matrix)* but using a different data set. The product requirements are placed on the rows of the L-matrix and the functions at the columns. As described in section 2.3.3.4.3.a.1.2, comparing rows to columns, the technical team assigns weights using the verbal scale, which later is substituted with the ratio scale obtained from the AHP.

2.3.3.4.3.b Technology Deployment

Technology deployment forms the second stage of the comprehensive QFD model. The core idea behind this stage is to identify the technology *(new or old)* to satisfy the performance requirements, product requirements and reliability requirements, and assure their quality at the product level, function level, component level and process level.

The correlation matrix mentioned in section 2.3.3.4.3.a.1.5 becomes relevant in this stage due to its technology-dependant while identifying positive and negative correlations among the product requirements. Often TRIZ is used to solve the technical contradiction by offering several concepts and tools to generate the solution that is from various scientific or engineering disciplines (Chrząszcz, 2018). Further, the knowledge of where the current technology lies in the evolutionary pattern can be useful to understand what the future generation of the technology look like (Terninko, et al., 1996). Then the concepts are generated, compared with the customer needs in an L-matrix *(Customer needs-Concepts matrix)* and selected using a Pugh or Super Pugh methods finishing with the build process (ISO 16355-5:2017, 2017).

2.3.3.4.3.c Cost Deployment

As the name suggests, cost deployment stage is used to keep the cost of the components or the design variables such that it maintains the economies of scale with minimal effect on the quality of the product (Park & Simpson, 2005). The process starts with the cost analysis of the competitor's products to determine their target costs. These costs are then allotted to the lower levels of the system. Value Analysis *(VA)* and Value Engineering *(VE)* are useful if the cost reduction is required on any of the levels.

2.3.3.4.3.d Reliability Deployment

Reliability deployment is the final stage in the comprehensive QFD model. This stage is adopted to avoid the risk associated with the use of new technology, components or processes. Similar to other deployment stages, the first process is the identification of the potential faults and getting the relationship between the customer needs- and faults using L-matrix *(Customer needs-Failure mode matrix)*. These are further analysed using Failure Mode and Effects Analysis *(FMEA)* tool, thus reducing the risk of product failure. Similarly, other deployment stages, *i.e., Part deployment, Process deployment, Production planning,* are carried out with their respective levels of design, *i.e., Product level, Function level, Component level, Process level.*

2.3.4 Advantage and Disadvantage of QFD

2.3.4.1 Advantage and Disadvantage of different QFD approaches

Although there are multiple versions of QFD, an organisation can select any approach for the QFD based on how the advantages of a particular approach help to achieve their goals and how much impact does the disadvantages cause while carrying out the process. Table 2.17 illustrates the advantage and disadvantage of the QFD approaches mentioned above.

Table 2.17 Advantage and Disadvantage of different QFD approaches

		Advantage	Disadvantage
Classical QFD	**Comprehensive QFD**	• Can pick and choose deployment phases as required • Exhaustive Coverage of application field • Easily Reusable	• Statistically irrelevant math • Time-consuming • Difficult to educate people
	4-phase QFD	• Tailored for Automotive suppliers • Less time to educate due to a single flow of the deployment phases	• Cannot be deployed in other industries wanting to use other matrices • Statistically irrelevant math
Modern QFD	**Blitz QFD**	• Faster to complete • Statistical relevant math • Can be used with Classical QFD	• Difficult to reuse - Must start fresh • Not useful when process deployment or reliability deployment is required • Developed mostly for the use in Software development industries
	QFD approach by Herzwurm & Schockert	• Uses most of the matrices of the Classical QFD • Statistical relevant math	• Developed mostly for the use in Software development industries
	ISO 16355 recommended QFD approach	• Statistical relevant math • Combines comprehensive QFD with modern QFD approaches to minimise the time • Recommends various tools to enhance the QFD process • Adaptable for any industry or application since the approach is generalised and not meant for particular application	• Needs time to understand the standard documents and map out the required process for a particular industry or application • Easy to lose focus from the critical customer needs due to the interaction of large numbers of low-relation values

2.3.4.2 Advantages of modern QFD over classical QFD

Usage of statistical relevant mathematics

As seen from the comparison below, since ordinal scale values have a varying interval between the values, it is not possible to compare or take average., *i.e., When going from weak (1) to moderate (2) it requires 100% effort compared to very strong (4) to extremely strong (5) which requires only 25% of the effort.* Moreover, addition, subtraction, multiplication or division of these ordinal numbers would result in decreased accuracy (Stevens, 1946). However, the ratio scale values have near even distribution between intervals. Therefore, it is recommended to use a ratio scale in the Modern QFD for the possibility of using different mathematical operations without losing the relationship between the elements. In a project, the mathematical limitations of numerical scales become crucial as it influences cost and resource allocation (ISO 16355-1:2015, 2015). Section 3.1.3 presents an in-depth review of the different scales.

Ordinal scale

$$4\ to\ 5 = \frac{5}{4} = 1.25\ or\ 25\%\ more\ effort$$

$$3\ to\ 4 = \frac{4}{3} = 1.33\ or\ 33\%\ more\ effort$$

$$2\ to\ 3 = \frac{3}{2} = 1.50\ or\ 50\%\ more\ effort$$

$$1\ to\ 2 = \frac{2}{1} = 2.00\ or\ 100\%\ more\ effort$$

Ratio scale

$$4\ to\ 5 = \frac{0.503}{0.260} = 1.934\ or\ 93.4\%\ more\ effort$$

$$3\ to\ 4 = \frac{0.260}{0.134} = 1.940\ or\ 94.0\%\ more\ effort$$

$$2\ to\ 3 = \frac{0.134}{0.068} = 1.970\ or\ 97.0\%\ more\ effort$$

$$1\ to\ 2 = \frac{0.068}{0.035} = 1.943\ or\ 94.3\%\ more\ effort$$

Increase in the resolution of judgement in decision-making

Classical QFD uses three or five-levels of ordinal scale values for judgments, i.e., Weak (1), Moderate (3), Strong (5 or 9) or Least important (1), Slightly important (2), Moderately important (3), Very important (4), Extremely important (5) respectively. However, according to Miller (1956), the limits of the human brain in absolute judgement and short-term memory are optimised at seven "chunks" of information with ± 2 for memory processing. Therefore, the three-level scale has too little detail about the judgement, and the values of the five-level are statistically insignificant. To overcome these limitations, in modern QFD the stakeholders can use between 5 to 9 levels of judgement in ordinal scale for ease of understanding, i.e., Weak (1), Moderate (3), Strong (5), Very strong (7), or Extremely strong (9), and if necessary, with intermediate intervals such as weak-to-moderate (2), and so forth. To obtain ratio scale values of these judgements, the modern QFD takes advantage of the AHP, which converts the numerical values from ordinal scale to ratio scale giving a more robust and error-free statistical result. Further, usage of a robust tool like AHP in modern QFD helps to make a group decision making easier, consistent and avoid *'the loudest voice in the room'* situation. Even if the whole group is not present, it is possible to use multiple AHP matrices, and the Geometric Mean of the cells of all the matrices helps in obtaining a final decision/priority (Saaty, 1989). Section 3.1.3 presents an in-depth review of the different levels of judgement used across different QFD approaches.

Reduced time for data collection

For projects with a shorter list of needs or tighter resources, modern QFD approaches like Blitz QFD® encourage the usage of the qualitative tool other than the matrices to collect and prioritise data mainly to reduce the cost, time and effort required to complete the matrices. Further, ISO 16355-1:2015 (2015) recommends avoiding the usage of the correlation matrix *(Roof of the HoQ)* in the Quality deployment *(HoQ)* and suggests its usage in the technology deployment stage since the relationship between the product requirement are technology agnostic and changes depending on the technology employed.

Robust tools

Having robust tools will help to avoid obtaining wrong priorities either by user disengagement or by user-error, which may result in disastrous consequences in the subsequent process. One such tool is AHP that has an inbuilt inconsistency checker which helps to determine the reliability of the data.

Helps to refrain the usage of technical solution in the quality deployment

To refrain the usage of technical solution in the customer need and product requirement data, modern QFD considers customer need as WHY's *(according to the ISO 16355-4:2017 (2017) real customer need is obtained when the customer is asked a follow up 'Why?' question multiple times)* and product requirement data as WHAT's *(by asking 'What can we do to satisfy this customer needs?')* compared to the earlier WHAT's for cusotmer needs *(might lead to getting surface level needs without knowing the reason)* and HOW's for product requirement *(by asking 'How can we satisfy this customer needs?' answers might lead to a technical solution).*

3 Methodology

The case company offered this thesis based on their interest to explore the methods of acquiring the required stakeholder data to build modular ships using the MFD™ process. The case company is a shipyard that has a rich history in building various types of ocean-going vessels, *i.e. cruise ships, ferries, gas carriers, artic cargo vessels, icebreakers,* and has many experienced technical specialists. Based on their interest, a primary objective is defined for this thesis, which is to determine an optimal QFD approach to integrate into the ship modularisation process.

The original data for the case study is collected and prioritised with the help of internal shipyard documents, publically available sources, shipyard representatives for the ship-owners and the technical experts of the shipyard. However, due to the confidentiality clauses, the original data is not presented in this thesis. For this thesis, the author has independently acquired and prioritised a separate set of data from the publicly available sources *(Appendix B)*. Therefore, the following data may or may not represent the real-life situation, and the author shall in no way be responsible for the accuracy of the data.

Following sections present the draft of the QFD approach, selection of tools, scales and the data obtained in each step.

3.1 Identifying suitable QFD steps

As discussed in 2.2.1, QFD is the recommended process to obtain the product requirement data for the MFD™ process. Therefore knowledge of the workings of MFD™ process was crucial to determine what type of data the QFD process shall yield such that there can be a seamless transition from QFD to MFD™ process. This, in turn, was essential to determine what steps the case company shall carry out as a part of the tailored QFD process to extract the required data.

3.1.1 Defining the scope of QFD

From the study of MFD™ literature, it was clear that the phase 2 of the MFD™ process needed only the product requirements to derive the functions *(2.2.1.2)*, which made it easier to determine the extent of the ISO recommended QFD approach that the case company shall use to obtain the needed product requirements. Further, it was evident from the study of the ISO 16355 documents that to obtain the product requirements, it would be sufficient to carry out only the Product Level of the Quality Deployment phase *(2.3.3.4.3.a.1)*, while also using some aspects of the Function Level of the Quality Deployment phase *(2.3.3.4.3.a.2)*. Therefore, this helped to define the scope of the QFD approach to use in the ship modularisation process.

3.1.2 Drafting an initial QFD process

Analysing the required part of the ISO recommended QFD approach helped to understand the compatibility of the processes with the shipyards internal process. An initial draft of the QFD approach *(figure 3.1)* was created according to the following observations.

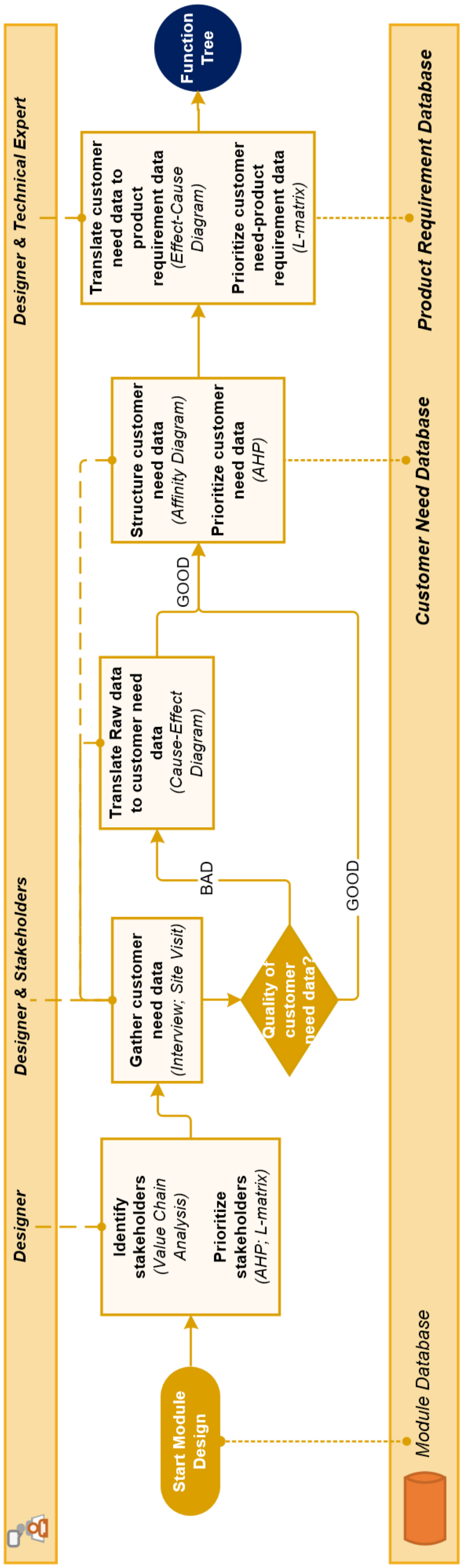


Figure 3.1 Initial draft of the QFD process

- As seen from figure 3.1, the steps in the *Strategy Deployment phase (2.3.3.4.1)* are omitted in the initial draft of the QFD process. These ommisions are because the case company's management team already carries out the process of defining business goals and strategy. Carrying out a similar process again would be redundant.
- *Project Selection phase (2.3.3.4.1.a)* is also omitted from the draft because the *'projects'* in ship modularisation process are the modules, whose product requirements have to be defined. Since the case company uniquely defines these modules, the process shall not be discussed in this thesis.
- The first step in the draft process is to identify *(2.3.3.4.2.1)* and prioritise *(2.3.3.4.2.2)* the stakeholders using Value Chain Analysis and the AHP/L-matrix respectively. The inclusion of this step was to help the module designers understand whom the module will affect and how the different stakeholders can affect the module design.
- The next step consisted of collecting the customer need data or VoC *(2.3.3.4.2.3)* according to their importance. Interviews or the Gemba visits where chosen as the techniques to carry out this step since the data is not readily available in a database and would require contacting the users and the technical experts.
- Translating the raw VoC into customer need helps to eliminate any data that may not qualify as the customer need. *(2.3.3.4.2.4)*.
- Structuring the customer need data *(2.3.3.4.2.5)* is included to reduce the time required to carry out the prioritisation of the customer needs *(2.3.3.4.2.6)*.
- The *Quantification* step *(2.3.3.4.2.7)* is also omitted from the draft of the QFD process because the quantification data is not required for the MFD™ process.
- Finally, to obtain the product requirements that satisfy the acquired customer needs, translation process for customer needs is included *(2.3.3.4.3.a.1.1)* along with the product requirements prioritisation step using an L-matrix *(2.3.3.4.3.a.1.2)*.
- To ease the transition from the QFD process to MFD™ process, one of the tools from *Function level* of the ISO recommended QFD approach called *Function Tree* is included in the draft process.
- The diagram also provides information on the storage of the data so that the process will be future proof, *i.e., if required, the data can be added or removed according to the market situation.*

3.1.3 Determining the scale

In QFD, it is easy to lose focus from the most critical customer need when deriving the product requirement priorities due to many lower strength relations interacting with the product requirements derived from lower priority customer needs. This can be reduced by choosing a scale that is biased towards the higher values. However, classical QFD used either the ordinal scale 1, 3, 5 in Japan (Akao, 1990) or the logarithmic scale 1, 3, 9 in the USA (Clausing, 1994) while judging the relations between the dataset in the relationship matrix (Wasserman, 1993). However, these scales had their drawbacks like the mathematical limit of the ordinal numbers due to its non-fixed intervals results in capturing only the order of the data and not the relative importance of the data (ISO 16355-5:2017, 2017). On the other hand, the values 1, 3, 9 being a logarithmic scale avoided the setback mentioned above and had a much more significant gap between the strong and moderate relation value such that the scale follows the Pareto Principle, *i.e., The law of vital few,* that most of the effects will come from a few critical needs (Terninko, 1997).

Despite being mathematically significant, values 1, 3, 9 have been criticised by researchers for a possibility of forcing the stakeholders to assign an intermediate relationship value to either a higher or a lower level value due to the lack of intermediate values (Fehlmann & Glenn, 2016). Instead, part 5 of the ISO 16355 standard suggests using at least five or nine level of judgement, *i.e., weak (W), moderate (M), strong (S), very strong (VS), or extremely strong (ES), and if necessary, with intermediate intervals such as weak-to-moderate (W-M), and so forth*; when making subjective decisions to optimise human decision making capabilities (ISO 16355-5:2017, 2017). This approach aligns with the Miller's Law written by George A. Miller in 1954, which states that *"The limits in absolute judgement of a humans short-term memory are optimised at seven 'chunks' of information with ± 2 for memory processing"* (Miller, 1956). These verbal judgements will then be assigned ratio scale values calculated using AHP by pairwise comparison of five (or nine) levels of values to themselves as shown in table 3.1. The AHP calculation from table 3.1 yields the following values to the ISO recommended scale, Extremely strong = 0.503, Very strong = 0.260, Strong = 0.134, Moderate = 0.068, Weak = 0.035.

Table 3.1 Calculation of 5-levels of subjective scoring using AHP

Score	Extremely Strong	Very Strong	Strong	Moderate	Weak	Normalised columns					Row Total	Row Avg.
Extremely Strong	1	3	5	7	9	0,56	0,64	0,52	0,42	0,36	2,514	**0,503**
Very Strong	1/3	1	3	5	7	0,18	0,21	0,31	0,30	0,28	1,301	**0,260**
Strong	1/5	1/3	1	3	5	0,11	0,07	0,10	0,18	0,20	0,672	**0,134**
Moderate	1/7	1/5	1/3	1	3	0,08	0,04	0,03	0,06	0,12	0,339	**0,068**
Weak	1/9	1/7	1/5	1/3	1	0,06	0,03	0,02	0,02	0,04	0,174	**0,035**
Total	1,79	4,68	9,53	16,33	25,00	1,00	1,00	1,00	1,00	1,00	5,000	1,000
											Inconsistency Ratio	**0,05**

To check the validity of the claims and to select between the 3-level or 5-level scale, a comparison study regarding the impact of only high-level relation values on the product requirement priority against all relation values using the 5-level scale ratio scale vs the 3-level logarithmic scale. Further another study to select linear or non-linear scale is conducted in 3.1.3.2.

3.1.3.1 Comparing 3-level and 5-level scale

A QFD study was conducted on the contemporary cruise segment for the Chinese market with 5-levels of judgement as recommended by the ISO 16355 standard series. The customer needs were sourced from Yang (2015) and CLIA (2018a) and prioritised using AHP. Product requirements where derived from the customer needs, and relation values for each customer needs, and the product requirement combination was assigned following the recommendation from Terninko (1997) and Fisher & Schutta (2003) that the relationship matrix of the QFD shall have no more than 50% of its cell filled. This QFD matrix is denoted as QFD1.1 and is shown in Figure 3.2.

Customer needs (WHY?) \ Product requirements (WHAT?)	Priority (%)	Capacity of life boats	Passengers watch live acts / shows	Passengers Gamble money	Recover thermal energy	Variety of shopping places for passengers	Variety of restaurants for passengers	Produce energy onboard	Distribute energy throughout the ship	Temperature in passenger cabin	Amenities in passenger cabins	Resting place in passenger cabins	Reduce exhaust emmisions	Reduce bilge emmisions	Variety of wellness areas onboard	Variety of relaxation areas onboard	Variety of adventourous areas onboard
Safety of humans onboard	26,57	ES	S	M		M	S	M	M	S	M	S	W		M	W	S
Passenger entertainment onboard	15,88		ES	ES			W	M	M								W
Fuel effeciency	9,05	M			ES			VS	M	M			S	M			
Passenger shop onboard	11,55		S			ES	M	W	W						M	M	
Passenger food and beverage experience	10,61		M	M		M	ES	W	W		W				W	M	
Availibility of energy in ship	8,73	VS	M	W	VS	M	M	ES	ES	M	W		M	W	W	W	S
Passenger comfort in cabins	5,85							M	M	ES	S	ES					
Emmisons	4,80		W		S	W	W	S					ES	ES			
Passenger wellness areas	3,15							W	W						ES		
Passenger relaxation areas	2,11							W	W							ES	
Passenger seek thrill onboard	1,70		W	W				S	M								ES
Absolute Weight (Product Requirement)	100,00	0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06
Normalised Weight (Product Requirement)		0,12	0,11	0,08	0,06	0,07	0,08	0,09	0,07	0,06	0,02	0,05	0,04	0,03	0,04	0,03	0,05

ES = Extremely Strong; VS = Very Strong; S = Strong; M = Moderate; W = Weak

Figure 3.2 QFD 1.1 on the contemporary cruise segment for the Chinese market with all relations

Absolute Weight (Product Requirement)	100,00	0,16	0,08	0,08	0,07	0,06	0,05	0,07	0,04	0,03	0,00	0,03	0,02	0,02	0,02	0,01	0,01
Normalised Weight (Product Requirement)		0,21	0,11	0,11	0,09	0,08	0,07	0,09	0,06	0,04	0,00	0,04	0,03	0,03	0,02	0,01	0,01

Figure 3.3 Absolute priorities of QFD 1.2 on the contemporary cruise segment for the Chinese market considering only the high-value relations

Comparing the absolute weight of QFD1.1 matrix *(figure 3.2)* against a similar matrix populated with only the high-value relations *(figure 3.3)*, *i.e., ES and VS,* helps to assess the impact of high-value relations on the Product requirement priority. Figure 3.4 shows this comparison in a visual format. On average, the impact of high-value relations on the product requirement in this dataset populated with 5-levels of judgement is 50.6 %. Therefore, ignoring the lower-value relations of the judgement scale can lead to an entirely different set of priorities.

On the other hand, comparing a matrix similar to the QFD1.1 populated with 3-levels of judgement, *i.e., Strong (9), Medium (3), Weak (1)*, with a matrix populated with only the high-value relations, *i.e., Strong,* resulted in a similar output, *i.e., changes to the product requirement priority ranking.* However, the average impact of high-value relations on the product requirement in this dataset populated with 3-levels of judgement is 40 %, which is lesser than the 5-level judgement impact value. Therefore, ignoring the other relations leads to a similar conclusion as of the 5-level judgement but with higher inconsistencies.

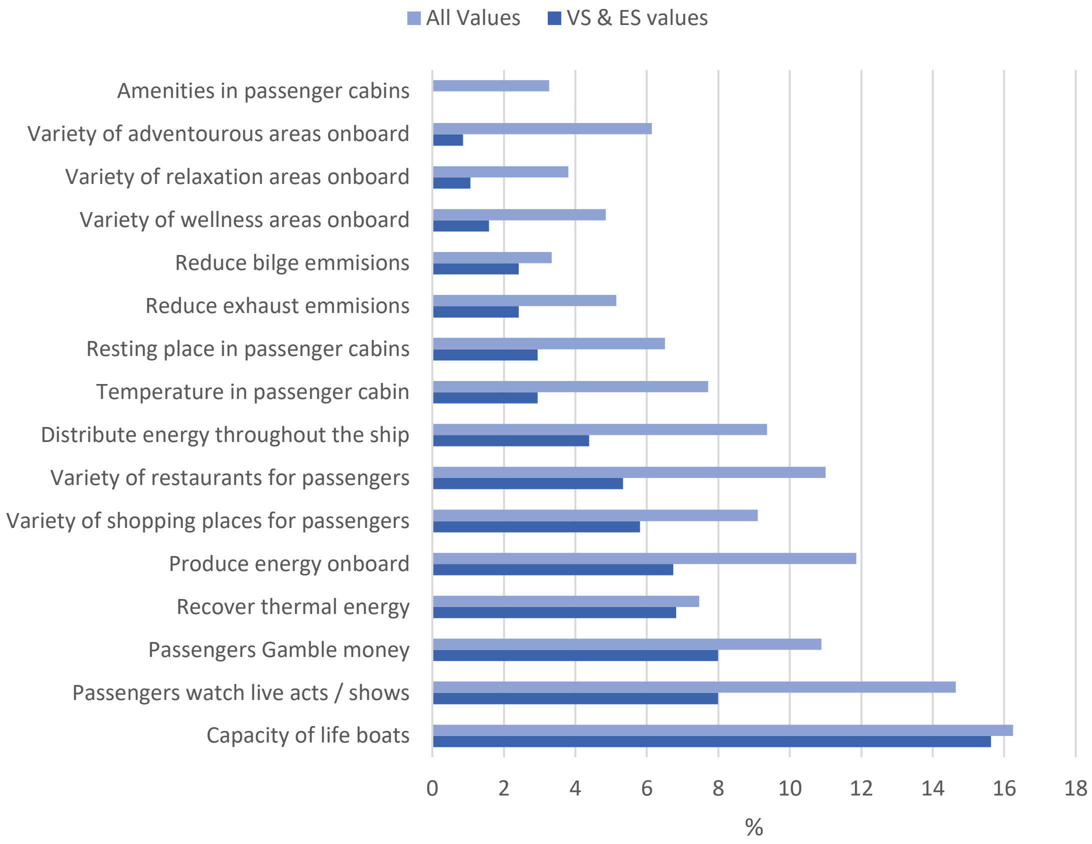


Figure 3.4 Comparing absolute priorities considering all 5-levels v/s only high-value relations

3.1.3.2 Comparing the ordinal scale with the ratio scale

This section intends to choose the best scale between the ratio and the ordinal scale. The selection process first starts by choosing the best scale within the various ratio and ordinal scales and finally comparing the normalised product requirement priority obtained from these scales according to the analogy discussed above.

3.1.3.2.1 Ratio Scales

Ratio scale can be obtained by using two types of values, *i.e., linear and non-linear.* The linear values used in AHP to obtain ratio scales are 1, 2, 3, 4, 5 and 1, 3, 5, 7, 9, and the non-linear values used in AHP to obtain ratio scale is 1, 2, 3, 5, 9 which is represented in table 3.2.

Table 3.2 Ratio scale values

	Priority %		
Relation Judgement	**1,2,3,4,5**	**1,3,5,7,9**	**1,2,3,5,9**
Weak	6,2	3,5	4,9
Moderate	9,9	6,8	8,7
Strong	16,1	13,4	15
Very Strong	26,2	26	25,7
Extremely Strong	41,6	50,3	45,7

As seen from the figure 3.5, the lower strength relations *(from 'Weak' to 'Strong')* of ratio scale obtained from the linear scale values 1, 3, 5, 7, 9 has the least importance when compared to other ratio scales. However, its importance nearly matches other scales in *Very Strong* and surpasses other scales in *Extremely Strong.* Therefore, in the ratio scale, it is clear that the scale obtained from linear value 1, 3, 5, 7, 9 behaves according to Pareto's principles and is used in the comparison.

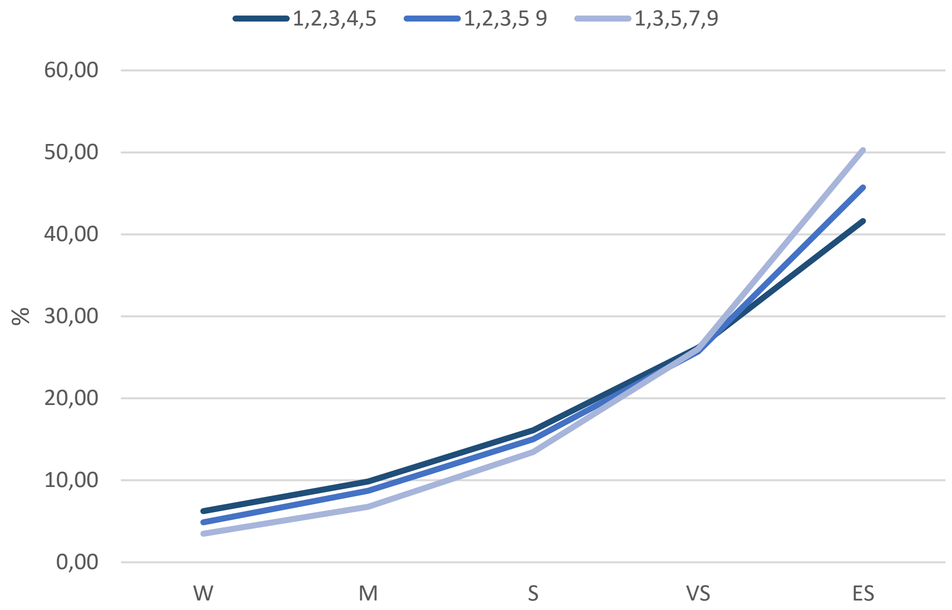


Figure 3.5 Comparison of ratio scale obtained from linear and non-linear values

3.1.3.2.2 Ordinal scales

For the comparison to be useful, same linear values are used for assigning relations in an ordinal scale, *i.e., linear values 1, 2, 3, 4, 5 and 1, 3, 5, 7, 9, and the non-linear values 1, 2, 3, 5, 9.*

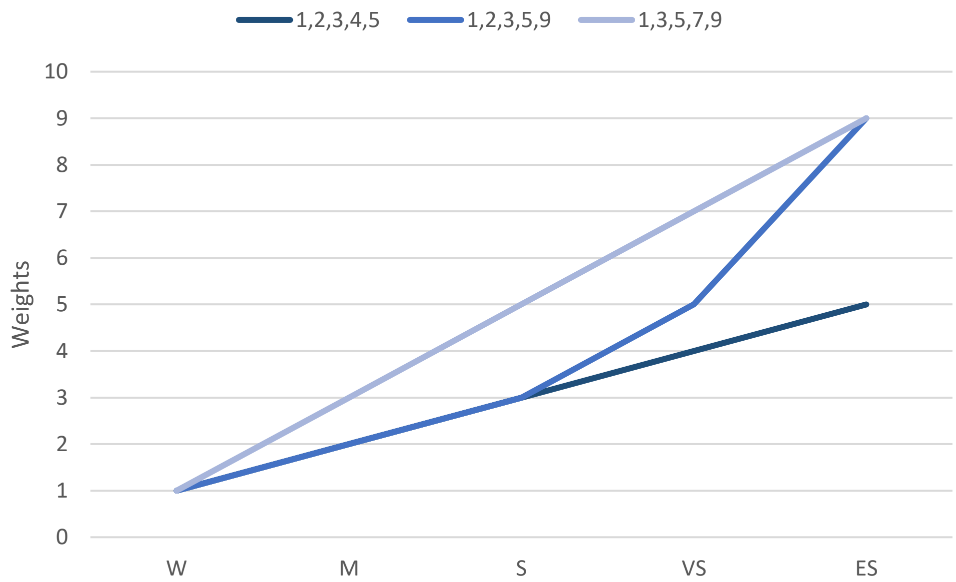


Figure 3.6 Comparison of ordinal scale obtained from linear and non-linear values

As seen from the figure 3.6, the lower strength relations *(from 'Weak' to 'Strong')* of ordinal scale obtained from the linear values 1, 2, 3, 4, 5 and non-linear values 1, 2, 3, 5, 9 have the least importance when compared to the linear 1, 3, 5, 7, 9 scale. However, for higher strength relations *('Very Strong' and 'Extremely Strong')* the non-linear scale 1, 2, 3, 5, 9 behaves according to Pareto's principles and is used in the comparison.

3.1.3.2.3 Comparison of product requirement obtained from linear ratio scale and non-linear ordinal scale

The selected ratio scale *(linear 1, 3, 5, 7, 9)* and ordinal scale *(non-linear 1, 2, 3, 5, 9)* are used to obtain the normalised values which is shown in table 3.3 and are compared with their respective product requirement priority as shown in figure 3.7. It is evident from figure 3.7 that most of the ratio scale values are inclined toward the higher values when compared to the respective ordinal scale priority values. Similarly, in the lower spectrum, the ratio scale has less influence over the product requirement priority when compared to the respective ordinal scale priority values.

Table 3.3 Normalised product requirement priority obtained from the selected ratio and ordinal scale

Customer need	CN Rank	Product Requirement	Normalised Priority %	
			Ordinal scale	Ratio Scale
Safety of humans	1	Capacity of life boats	10,62	12,37
Passenger entertainment	2	Passengers watch live acts / shows	10,68	11,15
Availability of energy in the ship	6	Produce energy onboard	9,43	9,03
Passengers F&B experience	4	Variety of restaurants for passengers	8,34	8,38
Passenger entertainment	2	Passengers Gamble money	8,04	8,29
Availability of energy in the ship	6	Distribute energy throughout the ship	7,91	7,13
Passengers shop onboard	3	Variety of shopping places for passengers	7,08	6,93
Passenger comfort in cabins	7	Temperature in passenger cabin	5,93	5,87
Fuel Efficiency	5	Recover thermal energy	4,92	5,68
Passenger comfort in cabins	7	Resting place in passenger cabins	4,67	4,95
Passenger seek thrill onboard	11	Variety of adventurous areas onboard	4,84	4,68
Emissions	8	Reduce exhaust emissions	4,04	3,92
Passenger wellness areas	9	Variety of wellness areas onboard	4,37	3,69
Passenger relaxation areas	10	Variety of relaxation areas onboard	3,48	2,90
Emissions	8	Reduce bilge emissions	2,47	2,54
Passenger comfort in cabins	7	Amenities in passenger cabins	3,18	2,49

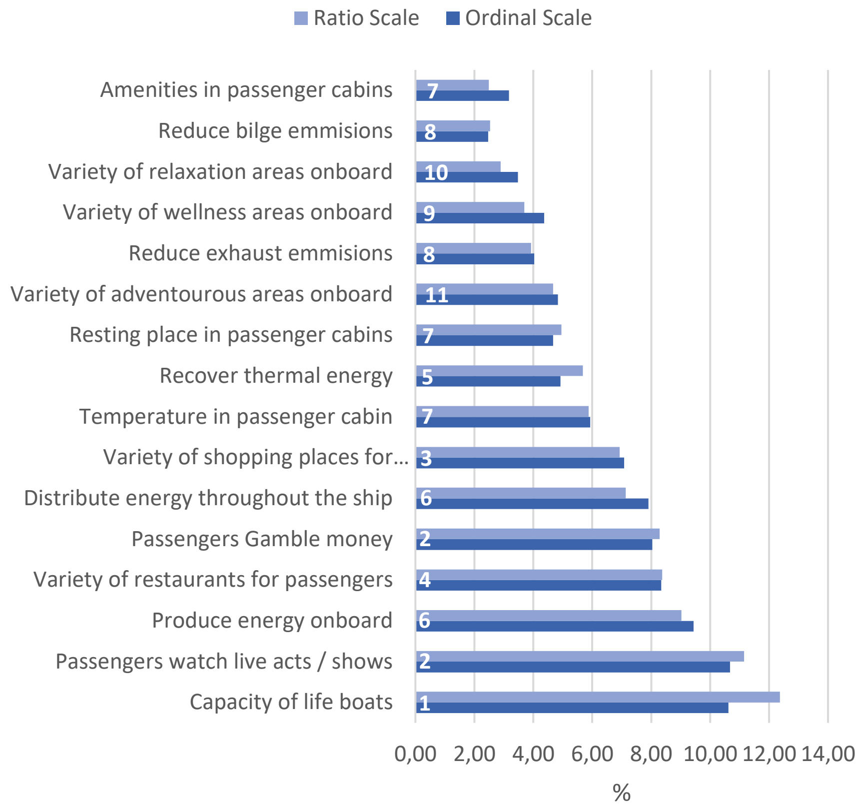


Figure 3.7 Comparison of Ratio scale and Ordinal scale on Normalised Product requirement priorities with their respective customer needs ranking

3.1.3.3 Recommendation of the scale

Selection of the scale for QFD is very critical since the results from the Quality deployment matrix is used as the input for the following processes. Due to the mathematical limit of the ordinal scale, it is recommended to use either a logarithmic scale or a ratio scale. There can be an argument that the 5-level judgement scale is too cumbersome and the stakeholders might assign values to a relation just because they have more choice. On the other hand, the same 5-level of judgment gives the stakeholders a finer scale, which, in an ideal condition will result in an accurate priority list. Similarly, a scale with 3-level of judgement will not have enough choices forcing the stakeholders to assign a higher or a lower level value to an intermediate relation due to the lack of choices but also help to shorten the time required to judge a relation. Additionally, as seen from 3.1.3.1, the impact of high-value relations on the product requirement priority is higher in the 5-level judgement scale than in 3-level judgement scale which follows the Pareto’s principle.

Secondly, it is important not to lose focus from the critical customer needs, which both the scales tend not to follow when a particular product requirement has many lower level relations. In some cases, the product requirements obtained from the lower priority customer needs is essential to fulfilling the product requirements obtained from the higher priority customer needs *(produce and distribute energy onboard so that the passengers can watch shows/acts, gamble etc.)*. On the other hand, the product requirement such as *Variety of shopping places for* *passengers* is placed much lower than the *Variety of restaurants for passengers* even though this ranking is contrary to their customer need ranking. However, we do know that some requirements tend to fulfil multiple customer needs, which is the reason we see the above behaviour.

Going purely based on the Pareto's principle and the advantage of 5-level judgement scale, the author recommends the use of *5-level judgement scale obtained from linear values 1, 3, 5, 7, 9* to be used in the QFD process.

3.1.4 Piloting the draft QFD process

To understand the suitability of the proposed draft process, it was crucial to implement the process in real life. With the help of the shipyards internal stakeholders, the process was implemented in the shipyard. During the implementation of the process, the steps to identify and prioritise stakeholder was skipped entirely to streamline the process as this data was already known. Therefore, these two steps are suggested as optional in the final process recommendation. It shall be noted that the data used in the following sections are only for illustration purposes.

3.1.4.1 Acquiring customer need data

The customer needs data for the pilot was collected from publically available sources, cruise lines websites and surveying the cruise passengers online. It is recommended to collect this data from the ship-owners and the cruise passengers. Table 3.4 shows the acquired raw customer data for the Chinese cruise market as compiled in appendix B (Yang, 2015; CLIA, 2018a).

Table 3.4 Raw customer need data of the Chinese Cruise market (Yang, 2015; CLIA, 2018a)

Raw VoC - China
• Loves to eat food, especially Asian food • Spends money buying gizmo, gift and souvenir for family and friends • Gambles money • Spends time singing karaoke • Likes to watch live shows and act • Prefers to stay indoors and socialise with relatives and friends, in public areas and cabins • Being fit has been trending onboard • Not a fan of sunbathing, but would like some relaxing massages • Adults generally are not adventurous when compared to kids • The preferred length of a travel itinerary is 4-6 days (47%) • The preferred destination within Asia (91%) • Safety of humans is paramount • Profitability and environmental impact

The data acquired contained complex information *(Prefers to stay indoors and socialise with relatives and friends, in public areas and cabins)*, statistical data *(Preferred length of travel)* along with customer needs *(Safety of humans is paramount)*. Using Cause-Effect diagram *(2.3.3.4.2.4)*, these raw data are converted into customer needs and then structured using an affinity diagram *(2.3.3.4.2.5)* resulting in the following customer needs as shown in table 3.5.

Table 3.5 Customer need after the translation process for the Chinese cruise market

Customer Needs – China
• Safety of humans onboard • Passengers entertainment onboard • Fuel efficiency • Passengers shop onboard • Passenger food and beverage experience • Availability of ship energy in the ship • Passenger comfort in the cabins • Emissions • Passenger wellness areas • Passenger relaxation areas • Passenger seek thrill onboard

3.1.4.2 Prioritising the customer need

With the help of AHP, the shipyards representative for a particular ship-brand prioritised the customer needs. Having the customer need priority according to their brand is essential to identify the module that shall have variants *(3.1.5)*. From table 3.6, it is evident that the *Safety of humans onboard* is the ranked highest, followed by the *Passenger entertainment*, *Passenger Food and Beverage experience* and *Passenger shop onboard.* Also, the inconsistency ratio is 5.7% which is below 0,1 or 10% that shows the inconsistency in prioritising the data is within the specified limits. These prioritised customer needs are used to derive the product requirements and their priorities.

Table 3.6 Prioritised Customer needs using AHP

Customer needs \ Customer needs	Trend	Passenger comfort in cabins	Passenger entertainment onboard	Passenger seek thrill onboard	Passenger food and beverage experience	Passenger relaxation areas	Passenger wellness areas	Passenger buy things onboard	Availibility of energy in ship	Safety of humans on board	Emmisons	Fuel effeciency	Priority %
Passenger comfort in cabins	↔	1	1/7	5	1/2	5	2	1/4	1	1/5	2	1/3	5,9
Passenger entertainment onboard	↑↑	7	1	6	2	5	3	2	2	1/3	5	2	15,9
Passenger seek thrill onboard	↓↓	1/5	1/6	1	1/5	1/2	1/3	1/5	1/5	1/8	1/5	1/6	1,7
Passenger food and beverage experience	↑	2	1/2	5	1	5	4	1	2	1/3	4	1	10,6
Passenger relaxation areas	↓	1/5	1/5	2	1/5	1	1/2	1/6	1/4	1/8	1/4	1/5	2,1
Passenger wellness areas	↑	1/2	1/3	3	1/4	2	1	1/4	1/4	1/7	1/3	1/4	3,1
Passenger buy things onboard	↑↑	4	1/2	5	1	6	4	1	2	1/3	4	1	11,6
Availibility of energy in ship	↑	1	1/2	5	1/2	4	4	1/2	1	1/3	3	2	8,7
Safety of humans on board	↔	5	3	8	3	8	7	3	3	1	6	5	26,6
Emmisons	↓	1/2	1/5	5	1/4	4	3	1/4	1/3	1/6	1	1/2	4,8
Fuel effeciency	↑	3	1/2	6	1	5	4	1	1/2	1/5	2	1	9,0
		24,4	7,0	51,0	9,9	45,5	32,8	9,6	12,5	3,3	27,8	13,5	100
												Inconsistency ratio	0,057

3.1.4.3 Translating customer needs into product requirements

The translation process was carried out with the help of multiple technical experts within the shipyard using the Effect-Cause diagram. The original data had more than 40 customer needs that required inputs from 9 different technical experts obtaining more than 90 product requirements. However, the data obtained during the pilot forms just a small portion of the data that is needed to build a cruise vessel. Figure 3.8 illustrates the process of translation of one of the customer needs using the Effect-Cause diagram.

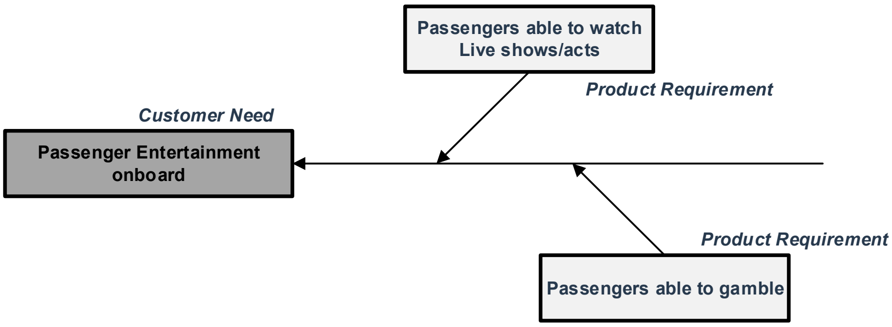


Figure 3.8 Effect-Cause diagram to translate Customer Need into Product Requirement

3.1.4.4 Prioritising product requirement

Similar to the previous process, product requirements where prioritised by a group of technical experts *(figure 3.2; Appendix A.2)* to get a broader view and come to consensus on the relations using the scale recommended in section 3.1.3.3.

3.1.4.5 Generating functions

To bridge the gap between the QFD and the MFD™ process, the product requirement where converted into functions with the help of technical experts using the function-mean tree *(2.3.3.4.3.a.2)*. Illustration of a function tree for one product requirement is shown in figure 3.9.

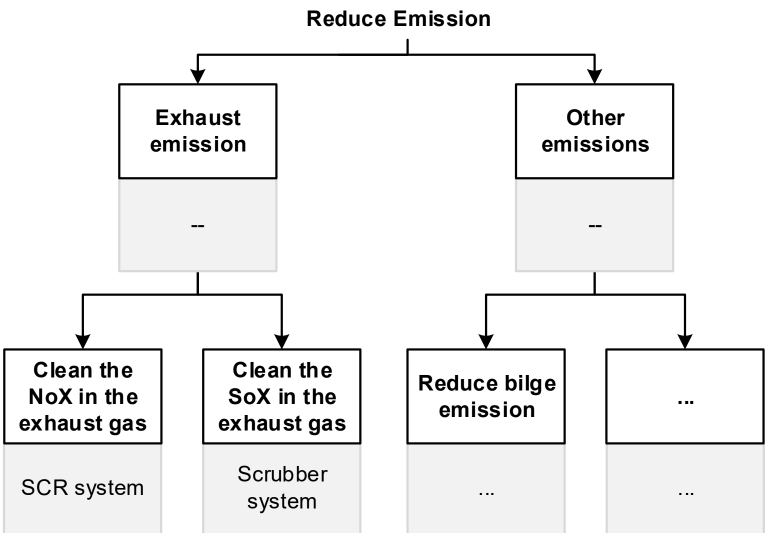


Figure 3.9 Example of a Function-mean tree to generate functions from product requirement

3.1.5 Segmentation

Modular product development *(MPD)* process helps to shorten the development time of a new product and reduces its cost by reusing the parts and modules. One of the drawbacks identified by the researchers is that the product developed using MPD results in the final product to be similar to other products developed within the same module library (Börjesson, 2012). This is a problem in a market where the brands strive hard to differentiate themselves from other brands and have a unique brand identity. However, it can also be argued that the combination of different modules can help to create variation in the developed products (Erixon, 1998). However to identify the modules that shall have multiple variations can be carried out with the help of market segmentation.

Smith (1956) popularised the concept of market segmentation as an alternative marketing strategy based on the economic theory of imperfect competition written by Robinson in 1934. According to him *"Market segmentation involves viewing the heterogeneous market as a number of smaller homogenous market, in response to differing preference, attributable to the desires of consumers for more precise satisfaction of their varying wants".* This view is further strengthened by Jones and Sasser (1995) statement that *"Serving wrong customers may be very expensive, especially in a long run as they do not bring any profit to the company*". Therefore, segmenting the customers become very crucial to keep the customers happy and make profits. The study in this thesis segments the market based on the geography of the market being served, *i.e., China vs the USA.* The data represented below are acquired from the publicly available sources *(Appendix B).* Therefore, the following data may or may not represent the real-life situation, and the author shall in no way be responsible for the accuracy of the data.

3.1.5.1 Comparison of the market segments

Each identified customer need priorities for a specific market segment is taken as the starting point of its own QFD. Apart from this, the derived product requirements and relationship matrix remain the same. The customer need priorities for China and the USA is represented in figure 3.10. From figure 3.10, the customer needs with similar priorities form a significant portion of the comparison, *i.e., Safety of humans onboard, passenger entertainment onboard, fuel efficiency etc.* On the contrary, there are customer needs with wider priority gap where the higher priority customer need forms the dominant theme of the respective market segment (Sudjianto & Otto, 2001). Going by this analogy, the dominant theme of the Chinese market segment will be to shop onboard and indulge themselves in a variety of food and beverages.

Similarly, for the North American market, the dominant theme will be adventurous and spend time relaxing onboard. The product requirement priority obtained from the segment-specific QFD assists in identifying the modules that shall have the variants. Figure 3.11 compares the normalised product requirement priorities between the Chinese and the North American market. As seen from figure 3.11, the product requirements with similar priorities form a significant portion of the product, *i.e., Capacity of the lifeboats, recovering thermal heat, reducing exhaust emissions etc.* On the contrary, the product requirements with a wider priority gap indicate the requirement for the variation in a certain module that will incorporate this product requirement, *i.e., Variety of shopping places for passengers, variety of adventurous areas onboard, variety of relaxation areas onboard.*

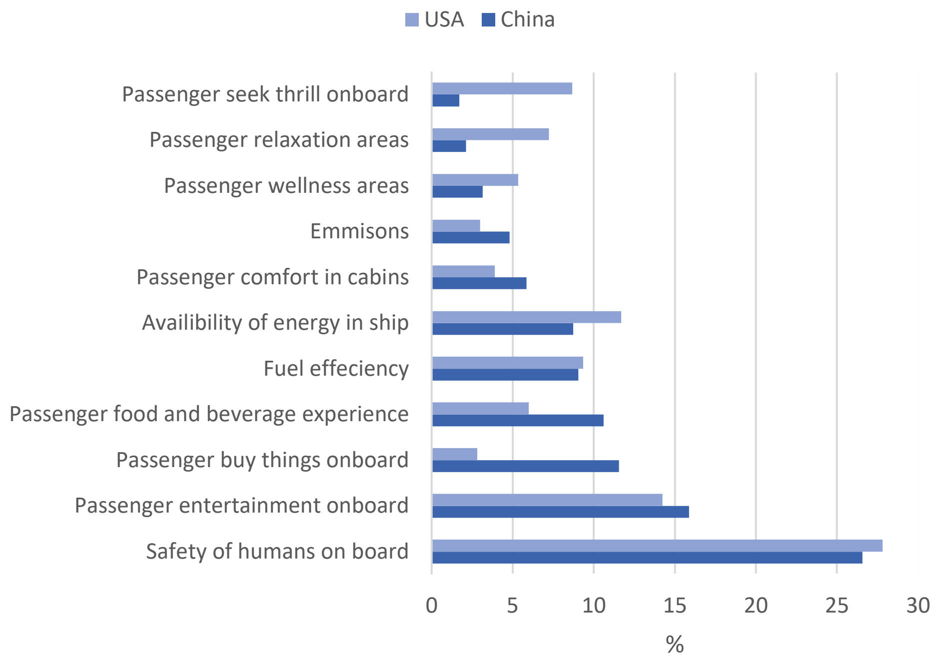


Figure 3.10 Comparison of Customer Need priorities between market segments

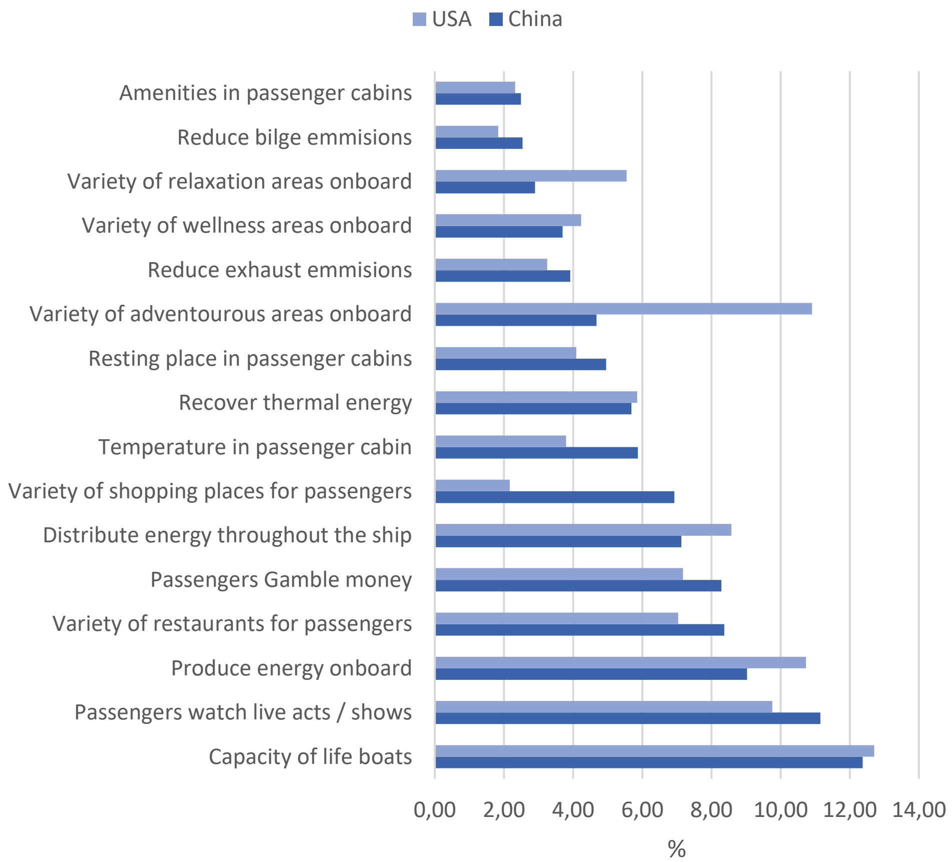


Figure 3.11 Comparison of Product Requirement priorities between market segments

4 Results and Discussion

This chapter explains the results of the thesis according to the research questions that were put forth to achieve the primary objective. Section 4.1 presents the answers for the first question and discusses the points to validate the rationale for selecting the draft QFD approach. Similarly section 4.2 and 4.3 answer and discuss the second and the third question, which focuses on bridging the gap between processes, reducing the uncertainty associated with a new process and recommending a tailored QFD process for use in the case company.

4.1 Question 1: QFD Steps to be implemented in the case company

The findings listed below are from the QFD, MFD™ and case company's process study that gives the rationale behind selecting the draft QFD approach *(Figure 4.1)*.

- Study of ISO 16355 documents showed the necessity of finding a tailored QFD approach because the ISO recommended approach is generalised to be used by any industries according to their needs *(Table 4.1)*.
- Since the method selected to develop the modular products was MFD™, a study of the MFD™ process provided insights on the input data needed for its second phase, *i.e., product requirements to derive functions.*
- Comparing the QFD steps suggested by the ISO and the case company's internal processes, it was observed that the business development phase was redundant since the case company already has their own process to define business goals and targets.
- It was also observed from the comparison that the project selection phase was also unnecessary for the case company since they have a unique method to define modules which later are individually selected as the *'project'* to be modularised.
- It was found out that the ratio scale obtained from linear values 1, 3, 5, 7, 9 were the most appropriate for the given application. The lower relation values of this scale have a lesser impact on the product requirement priority, and the higher relation value has a higher impact. This is important in terms of not losing focus from the critical customer needs, which is one of the drawbacks of QFD *(4.4.1)*. Therefore, reducing this effect is the best choice given the advantage of QFD over the observed drawback.
- As discussed in section 3.1, the suggested QFD approach uses only the needed levels of a deployment stage rather than using the entire comprehensive QFD approach. Further, the elimination of the unnecessary steps allows streamlining the process and saving time and resources needed otherwise.
- The differentiation of the products between the brands is essential to survive in the competitive market. The process of comparing the customer need between a group of market segments helps to determine their dominant theme, and the comparison of product requirement helps to identify the modules that shall have variants. This will give a competitive edge to the shipyard by saving design time while also satisfying customers of different market segments by considering their preferences.

4.2 Question 2: Seamless transition from QFD to MFD™

The findings listed below are from the study of the MFD™ and the QFD processes and also from the observations during the process implementation.

- As observed in question 1, the input data needed for the second phase of the MFD™ process is product requirements, which is used to derive functions.
- The suggested process by MFD™ to convert the product requirements into functions is the function tree. However, as discussed in section 2.3.3.4.3.a.2, function tree method also forms a part of the ISO recommended QFD in the functional level of the QFD process. This overlap between the MFD™ and the QFD helps to have a seamless transition from the QFD to MFD™.
- The observation obtained while exploring question 1 and 2 were helpful to put out an initial draft of the recommended QFD approach *(figure 3.1)*, which when tested provided insights on the challenges faced while implementing the process.

4.3 Question 3: Challenges while implementing the QFD process

The findings listed below are from the observations during the process implementation and the result analysis phase.

- One of the major criticism of the QFD process is that it takes a significant amount of time and effort to complete the QFD process. Since most of the QFD steps suggested uses matrices, the process can be implemented using a custom build software or a spreadsheet. Therefore, a well-developed process can help to drastically reduce the amount of work required to transfer the data, carry out complicated math to obtain the results and to gather the results in a presentable way.
- Since the suggested QFD approach heavily relies on the matrices, it is easy to incorporate changes occurring in the future, which is one of the most critical aspects of any product development projects.
- One of the significant drawbacks of any new process implementation is its acceptance by the users, and the introduction of the QFD process suffers from the same drawback. One critical reason for the resistance to change is the learning curve needed to absorb new tools and methods. The insights obtained from this and previous questions helped to design the steps in the tailored QFD approach to reduce this learning curve*, i.e., Usage of only the required tools by eliminating the redundant tools, Using similar tools as much as possible (Ishikawa diagram, AHP or L-Matrix), Designing the spreadsheet in such a way that it reduces the need to know the inner workings of the tools rather lets the designer focus on the data instead (Visual cues, process handouts).*
- Reliability of the tools is another critical measure while implementing a tool in the workflow. Therefore, having robust tools in QFD helps to avoid obtaining wrong priorities either by user disengagement or by user-error, which may result in disastrous consequences in the subsequent process. As discussed in 3.1.4.2, AHP is one such tool which has inbuilt inconsistency checker which helps to determine the usefulness of the data.

- Another major challenge in a project is to get a group of people in the same place at the same time. As mentioned in 2.3.4.2, implementation of AHP in QFD helps to resolve this issue by allowing the users to input their priorities separately and later combine these priorities with other priorities using the geometric mean to obtain the final priority.
- Even after incorporating the above improvements, it is easy to lose focus from the critical customer needs in QFD if the process is not carried out in an appropriate manner *(4.4.1)*.

The findings from all the questions where crucial in figuring out an appropriate QFD approach to be recommended to the case company. Incorporating the findings and the feedback received during the implementation phase of the draft QFD approach, it was clear that the stakeholder identification and prioritisation steps are not necessary for the use in the shipyard, therefore, left as an optional step if required. Other processes were considered useful to obtain the required data. Therefore, the author recommends the following QFD approach to be used by the case company *(Figure 4.1)*.

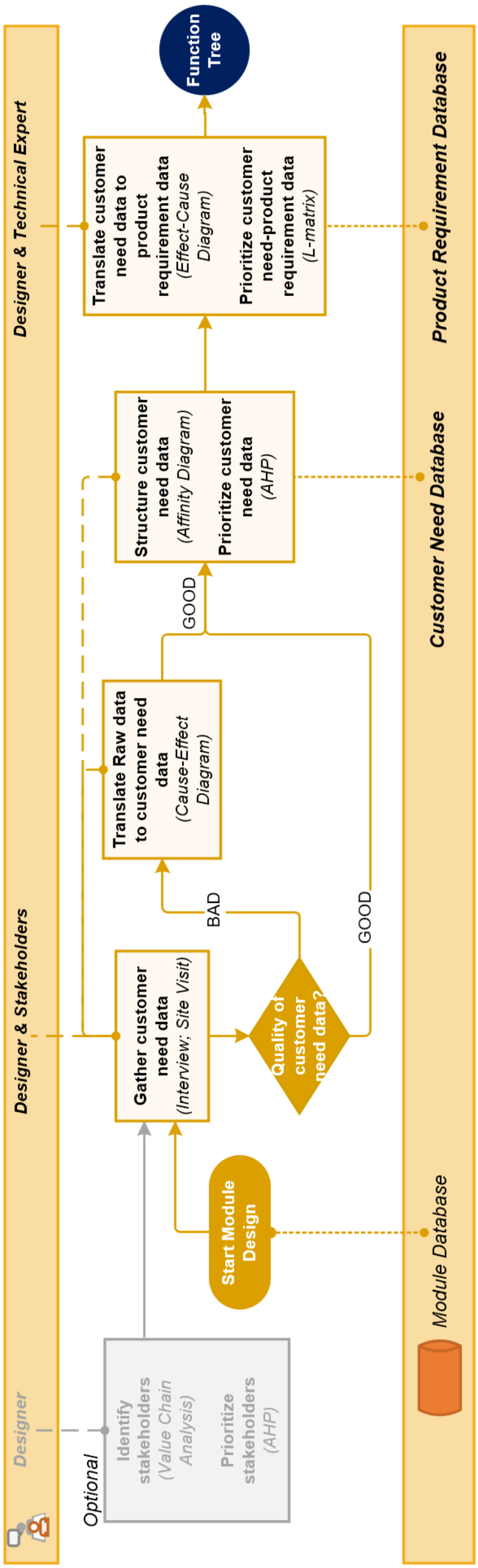


Figure 4.1 Proposed QFD approach for the shipyard

Table 4.1 List of ISO 16355 recommended QFD steps used in proposed QFD approach
X – Used; ! – Optional; - – Not Used

Dimension of Design	Levels of Design	Phase	Steps	Used in Tailored QFD
Quality Deployment	Product Level	Strategy Deployment Phase	Defining Business Goals	-
			Prioritising Business Goals	-
		Project Selection Phase	Prioritising the Projects	-
		Customer Analysis Phase	Defining the Stakeholders	!
			Prioritising the Stakeholders	!
			Sourcing the VoC/VoS	x
			Translating VoC to Customer Needs	x
			Structuring the Customer Needs	x
			Prioritising the Customer Needs	x
			Quantification (Customer)	-
		Deployment Phase	Translating Customer Needs to Product Requirements	x
			Prioritising CN-PR Matrix	x
			Quantification (Technical Experts)	-
			Assembling HoQ Matrix	x
	Functional Level		Function Identification	x
			Prioritising PR-Function Matrix	x
	Component Level		-	-
	Process Level		-	-
Technology Deployment	-	-	-	-
Cost Deployment	-	-	-	-
Reliability Deployment	-	-	-	-

4.4 Limitation of the study

As mentioned earlier, the data presented in this thesis is only for illustration purpose and is obtained independently by the author through the publically available sources, which may or may not be accurate. Therefore, readers shall be cautious when relying on this data even though the process in itself has no problems. Further, the readers shall be careful while selecting the scale for the use since the recommended scale in this thesis is appropriate for the use by the case company. Also, the author suggests the readers be aware of the requirement traceability within QFD to avoid losing focus from the critical customer needs.

4.4.1 Requirement traceability

One of the concerns with any product development project is the requirement traceability. It is essential to link the design decisions and justification made during the development of the product (Ramesh & Jarke, 2001). Similarly, for QFD to be a robust tool for the shipyard, it shall be able to trace the requirements. Researchers have repeatedly pointed out that the QFD process has excellent traceability when it comes to tracking information between various deployment levels (Madu, 2006; Burge, 2007). However, it is also crucial to trace the information set within the matrix, *i.e., getting Product Requirements priority from Customer Need priority and the Customer Needs – Product Requirements relationship matrix, and vice versa.* Following section explores the possibilities of getting a mathematical solution for the requirement traceability within a QFD matrix with the help of matrix algebra and comparing it with the logical interpretation of the data.

4.4.1.1 Requirement traceability in QFD1.1 matrix

4.4.1.1.1 Tracing Product Requirement priority with Customer Need priority

In figure 4.2, the QFD1.1 is represented with the ratio scale instead of a Likert-verbal scale *(figure 3.2)*. Taking the Customer Need priority as a column matrix P_{cn} with m rows, and the Relationship matrix as the R with m rows and n columns, such that for all m and n in I, were I is set of values belonging to the rational numbers and $n \geq m$, using equation 2, it is possible to obtain the absolute Product Requirements priority as a row matrix $abs\ P_{pr}$ with n columns.

$$abs\ P_{pr} = (R^T . P_{cn})^T \quad (2)$$

As per the equation 2, the Customer Need priority matrix is multiplied by the transpose of the Relationship matrix *(to satisfy the Dimension property of matrix multiplication)* to obtain an intermediate matrix which when transposed gives an absolute Product Requirement priority matrix. As seen from figure 4.3, the values obtained after the calculation using equation 2 match the values obtained from the QFD matrix, which implies that the equation 2 holds useful for forward requirement tracing.

NOTE: *The relation values in QFD1.1, figure 4.2, 4.3 & 4.5, is rounded to one decimal point for visual purpose even though it carries the original values for calculation.*

Customer needs (WHY?) \ Product requirements (WHAT?)	Priority (%)	Capacity of life boats	Passengers watch live acts / shows	Passengers Gamble money	Recover thermal energy	Variety of shopping places for passengers	Variety of restaurants for passengers	Produce energy onboard	Distribute energy throughout the ship	Temperature in passenger cabin	Amenities in passenger cabins	Resting place in passenger cabins	Reduce exhaust emmisions	Reduce bilge emmisions	Variety of wellness areas onboard	Variety of relaxation areas onboard	Variety of adventourous areas onboard
Safety of humans onboard	26,57	0,5	0,1	0,1	0	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0	0	0,1	0	0,1
Passenger entertainment onboard	15,88	0	0,5	0,5	0	0	0	0,1	0,1	0	0	0	0	0	0	0	0
Fuel effeciency	9,05	0,1	0	0	0,5	0	0	0,3	0,1	0,1	0	0	0,1	0,1	0	0	0
Passenger shop onboard	11,55	0	0,1	0	0	0,5	0,1	0	0	0	0	0	0	0	0,1	0,1	0
Passenger food and beverage experience	10,61	0	0,1	0,1	0	0,1	0,5	0	0	0	0	0	0	0	0	0,1	0
Availibility of energy in ship	8,73	0,3	0,1	0	0,3	0,1	0,1	0,5	0,5	0,1	0	0	0,1	0	0	0	0,1
Passenger comfort in cabins	5,85	0	0	0	0	0	0	0,1	0,1	0,5	0,1	0,5	0	0	0	0	0
Emmisons	4,80	0	0	0	0,1	0	0	0,1	0	0	0	0	0,5	0,5	0	0	0
Passenger wellness areas	3,15	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0	0
Passenger relaxation areas	2,11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0
Passenger seek thrill onboard	1,70	0	0	0	0	0	0	0,1	0,1	0	0	0	0	0	0	0	0,5
Absolute priority (Product Requirements)	100,00	0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06
Normalized priority (Product Requirements)		0,12	0,11	0,08	0,06	0,07	0,08	0,09	0,07	0,06	0,02	0,05	0,04	0,03	0,04	0,03	0,05
Normalized priority % (Product Requirements)		12,4	11,1	8,3	5,7	6,9	8,4	9,0	7,1	5,9	2,5	5,0	3,9	2,5	3,7	2,9	4,7

Figure 4.2 QFD1.1 for the contemporary cruise segment for the Chinese market

Customer Needs (CN)	Pcn	CN-PR relationship (R)																	Ppr^T
Safety of humans onboard	26,6	0,5	0,1	0,1	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,1	0,0	0,1		0,16
Passenger entertainment onboard	15,9	0,0	0,5	0,5	0,0	0,0	0,0	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		0,15
Fuel effeciency	9,0	0,1	0,0	0,0	0,5	0,0	0,0	0,3	0,1	0,1	0,0	0,0	0,1	0,1	0,0	0,0	0,0		0,11
Passenger shop onboard	11,6	0,0	0,1	0,0	0,0	0,5	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,0		0,07
Passenger food and beverage experience	10,6	0,0	0,1	0,1	0,0	0,1	0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0		0,09
Availibility of energy in ship	8,7	0,3	0,1	0,0	0,3	0,1	0,1	0,5	0,5	0,1	0,0	0,0	0,1	0,0	0,0	0,0	0,1		0,11
Passenger comfort in cabins	5,9	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,5	0,1	0,5	0,0	0,0	0,0	0,0	0,0		0,12
Emmisons	4,8	0,0	0,0	0,0	0,1	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,5	0,5	0,0	0,0	0,0		0,09
Passenger wellness areas	3,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0		0,08
Passenger relaxation areas	2,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0		0,03
Passenger seek thrill onboard	1,7	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5		0,07
																			0,05
Absolute Ppr (QFD)		0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06	**Sum**	0,03
Absolute Ppr (Matrix)		0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06	1,31	0,05
Normalised Ppr % (Matrix)		12,4	11,1	8,3	5,7	6,9	8,4	9,0	7,1	5,9	2,5	5,0	3,9	2,5	3,7	2,9	4,7		0,04
																			0,06

Figure 4.3 Calculating the absolute Product Requirement priority using Matrix algebra

4.4.1.1.2 Tracing Customer Need priority with Product Requirement priority

To be able to say that the QFD is a reliable tool when it comes to requirement tracing mathematically, it shall be able to backtrack the product requirement priority to the customer need priority when considering both the normalised and the absolute P_{pr} values. In the QFD matrix, the number of identified product requirements will always be greater or equal to the number of customer needs. When they are equal, equation 3 holds good.

$$P_{cn} = (R^T)^{-1}.(abs\ P_{pr})^T \tag{3}$$

$$P_{cn} = (R\,.\,R^T)^{-1}\,R\,.\text{abs}\ P_{pr} \tag{4}$$

However, in most QFD cases equation 3 does not hold good since the number of identified product requirements will be higher than the number of customer needs, which brings difficulty in calculating the inverse of a relationship matrix, *i.e., a matrix must have the same number of rows and columns to calculate the inverse of it*. Instead, with equation 4 it is possible to take pseudo-inverse of the relationship matrix with either equal or higher number of product requirement based on Moore–Penrose inverse (Penrose, 1956). From equation 4, pseudo-inverse of the relationship matrix is obtained and multiplied with the absolute product requirement priority to get the customer need priority matrix as shown in figure 4.5. It is also possible to backtrack the customer need priority with the normalised product requirement priority and relationship matrix if the *Normalising Factor* is known *(sum of the absolute product requirement priorities - Figure 4.4)*.

																	SUM
Absolute Ppr (QFD)	0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06	1,31
Normalised Ppr % (QFD)	12,37	11,15	8,29	5,68	6,93	8,38	9,03	7,13	5,87	2,49	4,95	3,92	2,54	3,69	2,90	4,68	
Absolute Ppr (Matrix)	0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06	

Figure 4.4 Calculating absolute Product requirement priority from normalised Product requirement

Customer Needs (CN)	Pcn % (QFD)	Pcn % (Matrix)	CN-PR relationship (R)															
Safety of humans onboard	26,57	26,57	0,5	0,1	0,1	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,1	0,0	0,1
Passenger entertainment onboard	15,88	15,88	0,0	0,5	0,5	0,0	0,0	0,0	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Fuel effeciency	9,05	9,05	0,1	0,0	0,0	0,5	0,0	0,0	0,3	0,1	0,1	0,0	0,0	0,1	0,1	0,0	0,0	0,0
Passenger shop onboard	11,55	11,55	0,0	0,1	0,0	0,0	0,5	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,0
Passenger food and beverage experience	10,61	10,61	0,0	0,1	0,1	0,0	0,1	0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0
Availibility of energy in ship	8,73	8,73	0,3	0,1	0,0	0,3	0,1	0,1	0,5	0,5	0,1	0,0	0,0	0,1	0,0	0,0	0,0	0,1
Passenger comfort in cabins	5,85	5,85	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,5	0,1	0,5	0,0	0,0	0,0	0,0	0,0
Emmisons	4,80	4,80	0,0	0,0	0,0	0,1	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,5	0,5	0,0	0,0	0,0
Passenger wellness areas	3,15	3,15	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0
Passenger relaxation areas	2,11	2,11	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0
Passenger seek thrill onboard	1,70	1,70	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5
		Absolutes Ppr (QFD)	0,16	0,15	0,11	0,07	0,09	0,11	0,12	0,09	0,08	0,03	0,07	0,05	0,03	0,05	0,04	0,06

Customer Needs (CN)	(R . R^(T))^-1 . R																Pcn % (Matrix)
Safety of humans onboard	2,0	0,2	0,0	0,0	0,0	0,0	-0,5	-0,7	0,0	0,1	0,1	0,1	0,0	0,1	0,1	0,2	26,57
Passenger entertainment onboard	-0,3	1,0	1,0	0,0	-0,2	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-0,1	15,88
Fuel effeciency	0,0	0,1	0,1	2,2	0,0	0,0	0,0	-1,2	0,2	-0,1	0,0	-0,1	-0,5	0,1	0,1	0,2	9,05
Passenger shop onboard	-0,2	0,3	-0,2	0,1	2,0	-0,3	0,0	-0,1	0,0	-0,1	0,0	-0,1	-0,1	0,0	0,0	0,0	11,55
Passenger food and beverage experience	-0,5	-0,2	0,0	0,1	-0,2	2,0	0,0	0,0	0,0	0,1	0,0	-0,1	-0,1	0,0	0,0	0,0	10,61
Availibility of energy in ship	0,0	-0,2	-0,1	-0,6	-0,1	-0,1	0,9	1,6	-0,2	0,0	-0,2	-0,1	0,1	-0,2	-0,2	-0,4	8,73
Passenger comfort in cabins	-0,5	0,0	0,0	-0,1	0,0	0,0	0,1	0,1	0,9	0,2	1,0	0,0	0,0	0,0	0,0	0,0	5,85
Emmisons	-0,1	0,0	0,0	-0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	1,1	0,0	0,0	0,0	4,80
Passenger wellness areas	-0,2	0,0	0,0	0,0	-0,2	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,0	0,0	0,0	3,15
Passenger relaxation areas	0,0	0,0	0,0	0,0	-0,2	-0,2	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	2,0	0,0	2,11
Passenger seek thrill onboard	-0,5	-0,1	0,0	0,1	0,0	0,0	0,1	-0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,0	1,70

Figure 4.5 Calculating the Customer Need priority using Matrix algebra

Even though mathematically we get back the data without losing any information, logically as discussed in 3.1.3.3, we do lose some focus from the critical customer needs when getting prioritised product requirement results, *i.e., the product requirement such as Variety of shopping places for passengers is placed much lower than the Variety of restaurants for passengers even though this ranking is contrary to their customer need ranking*. The observed effect in this thesis study is not eliminated, instead is minimised by using the recommended ratio scale obtained from linear 1, 3, 5, 7, 9 values.

Traceability of the requirements is essential to link the design decisions and justification made during the development of the product. From section 4.4.1.1.1 and 4.4.1.1.2, it is clear that with the availability of required data, mathematically, it is possible to trace the absolute product requirement priority or the customer needs priority respectively. However, logically, the increase in the number of lower-value relations deviates the customer need orders, which goes against the principle of traceability. Therefore, the readers must be careful regarding this.

5 Conclusion

This thesis explores the methodology of assisting the design process of the ship modules by obtaining the product requirements with the help of Quality Function Deployment and to use them as inputs for the Modular Function Deployment™ process according to the suggestions of the ISO 16355 standards. To achieve this objective, answering the three research questions was necessary.

To answer the first research question, it was crucial to understanding the ISO recommended QFD process, MFD™ process and the case company's internal product development process. This, in turn, uncovered the unnecessary steps from the ISO recommended QFD approach, which then were eliminated in the draft QFD approach recommended by the author to carry out the trial in the shipyard. The recommended QFD approach to obtain the product requirement starts by identifying the customers who will provide significant insights while acquiring the customer needs because the customers know their problems better than anyone else does. However, these needs sometimes may be latent, which requires conversion into the customer needs by the designers with the help of the customers. Prioritising the customer needs helps to understand what the customer really cares about and keeps the team focused on the crucial needs. Converting these customer needs into product requirements gives the required input for the MFD™ process and prioritising the product requirement again gives the team an idea of the critical product requirements that the team shall focus on to incorporate in the product. Additionally, the author explores different judgement scales recommended by various QFD researchers and recommends the ratio scale obtained from linear values 1, 3, 5, 7, 9 for the case company's application.

After obtaining the product requirements, with the help of the technical experts, the functions that fulfil the product requirements were determined and used in the second phase of the MFD™ process, which bridges the gap between the two processes. This answers the question of having a seamless transition from QFD to the subsequent phases of the MFD™ process. One of the additional points discussed in this thesis is the approach to segment consumers from different markets since the main intention for developing the products in a modular way is to have common parts between the modules of different vessels while retaining the ability to offer variation in the modules. This approach of segmentation will ease the process to define the modules that shall have variants.

Finally, the trial of the draft QFD process uncovered challenges related to the implementation of the ISO recommended QFD process which had a greater influence in the development of an optimal QFD approach for the case company's modularisation application.

To conclude, when it comes to having a systematic approach to derive the product requirements from the customer's own voice, the author recommends the use of the QFD process. In the case of the case company, the tailored QFD approach recommended by the author is concise, requires lesser time and is suitable for the case company design processes.

5.1 Future research

Balancing the quality and resources needed for AHP data:

In this thesis, all the relations in the AHP process were quantified which took a lot of time and effort by both the technical experts and the QFD team to get prioritised data. In theory, priorities between quantities can be obtained by extrapolating input relationship values to obtain relationships for other quantities (Opydo, 2019). However, finding the right balance between the number of relationships to acquire and quality of the data to obtain is crucial. Therefore, a study regarding this helps to collect quality data using fewer resources.

Large-scale data collection and quantification:

This thesis does not collect the expected performance levels, the competitor performance level of the identified features from the end users point of view. Therefore, a study regarding the usefulness of these data in modularisation context will help prevent over-engineering or under-engineering the product.

Automated data collection and relationship prediction:

The author also recommends a study into efficient retrieval of large scale data extraction from online sources *(forums, reviews, reports etc.)* using text mining to always be updated with the current fast-changing trends. For this data to be beneficial in future, a study regarding the use of Machine Learning/Artificial Intelligence techniques to segregate the collected data and to predict the relationships in the matrices with the use of historical data collected would give an advantage for the shipyard to be innovative.

References

Akao, Y., 1972. New product development and quality assurance - quality deployment system. *Standardization and Quality Control,* 25(4), pp. 7-14.

Akao, Y., 1990. *Quality Function Deployment: Integrating Customer Requirements into Product Design.* 1 ed. Portland: Productivity Press.

Akao, Y., Kogure, M. & Furukawa, Y., 1983. *Company wide Quality Control and Quality Deployment Seminar.* Chicago, s.n.

Akao, Y. & Mazur, G. H., 2003. The leading edge of QFD: past, present and future. *International Journal of Quality & Reliability Management,* 20(1), pp. 20-35.

Akao, Y. & Ohfuji, T., 1989. *Recent aspects of Quality Function Deployment in service industries in Japan.* Rio de Janeiro, Quality Control.

American Supplier Institute (ASI), 1989. *Quality Function Deployment - Three Day Workshop.* Dearborn, American Supplier Institute Inc..

Andersson, R., 1991. *QFD: A System for Effecient Product Development,* Lund: Studentlitteratur.

ASI, 1992. *American Supplier Institute: Kundorienterad produktutveckling hardvara & process.* Dearborn, American Supplier Institute Inc..

Bendjenna, H., Charre, P.-J. & Zarour, N. E., 2012. Using multi-criteria analysis to prioritize stakeholders. *Journal of Systems and Information Technology,* 14(3), pp. 264-280.

Bertram, V., 2005. *Modularization of Ships,* Brest; Gdansk: Report Number: s/03/G, InterMareC – Interregional Maritime Cluster. Project partly-Financed by the European Union.

Beyer, H., 2010. *User-centered agile methods.* California: Morgan & Claypool Publishers.

Brodie, C. H. & Burchill, G., 2005. *Voices into Choices: Acting on the Voice of the Customers.* Madison: Oriel Incorporated.

Burge, S., 2009. *Systems Engineering Tools & Techniques.* [Online] Available at: https://www.burgehugheswalsh.co.uk/Systems-Engineering/Tools.aspx [Accessed 11 February 2019].

Börjesson, F. & Hölttä-Otto, K., 2014. A module generation algorithm for product architecture based on component interactions and strategic drivers. *Research in Engineering Design,* Volume 25, pp. 31-51.

Börjesson, F. S., 2009. Improved Output in Modular Function Deployment using Heuristics. *17th International Conference of Engineering Design,* Volume 4, pp. 1-12.

Börjesson, F. S., 2012. *Approaches to Modularity in Product Architecture.* s.l.:Licentiate thesis, Royal Institute of Technology, Stockholm.

Cable, B., 1937. *A Hundred year History of P&O.* 1st ed. London: Ivor Nicholson & Watson Ltd..

Carnevalli, J. A. & Carpinetti, M. A. P., 2002. QFD aplication in different countries: a comparison of an exploratory study in Brazil with other surveys. *Product: Management & Development,* 1(2), pp. 5-18.

Carter, R., 2006. Boat remains and maritime trade in the Persian Gulf during the sixth and fifth millennia BC. *Antiquity,* 80(307), pp. 52-63.

Cauchick, M. P. A. & Carpinetti, L. R., 1999. Some Brazilian experiences on QFD application. *5th International Symposium on Quality Function Deployment, Belo,* pp. 229-239.

Chandler, A. D., 1962. *Strategy and Structure: Chapters in the History of the American Industrial Enterprise.* Cambridge: The MIT Press Ltd.

Chan, L.-K. & Wu, M.-L., 2002. Quality Function Deployment: A Comprehensive Review of Its Concepts and Methods. *Quality Engineering,* 15(1), pp. 23-35.

Christenses, C. M., Hall, T., Dillon, K. & Duncan, D. S., 2016. Know Your Customers' "Jobs to Be Done". *Harvard Business Review,* 94(9), pp. 54-62.

Christiano, J. J., Liker, K. J. & White III, C. C., 2000. Customer-Driven Product Development Through Quality Function Deployment in the U.S. and Japan. *Journal of Product Innovation Management,* Volume 17, pp. 286-308.

Chrząszcz, J., 2018. *TRIZ inventive principles and computer design.* Dziwnów, RUC'2018 - 21st Conference on Reconfigurable Ubiquitous Computing.

CIN, 2019. *Cruise Industry News: Cruise Ship Orderbook.* [Online] Available at: https://www.cruiseindustrynews.com/cruise-news/cruise-ship-orderbook.html [Accessed 2 February 2019].

Clausing, D., 1994. *Total Quality Development: A Step-by-Step Guide to World Class Concurrent Engineering.* 1st ed. New York: ASME Press.

CLIA, 2018a. *Asia Cruise Trends: 2018 Edition.* [Online] Available at: https://cliaasia.org/wp-content/uploads/2018/08/asia-cruise-trends-2018.pdf [Accessed March 2019].

CLIA, 2018b. *Cruise Travel Report: 2018.* [Online] Available at: https://cruising.org/-/media/research-updates/research/consumer-research/2018-clia-travel-report.pdf [Accessed March 2019].

CLIA, 2019. *2019 Cruise Trends & Industry Outlook,* Washington DC: Cruise Lines International Association.

Cohen, L., 1995. *Quality function deployment: How to make QFD work for you.* 1 ed. Massachusetts : Prentice Hall.

Cook, H. E., 1997. *Product Management: Value, quality, cost, price, profit and organization.* Heidelberg: Springer Netherlands.

Dahmus, J. B., Gonzalez-Zugasti, J. & Otto, K. N., 2001. Modular product architecture. *Design Studies,* 22(5), pp. 409-424.

Donaldson, K. M., Ishii, K. & Sheppard, S. D., 2006. Customer Value Chain Analysis. *Research in Engineering Design,* Volume 16, pp. 147-183.

Ekdahl, F. & Gustafsson, A., 1997. QFD: the swedish experience. *The Ninth Symposium On Quality Function Deployment,* pp. 15-27.

Ericsson, A. & Erixon, G., 1999. *Controlling Design Variants: Modular Product Platforms.* Michigan: Society of Manufacturing Engineers.

Erixon, G., 1998. Modular function deployment—a method for product modularization. *PhD thesis, The Royal Institute of Technology, Stockholm.*

Evans, J., 1959. Basic Design Concepts. *Journal of the American Society for Naval Engineers,* 71(4), pp. 671-678.

Eyres, D. J., 2006. *Ship Construction.* 6th ed. s.l.:Elsevier Science & Technology.

Fehlmann, M. & Glenn, T., 2016. Using AHP in QFD - The impact of the New ISO 16355 Standard. *The International Symposium on the Analytic Hierarchy Process.*

Fisher, C. & Schutta, J., 2003. *Developing New Service: Incorporating the Voice of the Customer into Strategic Service Development.* Milwaukee, WI: ASQ Quality Press.

Gérard, P., 2009. *L'Âge d'or des voyages en paquebot.* s.l.:Éditions du Chêne.

Görener, A., 2012. Comparing AHP and ANP: An Application of Strategic Decisions Making in a Manufacturing Company. *International Journal of Business and Social Science,* 3(11), pp. 194-208.

Hauser, J. R., 1993. How Puritan-Bennett Used the House of Quality. *Sloan Management Review ,* Volume Spring 1993, pp. 61-70.

Hauser, J. R. & Clausing, D., 1988. The House of Quality. *Harvard Business Review,* 66(3), pp. 63-73.

Hauser, J. R. et al., 2010. Voice of the Customer. In: *Wiley International Encyclopedia of Marketing.* s.l.:Wiley-Blackwell Publishing.

Hauser, J. R. & Griffin, A., 1993. The Voice of the Customer. *Marketing Science,* 12(1), pp. 1-27.

Herrmann, A., Huber, F. & Braunstein, C., 2000. Market-driven product and service design: Bridging the gap between customer needs, quality management, and customer satisfaction. *International Journal of Production Economics,* 66(1), pp. 77-96.

Hill, A., 1992. *New product introduction through QFD in a total quality environment.* Milano, First European Conference on Quality Function Deployment.

Hunter, L. C., 1985. A History of Industrial Power in the United States, 1730–1930. *Steam Power,* Volume 2.

Ishikawa, K., 1985. *What Is Total Quality Control?: The Japanese Way.* 1st ed. New Jersey: Prentice Hall Direct.

ISO 16355-1:2015, 2015. *Application of statistical and related methods to new technology and product development process -- Part 1: General principles and perspectives of Quality Function Deployment (QFD),* Switzerland: International Organization for Standardization.

ISO 16355-2:2017, 2017. *Applications of statistical and related methods to new technology and product development process -- Part 2: Non-quantitative approaches for the acquisition of voice of customer and voice of stakeholder,* Geneva: International Organization for Standardization. Extracts used with the permission of the Finnish Standards Association SFS.

ISO 16355-3:2019, 2019. *Applications of statistical and related methods to new technology and product development process -- Part 3: Quantitative approaches for the acquisition of voice of customer and voice of stakeholder,* Geneva: International Organization for Standardization. Extracts used with the permission of the Finnish Standards Association SFS.

ISO 16355-4:2017, 2017. *Applications of statistical and related methods to new technology and product development process -- Part 4: Analysis of non-quantitative and quantitative Voice of Customer and Voice of Stakeholder,* Geneva: International Organization for Standardization. Extracts used with the permission of the Finnish Standards Association SFS.

ISO 16355-5:2017, 2017. *Applications of statistical and related methods to new technology and product development process -- Part 5: Solution strategy,* Geneva: International Organization for Standardization. Extracts used with the permission of the Finnish Standards Association SFS.

ISO 16355-6, [Under Development]. *Applications of statistical and related methods to new technology and product development process -- Part 6: QFD -- related approaches to optimization,* Geneva: International Organization for Standardization.

ISO/CD 16337, [Under Development]. *Application of statistical and related methods to new technology and product development process -- Robust Tolerance Design (RTD),* Geneva: International Organization for Standardization.

ISO/TR 16355-8:2017, 2017. *Applications of statistical and related methods to new technology and product development process -- Part 8: Guidelines for commercialization and life cycle,* Geneva: International Organization for Standardization. Extracts used with the permission of the Finnish Standards Association SFS.

ISO, 2019a. *ISO: About ISO.* [Online]
Available at: https://www.iso.org/about-us.html [Accessed 04 January 2019].

ISO, 2019b. *ISO: Taking part.* [Online]
Available at: https://www.iso.org/developing-standards.html
[Accessed 31 January 2019].

Jones, T. O. & Sasser, W. E., 1995. Why satisfied customers defect. *Harvard Business Review,* 73(6), pp. 88-99.

Krishnan, V. & Ulrich, K. T., 2001. Product development decisions: A review of the literature. *Management Science,* 47(1), pp. 1-21.

Laidlaw, R., 1984. Aboriginal Society before European settlement. In: *The European Occupation.* s.l.:Heinemann Educational Australia, p. 40.

Lange, M. W. & Imsdahl, A., 2014. Modular Function Deployment: Using Module Drivers to Impart Strategies to a Product Architecture. In: T. W. Simpson, J. Jiao, Z. Siddique & K. Hölttä-Otto, eds. *Advances in Product Family and Product Platform Design.* New York: Springer, pp. 91-118.

Langlois, R. N., 2002. Modularity in technology and organization. *Journal of Economic Behavior & Organization,* Volume 49, pp. 19-37.

Le Goff, O., 1998. *Les Plus Beaux Paquebots du Monde.* s.l.:Solar.

Lillrank, P., 1990. *Laatumaa: Johdatus japanin talouselämään laatujohtamisen.* Helsinki: Gaudeamus.

Maritan, D., 2015. *Practical Manual of Quality Function Deployment.* 1st ed. Switzerland: Springer International Publishing.

Mars, C. & Jubelin, F., 2001. *Paquebots.* s.l.:Sélection du Reader's Digest.

Marshall, R., 1998. Design Modularity: A System Engineering based Methodology for Enhanced Product Realisation. *Doctoral Thesis, Loughborough University, Leicestershire,* pp. 223-226.

Martins, A. & Aspinwall, E. M., 2001. Quality function deployment: an empirical study in the UK. *Total Quality Management,* 12(5), pp. 575-588.

Matzler, K. & Hinterhuber, H., 1998. How to make product development projects more successful by integrating Kano's model of customer satisfaction into quality function deployment. *Technovation,* 18(1), pp. 25-38.

Mazur, G. H., 2007. *How does Modern QFD differ from Traditional 4-Phase QFD?,* Michigan: QFD Institute.

Mazur, G. H., 2012. Blitz QFD® - The Lean Approach to Product Development. *Proceedings of the World Conference on Quality and Improvement,* p. ASQ.

Mazur, G. H., 2016. Keeping Up with Global Practices: ISO 16355 - Applications of statistical and related methods to new technology and product development process. *The 22nd International Symposium on QFD.*

Miller, G. A., 1956. The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information. *Psychological Review,* 63(2), pp. 81-97.

Mizuno, S. & Akao, Y., 1978. *Quality Function Deployment: A Company-wide Quality Approach.* Tokyo: JUSE Press.

Mu, E. & Pereyra-Rojas, M., 2017. Understanding the Analytic Hierarchy Process. In: *SpringerBriefs in Operations Research.* s.l.:Springer, Cham, pp. 7-22.

Nishimura, K., 1972. Ship design and quality chart. *Quality Control,* 23(Special Issue), pp. 71-4.

Otto, K. N. & Wood, K. L., 2001. *Product Design: Techniques in Reverse Engineering and New Product Development.* 1st ed. New Jersey: Prentice Hal.

Pahl, G., Beitz, W., Feldhuse, J. & Grote, K. H., 2007. *Engineering Design: A Systematic Approach.* 3rd ed. London: Springer-Verlag London Limited.

Park, J. & Simpson, T. W., 2005. Development of production cost estimation framework to support product family design. *International Journal of Production Research,* 43(4), pp. 731-772.

Pugh, S., 1981. *Concept Selection: A Method that Works.* s.l., Proceedings of International Conference on Engineering Design, Zürich, pp. 497-506.

Pugh, S., 1991. Design Core: Conceptual Design. In: *Total Design: Integrated Methods for Successful Product Engineering.* s.l.:Addison-Wesley, pp. 67-99.

Robinson, J., 1934. *The Economics of Imperfect Competition.* 1st ed. London: MacMillan.

Ronney, E., Olfe, P. & Mazur, G., 2000. Gemba Research in the japanese Cellular Phone Market. *Transaction from the Twelfth Symposium on Quality Function Deployment.*

Saaty, T. L., 1989. Group Decision Making and the AHP. In: B. L. Golden, E. A. Wasil & P. T. Harker, eds. *The Analytic Hierarchy Process.* Berlin: Springer, pp. 59-67.

Saaty, T. L., 2003. Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research,* Volume 145, pp. 85-91.

Saaty, T. L. & Saaty, R. W., 2016. *Decision Making In Complex Environments: The Analytic Network Process (ANP) for Dependence and Feedback.* Pittsburgh: s.n.

Shillito, L. M., 1994. *Advanced QFD: Linking Technology to Market and Company Needs.* s.l.:John Wiley & Sons.

Shillito, L. M., 1997. Function is the Foundation. *Transaction of 9th Symposium on QFD (ISQFD).*

Short, T. et al., 2009. Matching the Voice of the Engineering to the Voive of the Customer: An Evolution of QFD. *International Conference of Engineering Design,* Volume 6, pp. 123-134.
Smithsonian, 1819. *Logbook for First Transatlantic Steamship Savannah, 1819.* [Online] Available at: http://americanhistory.si.edu/collections/search/object/nmah_842432 [Accessed 04 February 2019].
Smith, W. R., 1956. Product Differentiation and Market Segmentation as Alternative Marketing Strategies. *The Journal of Marketing,* 21(1), pp. 3-8.
Steward, D. V., 1981. The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management,* 28(3), pp. 71-74.
Stevens, S. S., 1946. On the Theory of Scales of Measurement. *Science,* 103(2684), pp. 677-680.
Stone, R. B., Kurtadikar, R., Villanueva, N. & Arnold, C. B., 2008. A customer needs motivated conceptual design methodology for product portfolio planning. *Journal of Engineering Design,* 19(6), pp. 489-514.
Stone, R. B., Wood, K. L. & Crawford, R. H., 2000. A heuristic method for identifying modules for product architectures. *Design Studies,* 21(1), pp. 5-31.
Sudjianto, A. & Otto, K., 2001. *Modularization to Support Multiple Brand Platforms.* Pittsburgh, PA, ASME Design Engineering Technical Conferences.
Sullivan, L. P., 1986. Quality function deployment. *Quality Progress,* 19(6), pp. 39-50.
Takayanagi, A., 1972. Quality Control in Production-to-Order at Our Company (1): Quality Control Activities for Made-to-Order Products – re: Concept of a Quality Chart. *Quality Control,* 23(Special Edition), pp. 63-67.
Terninko, J., 1997. *Step-by-Step QFD: Customer-Driven Product Design.* 2nd ed. s.l.:CRC Press.
Terninko, J., Zlotin, B. & Zusman, A., 1996. *Step-by-Step TRIZ: Creating Innovative Solution Concepts.* s.l.:Responsible Management Inc..
Timoshenko, A. & Hauser, J. R., 2018. Identifying Customer Needs from User Generated Content. *Marketing Science,* Issue Forthcoming.
Ulrich, K. T. & Eppinger, S. D., 2016. *Product design and development.* 6th ed. New York: McGraw-Hill Education.
Wasserman, G. S., 1993. On How to Prioritize Design Requirements During the QFD Planning Process. *IIE Transaction,* 25(3), pp. 59-65.
Vossen, C., Kleppe, R. & Hjørungnes, S. R., 2013. *Ship Design and System Integration.* Dresden, s.n.
Yang, Y., 2015. *What Chinese cruisers want: An analysis of product preferences,* 632: Open Access Theses.
Yüksel, İ. & Dağdeviren, M., 2007. Using the analytic network process (ANP) in a SWOT analysis-A case study for a textile firm. *Information Sciences,* 117(16), pp. 3374-3382.
Zamirowski, E. J. & Otto, K. N., 1999. *Identifying Product Portfolio Architecture Modularity Using Function and Variety Heuristics.* , Proceedings of the 1999 ASME design engineering technical conference (DETC99/DTM-8760), Las Vegas.
Zultner, R. E., 1995. Blitz QFD: Better, faster, and cheaper forms of QFD. *American Programmer,* Volume 8, pp. 24-24.

Appendix A: Tools used to enhance QFD

A.1 Analytical Hierarchy Process (AHP)

A.1.1 What is AHP?

- A multi-criteria decision-making tool
- Can be used when group consensus on a decision is required

A.1.2 When to use AHP?

- When comparing a set of information with itself

Table A.1.1 AHP Tool

Variables	Variable 1	Variable 2	Variable 3	Normalised columns			Sum	Priority
Variable 1	V_{11}	V_{12}	V_{13}	V_{11} / S_{c1}	V_{12} / S_{c2}	V_{13} / S_{c3}	S_{nr1}	**S_{nr1} / 3**
Variable 2	$1/ V_{12}$	V_{22}	V_{23}	V_{21} / S_{c1}	V_{22} / S_{c2}	V_{23} / S_{c3}	S_{nr2}	**S_{nr2} / 3**
Variable 3	$1/V_{13}$	$1/V_{23}$	V_{33}	V_{31} / S_{c1}	V_{32} / S_{c2}	V_{33} / S_{c3}	S_{nr3}	**S_{nr3} / 3**
SUM	S_{c1}	S_{c2}	S_{c3}	$S_{nc1} = 1$	$S_{nc2} = 1$	$S_{nc3} = 1$	$S_{nrc} = x$	$S_P = 100$
					Inconsistency Ratio			**<10%**

Table A.1.2 AHP Tool scoring scale

Use these scores when you prefer **Row variable** over **Column variable**								Equally preferred	Use these when you prefer **Column variable** over **Row variable**							
Extremely Preferred		Very Strongly preferred		Strongly preferred		Moderately preferred			Moderately preferred		Strongly preferred		Very Strongly preferred		Extremely preferred	
9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9

A.1.3 Steps:

- Moving row-by-row only for highlighted cells, *(i.e., V_{12}, V_{13} ….. V_{1y}; V_{23}, V_{24} …… V_{2y}; $V_{x(x+1)}$….. V_{yy})*, compare the row variable with their column variable
- Ask – "*Which do you prefer – Row or Column? By how much do you prefer the selected choice?*"
- Assign the value for the preference as shown from the table A.1.2 *(The diagonal cells, i.e., V_{xx}, will always be 1)*
- Check if the ***Inconsistency Ratio**** is below 10%. If not, recheck your judgement
- Priority of the variables can be found from their respective ***Priority*** row cell

** Refer Mu & Pereyra-Rojas (2017) book for more information about Inconsistency Ratio*

A.2 L-matrix

A.2.1 What is L-matrix?

- A decision-making tool
- Can be used when group consensus on a decision is required

A.2.2 When to use L-matrix?

- When comparing a set of information with a different set of information or criteria

Table A.2.1 L-matrix Tool

Product requirements / Customer Needs	Priority (%)	Product Requirement 1	Product Requirement 2	Product Requirement 3	Product Requirement 4	Product Requirement 5	Product Requirement 6
Customer need 1.1	P_1	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}
		$R_{11} \cdot P_1$	$R_{12} \cdot P_1$	$R_{13} \cdot P_1$	$R_{14} \cdot P_1$	$R_{15} \cdot P_1$	$R_{16} \cdot P_1$
Customer need 1.2	P_2	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	R_{26}
		$R_{21} \cdot P_2$	$R_{22} \cdot P_2$	$R_{23} \cdot P_2$	$R_{24} \cdot P_2$	$R_{25} \cdot P_2$	$R_{26} \cdot P_2$
Customer need 1.3	P_3	R_{31}	R_{32}	R_{33}	R_{34}	R_{35}	R_{36}
		$R_{31} \cdot P_3$	$R_{32} \cdot P_3$	$R_{33} \cdot P_3$	$R_{34} \cdot P_3$	$R_{35} \cdot P_3$	$R_{36} \cdot P_3$
Customer need 1.4	P_4	R_{41}	R_{42}	R_{43}	R_{44}	R_{45}	R_{46}
		$R_{41} \cdot P_4$	$R_{42} \cdot P_4$	$R_{43} \cdot P_4$	$R_{44} \cdot P_4$	$R_{45} \cdot P_4$	$R_{46} \cdot P_4$
Customer need 1.5	P_5	R_{51}	R_{52}	R_{53}	R_{54}	R_{55}	R_{56}
		$R_{51} \cdot P_5$	$R_{52} \cdot P_5$	$R_{53} \cdot P_5$	$R_{54} \cdot P_5$	$R_{55} \cdot P_5$	$R_{56} \cdot P_5$
Absolute priority (%)		S_{PR1}	S_{PR2}	S_{PR3}	S_{PR4}	S_{PR5}	S_{PR6}
Product Requirement Priority (%)		S_{PR1}/S_{PR}	S_{PR2}/S_{PR}	S_{PR3}/S_{PR}	S_{PR4}/S_{PR}	S_{PR5}/S_{PR}	S_{PR6}/S_{PR}

Table A.2.2 L-matrix Scoring Table

	Extremely Strong	**Very Strong**	**Strong**	**Moderate**	**Weak**	**None**
Score	0,503	0,26	0,134	0,068	0,035	0
Symbol	●	◕	◑	◔	○	.
	X	VS	S	M	W	.
	5	4	3	2	1	0

A.2.3 Steps:

- Moving row-by-row only for highlighted cells, *(i.e.,* R_{11}, R_{12} …… R_{1y}; R_{x1} …… R_{xy}*)*, compare the row variable with their column variable
- Ask – *"What is the relationship between row variable and the column variable."*
- Assign the value for the preference as shown from the table A.2.2
- Priority of the product requirements can be found from their respective ***Product Requirement Priority*** cell

A.3 Customer Value Chain Analysis (CVCA)

A.3.1 What is CVCA?

- A tool used to comprehensively identify potential stakeholders, their relationship with each other, and their role in the product's life cycle
- Figure A.3.1 shows an example taken from Donaldson et al. (2006)

A.3.2 When to use CVCA?

- When we need to know how the resources flow between the stakeholders

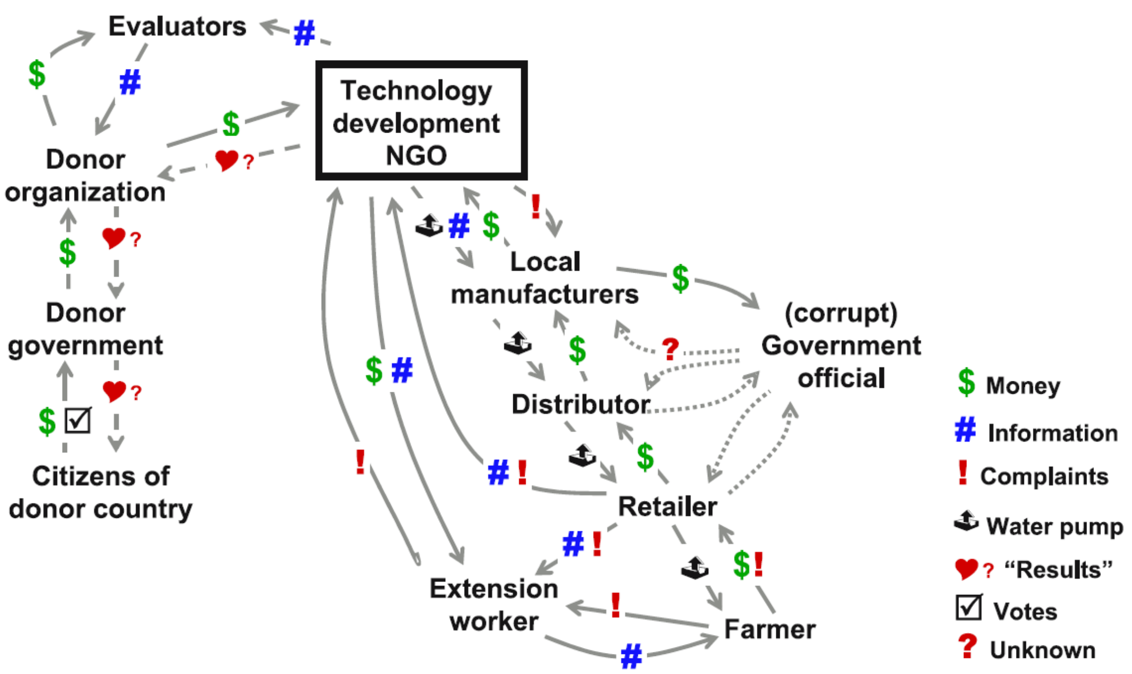


Figure A.3.1 CVCA for a micro-irrigation pump (Donaldson, et al., 2006)

A.3.3 Steps:

- Layout the stakeholders for a particular product/service randomly across the paper and try to input their relations and the

Appendix B: Data used in the QFD

Market segmentation for Contemporary cruise ships

China – (Yang, 2015) (CLIA, 2018a)

- Loves to eat food, especially Asian food
- Spends money buying gizmo, gift and souvenir for family and friends
- Gambles money
- Spends time singing karaoke
- Likes to watch live shows and act
- Prefers to stay indoors and socialize with relatives and friends, in public areas and in cabins
- Being fit has been trending onboard
- Not a fan of sun bathing, but would like some relaxing massages
- Adults generally are not adventurous when compared to kids
- Preferred length of travel itinerary is 4-6 days (47%)
- Preferred destination within Asia (91%)

USA – (CLIA, 2018b)

- Likes to explore different kind of cuisines
- Spends minimal amount of time shopping onboard
- Gambles money
- Preferred choice of entertainment is watch live shows and act
- Being fit onboard is a priority for most individuals
- Loves to sun bathe and relax onboard
- Adrenalin junkies – both adults and kids
- Preferred length of travel itinerary is 6-8 days (51%)
- Preferred destination Latin-America (43%)