MODULE 2

Requirements Development

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Transdisciplinary modules are dedicated to Dr. Raymond T. Yeh and Mr. Bob Block, for their continued support of ATLAS, enthusiasm, dedication, and passion!

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Requirements Development

The most difficult part of requirements gathering is not the act of recording what the user wants, it is the exploratory development activity of helping users figure out what they want.

Steve McConnell

When you are out to describe the truth, leave elegance to the tailor.

Albert Einstein

2.1 Introduction

The requirement is specific documented physical and functional capabilities and attributes that a particular design, product, or process must be able to perform. The process of developing correct requirements is not an easy issue–it is a comprehensive, iterative, and recursive process. It is important to note that the fundamentals of well-defined requirements are clarity, brevity, and simplicity. The elegant and entertaining requirement writing style is not necessary. This is a task that will be accomplished after the concept has been selected. Requirements are used throughout the system development lifecycle activities – from beginning to completion.

2.2 Requirements Development Steps

As shown in Figure 2.1, the following six steps are used for developing requirements:[1]

1. **Develop High-Level Requirements** – before the six steps requirement development starts, as seen from Figure 2.1, customer needs should be defined through the general process shown in Figure 2.2. After operational needs are evaluated and the design concept is completed, the next step is to develop high-level requirements. The customer needs data collection is performed through interviews, surveys, focus groups discussion, secondary data sources, and observation of lectures, seminars, or lab classes. The project's purpose and important details of the project must be understood through customer communication.

[1]Requirements Development Steps. http://acqnotes.com/acqnote/tasks/requirements-development-steps. Accessed January 11, 2020.

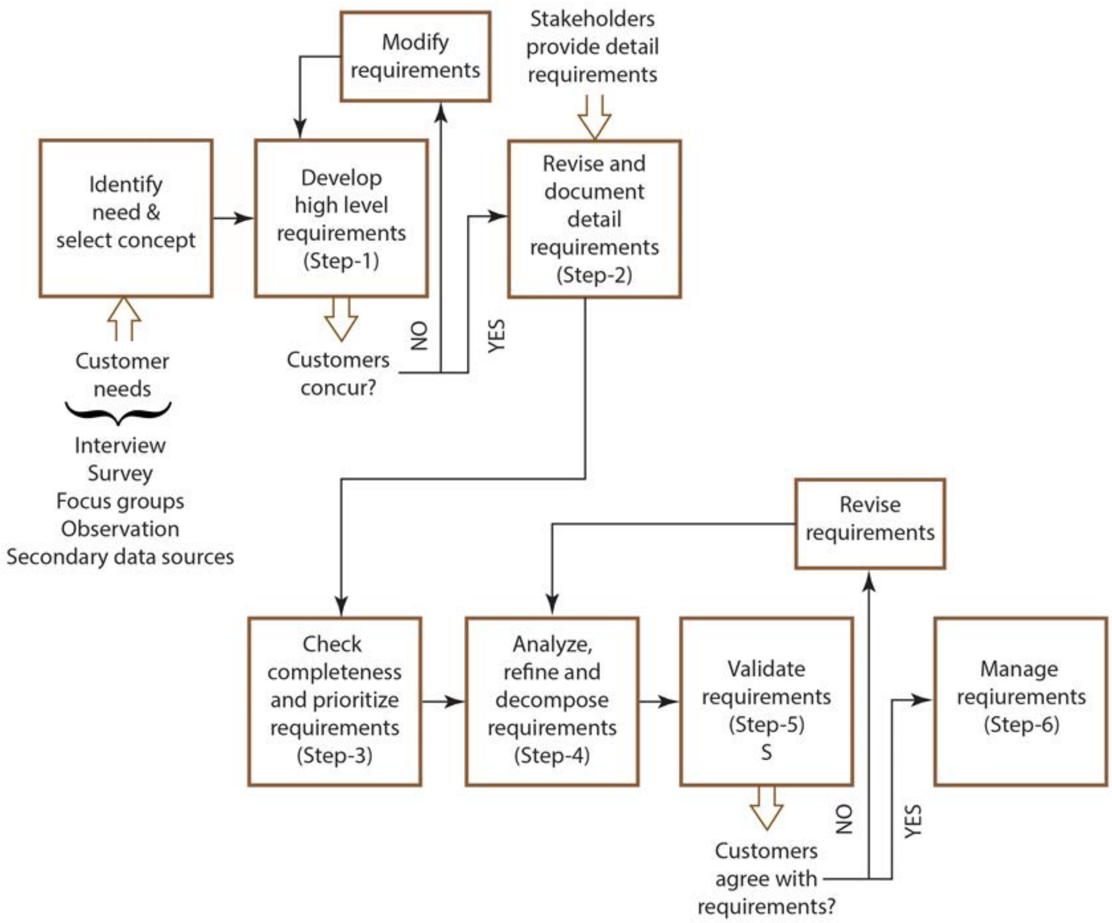

Figure 2.1: Requirements development process.

2. **Revise and Document Detail Requirements** – after all the characteristics (functional, physical, and performance) desired by the customer are defined, detail requirements should be documented. For each characteristic (attributes) constraints should also be determined during this step.
3. **Check Completeness** – the next step is toward developing and checking accurate and complete requirements that capture the essence of a concept.
4. **Analyze, Refine, and Decompose Requirements** – this step assesses each requirement to see if it meets the physical and functional characteristics of the project. Since not all requirements are equally important, they can be arranged hierarchically. Higher-level requirements could be unclear and should be decomposed into a more refined set of sub-requirements. Decomposition of the requirements should be carried out to a *simple* level so that the requirement is *self-evident* at the lowest level. As a general rule, decomposition

should be done from the highest level (most abstract, least concrete) to the lowest (least abstract, most concrete) level.

5. **Validate Requirements** – in this step, each requirement must be verified and validated to ensure that they are consistent, complete, understood, not vague, and reflect the actual needs and expectations of the customers.
6. **Manage Requirements** – in step six, ensure that a common understanding of the requirements exists, the requirements have been approved, and a baseline is recognized by the customer. Any changes to the requirements are tested on a regular basis to determine if the customer will be satisfied with the changes. During this step, some sort of transdisciplinary coordination group needs to be established to discuss the design effort ongoing in each discipline and how the design requirements are being interpreted and applied. This process will force the transdisciplinary coordination to focus on a task that ensures proper subsystem integration and uniform understanding of design requirements.

It is important to have well-defined and well-controlled requirements, but, it is also crucial to minimize requirement changes as the systems are implemented. Changes to the requirements during the design process can have a profound and negative impact on the final quality of the design project. In many high-tech companies, requirement changes may cause long lead times for the design effort. On large-scale complex systems, it is normal to experience requirements problems late in the design process.

2.3 Process of Defining Customer Needs/Requirements

Figure 2.2 shows a generic process of defining customer needs (requirements). Customer needs project (product) characteristics desired or needed by the customer. Just asking the question of what is important to them may not give you enough information to make a decision on the requirements. Customers may deliver you with poor and misleading a lot of unrealistic information because they may struggle to articulate their needs or they may change the project needs over time.

2.3.1 Customer Data Collection and Analysis

The following qualitative and quantitative data collection methodologies can be used to gather data for customers' needs.

2.3.1.1 Interviews

Interviews are a key qualitative data collection method one-on-one between an interviewer and an individual to gather information on a specific set of project topics. Interviews can be conducted in-person, over the phone, or by submitting a proposal.

2.3.1.2 Observation

Observation is s systematic data collection method by observing people in which the researcher does not participate in the communications, for example, observing learning and teaching activ-

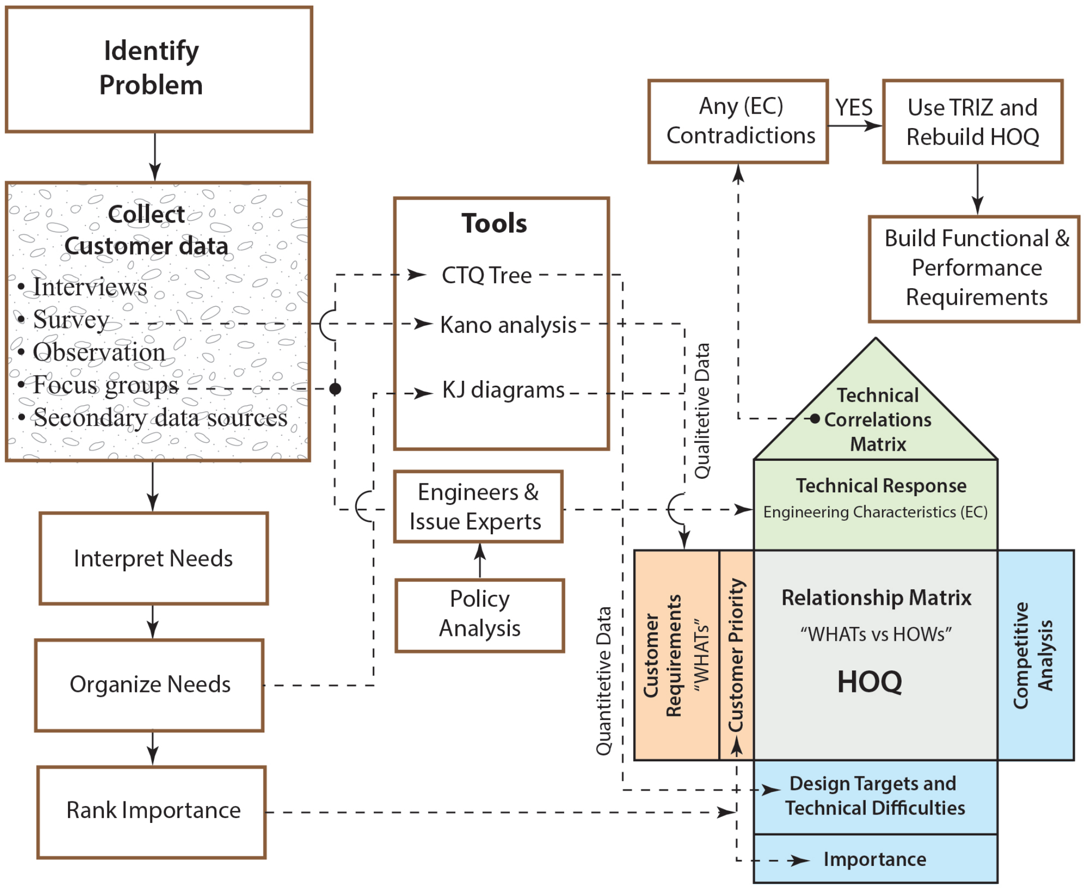

Figure 2.2: Process of defining customer needs/requirements.

ities (lectures, seminars, lab classes).

2.3.1.3 Focus Groups

A *Focus groups* is a qualitative data collection method as opposed to quantitative data collection that involves numerical-based data collection. This is a dynamic group discussion of approximately six to twelve participants engaged to share similar common interests. A moderator leads the group based on a prearranged set of topics.

2.3.1.4 Secondary Data Sources

Secondary data sources are public information in the open literature that are collected by others. It is usually free or low-cost to obtain and can support as a strong foundation to any research project.

2.3.1.5 Surveys

Surveys are important qualitative or quantitative data collection methods that are usually used with customers to discover customer needs. It includes a structured questionnaire that can be administered by paper and pencil, as a Web form, or by an interviewer who follows a strict script.

As shown in Figure 2.3, Griffin et al. handled a survey interviewing 30 customers to find out 220 needs.[2] It is evident from this figure that 15-20 respondents should be enough to get a reasonably good understanding of their customers' needs. Details for surveys will be discussed in the following section.

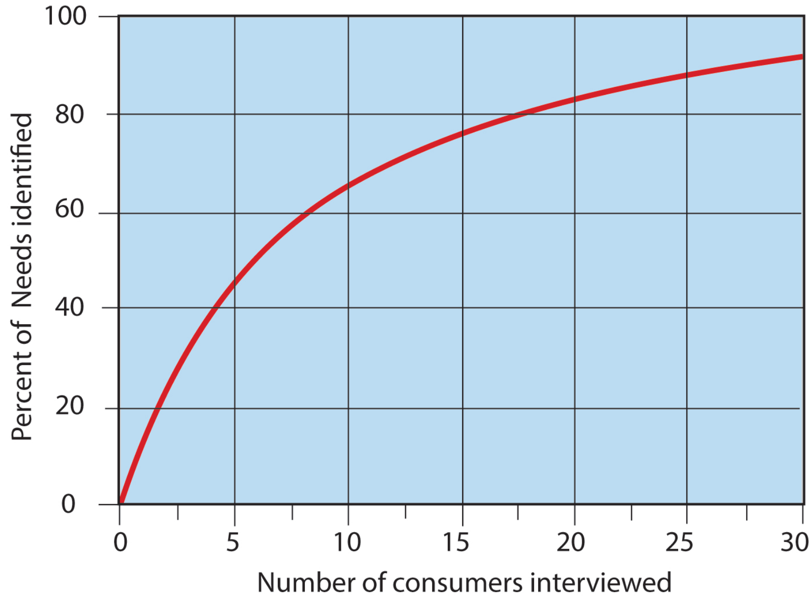

Figure 2.3: Survey result for customer need (Griffin, Abbie and John R. Hauser, 1993).

2.3.2 Kano Model – Understanding Customer Needs

Think about your new startup company design team who is trying to come up with something that no one has ever done before–a new invention. The design team is very excited about this new discovery–the goal is to create the best-selling product of the year. But, the project director has some doubts about the extra features that will increase the cost of the product, thus not maintaining a good profit margin and also keeping up with the competition. The project director wants to create a vision and direction of the product offering over time with the right features. There could be many reasons why the design team might need to include a given feature, but they have to decide in order to know which feature will make their customers happy and prefer it over others? There is no easy answer to this question, but luckily there is a very effective tool to

[2] Griffin, Abbie, and John R. Hauser, 1993. The Voice of the Customer. Marketing Science, Vol 12, No. 1.

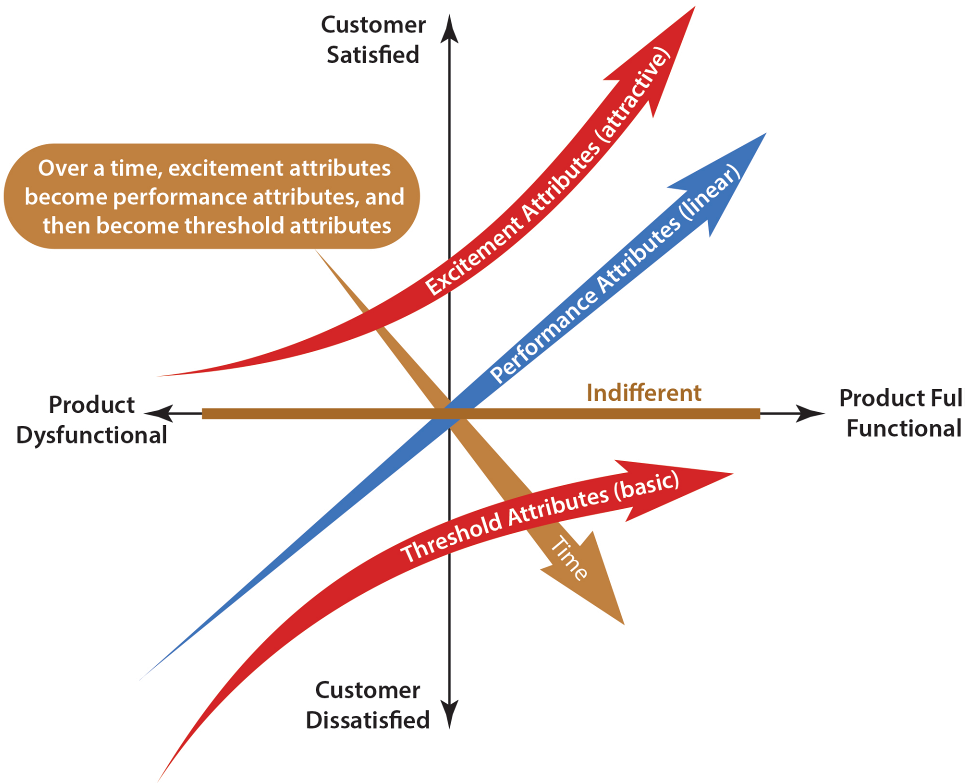

Figure 2.4: Kano model.

guide the design team in deciding which features should be included in the product development: the Kano Model as shown in Figure 2.4.

2.3.2.1 Kano Model: Prioritizing Customer Satisfaction

The *Kano Model* is a method for product development and customer satisfaction that was proposed in the 1980s by Professor Noriaki Kano. As shown in Figure 2.4, the Kano Model considers three types of product/service attributes:

1. **Threshold Attributes (Basic Requirements)**.

   These are necessary product/service attributes that are expected by the customers. A competitive product must meet basic attributes. For example, when you book into a hotel you would expect a shower with hot water as a minimum feature – no hot water makes customers unhappy.

2. **Performance Attributes (Linear Requirements)**. These attributes are not absolutely necessary, but they improve customer satisfaction. For example, you would be happy to have a free internet connection, when you would normally expect to pay.

3. **Excitement Attributes (Attractive Requirements)**. These are the unexpected attributes (delighted) of a product or service that can result in high levels of customer satisfaction. They are the features that customers are not aware of, but are delighted with when they see them. For example, in your hotel room when you notice a delicious selection of goodies and wonderful relaxing a glass of wine to enjoy during your stay when you wouldn't normally expect to see such a welcome gift.

As seen from Figure 2.4, if a product's features don't meet a customer's threshold attributes, it will cause extreme customer dissatisfaction. However, even if you fully deliver on these features, it will not excite customers so much. Note that, over time, excitement attributes become performance attributes, and then become threshold attributes (see Figure 2.4). For example, an iPhone touchscreen that caused such admiration back in 2007 and is now just an expectation when purchasing a phone – the steady advancement of technology and emergence of competitors cause this decay in delight.

Most products compete on performance attributes, where a customer compares one product against another and makes a decision on satisfaction by the presence of different features. For example, a family with five children would be willing to pay more for a minivan that provides them comfort with better fuel economy. Reverse features may cause dissatisfaction to some customers. For example, providing fully automated high-tech cars with many features may cause dissatisfaction. Some customers prefer the basic model of a car without having too many extra features. if these features are present, customers' dissatisfaction will grow and they will actively reject these futures. The summary of the Kano model to help design teams to classify customer needs and attributes into a five-step guide is shown in Table 2.1.[3]

Table 2.1: Classification of customer needs and attributes.

Requirement Type	**Definition**
Must be (threshold attributes)	These are the basic (must be) features of a product or service – customers expect these requirements that are fulfilled.
One-Dimensional/Linear (performance quality)	These qualities are not absolutely necessary, but they increase a customer's satisfaction.
Excited attractive quality	These are the surprise qualities of a product or service. If these qualities are absent, it does not cause customer dissatisfaction.
Indifferent quality	Customers don't care if these features are provided or not provided.
Reverse quality	Providing more features may cause dissatisfaction.

[3]Ertas, A. *Transdisciplinary Engineering Design Process*, John Wiley & Sons Inc., 2018.

2.3.2.2 Kano Model Analysis

A rather easy approach to apply the Kano Model analysis is to develop a set of survey questionnaires. In order to eliminate inconsistency each set of questions will have a positive statement/question and a negative statement/question about each requirement. Then the questionnaire is sent to a group of prospective customers. As shown in Table 2.2, the question can be phrased in two ways and then can be allowed for multiple choice answers to the question.

Table 2.2: Example of Kano questionnaire.

If gym memberships & fitness programs is free, how do you feel? (positive question)	(a) I like it (b) It must be that way (c) I am neutral (d) I can live with it (e) I dislike it
If gym memberships & fitness programs is not free, how do you feel? (negative question)	(a) I like it (b) It must be that way (c) I am neutral (d) I can live with it (e) I dislike it

Customer Response (Requirement)		Negative Question (dysfunctional)				
		(a) I like it	(b) must be	(c) neutral	(d) live with	(e) dislike it
Positive Question (functional)	(a) I like it	Q	E	E	E	L
	(b) It must be that way	R	I	I	I	M
	(c) I am neutral	R	I	I	I	M
	(d) I can live with it	R	I	I	I	M
	(e) I dislike it	R	R	R	R	Q

M = Must be; R = Reverse (can be either way); L= Linear (one-dimensional); Q = Questionable (incorrect answer); E= Exciter (attractive); I = Indifference (no preference)

Figure 2.5: Kano model questionnaire evaluation.

2.3.2.3 Evaluating Kano Questionnaire

To translate the survey results, the category of each attribute can be classified through Kano's paired functional/dysfunctional questionnaire as shown in Figure 2.5. As indicated in this figure, the rows of the Kano matrix correspond to the answers to the functional question, the columns correspond to the answers to the dysfunctional question. As an example, suppose a customer likes free gym membership and fitness program (see Table 2.2), he/she would likely give an

Table 2.3: Results of Kano Analysis for 45 responses.

Gym Features	Exciter	Linear	Must be	Indifferent	Reserve	Questionable
Acceptable price range	1	29	11	3	1	0
Variety of exercise equipment	4	17	21	1	1	1
Pleasant Personal Trainers	5	15	21	2	1	1
Pleasant atmosphere	22	8	7	6	1	1

answer (a) to the positive question and (e) to the negative question. Following the evaluation matrix given in Figure 2.5, this option will fall into "Linear" attribute 'L'.

2.3.2.4 Kano Analysis of Results

Let's consider a gym with features evaluated by customers shown in Table 2.3. A questionnaire should be sent to enough customers to have realistic results that represent the majority of customers' requirements. Let's assume that we have 45 customers. After the survey results through the Kano evaluation chart shown in Figure 2.5 is completed. The next stage of the analysis is assigning a letter score to every attribute as shown in Table 2.3.

In this example, the main aim is to identify and evaluate the attributes of *gym* service which affect its quality from the point of view of customers. More than %60 of the customers required performance future (linear): customers' satisfaction increased proportionally when they see the acceptable price range. The following are identified among the "must be" category: offering a variety of exercise equipment as well as pleasant personal trainers. Poor quality of exercise equipment results in a customer's dissatisfaction and eventually loss of business. As shown in this table, almost %50 of the customers are excited when they see a clean and pleasant atmosphere: this is a feature that customers didn't expect.

The results of the analysis should show us which features are considered important by the customers and how the implementation of those features affects the customers' satisfaction. This allows the designers to prioritize the accepted feature list of products/services during the product/service development. Note that "must-be" and "performance" features should be implemented at as high of a rating as possible. Designers should reserve a room for delighters during the product development process: attractive attributes give the competitive advantage that allows a company to outperform compared with competitors. Because most customers simply don't care about whether indifferent features are present or absent, it will not affect their satisfaction. Therefore, indifferent features can be carefully evaluated or avoided because they are essentially money sinks. The reverse or questionable results would need to be further analyzed in order to properly determine their place or they should be excluded from further considerations.

The Kano model is a tool that can be used for KJ-Method to organize data collected from customers and prioritize the Critical to Quality (CTQ) characteristics.

2.3.3 KJ Method

The KJ-Method, named after its inventor Kawakita Jiro, is a useful tool used to organize data and ideas. KJ method allows the research team to reach a quick and effective way to get team consensus on priorities of qualitative data collected from customers and develop a set of customer requirements. The following simple steps can be used for the KJ analysis:[3]

- Collect all ideas without considering their reasons
- Cluster (group) the ideas that seem to be related
- Develop hierarchies of groups and subgroups

2.3.4 Critical to Quality Characteristics

Once the customer needs are recognized, an effort can be made to translate them into quantitative terms known as Critical to Quality (CTQ) characteristics. CTQs are the key measurable characteristics of a product or process that help a company to translate the most important needs of products/services into requirements to ensure their quality. These requirements include the upper and lower specification limits or any other factors related to the product/service defined by the customer. In general, a CTQ is translated from a qualitative customer statement to a quantitative product specification. Below are some examples of the translation that needs to be made in order to define quantitative product specifications. Let's consider the CTQ of a minivan.

- Customer requirement – an SUV with good fuel mileage.

  CTQ – a quantitative specification could be 27 miles per gallon.
- Customer requirement – a fast acceleration.

  CTQ – a quantitative specification could be 3.7 seconds from 0 to 60 mph.
- Customer requirement – an acceptable price range.

  CTQ – a quantitative specification could be more priceless than $40K.
- Customer requirement – powered by the strong engine.

  CTQ – a quantitative specification could be: the engine has 300 hp.
- Customer requirement – safety.

  CTQ – a quantitative specification could be a 5-star National Highway Traffic Safety Administration (NHTSA) safety rating.

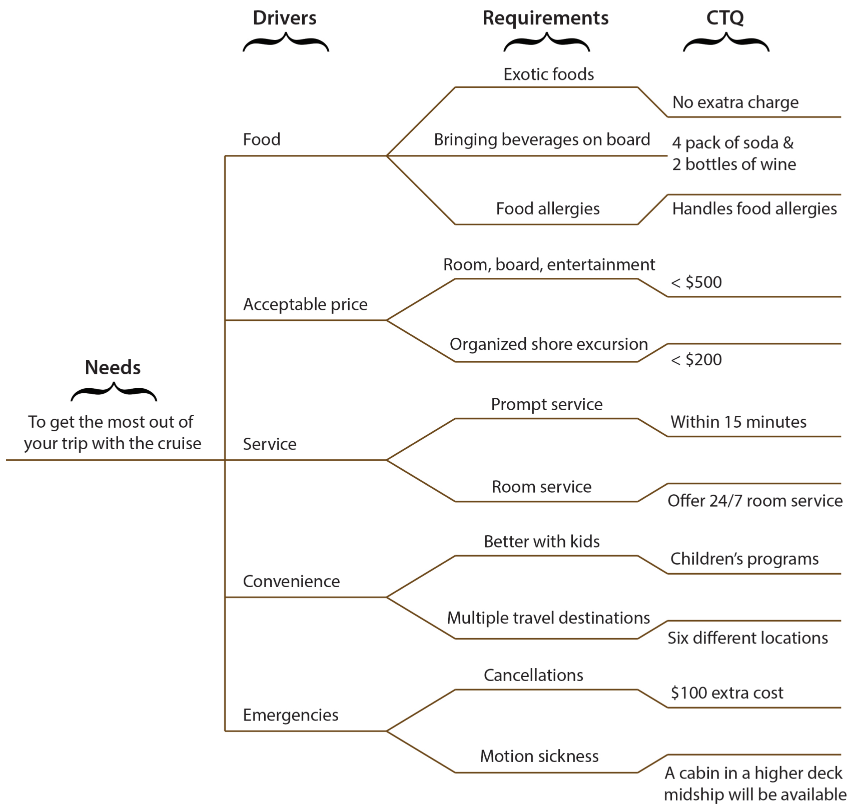

Figure 2.6: CTQ tree.

2.3.4.1 Critical to Quality Characteristics Tree

The next step is for the project team to brainstorm customer requirements with the people who investigated the customer needs to identify the specific features (*drivers*) that have to be decided to meet the needs that were identified: the minimum performance requirements that are to be satisfied for each driver. A CTQ tree is a form of a simple effective diagram that helps design teams identify and list what the customer really wants and helps the designers to ensure that customers get what they want. Now, consider the CTQ tree to get the most out of your trip with the cruise. Although most people can identify dozens of things they love about cruising, as shown in Figure 2.6, in this example, we have included some main drivers of cruise travel that will appeal to almost everyone: food, acceptable price, service, convenience, and emergencies.

For this example, the following are some of the simple questions you'll want to ask before booking a cruise: How cruise line handles food allergies and emergencies? When is the best time to sign up for a shore excursion? How do we prevent getting motion sickness? How big is the cruise ship? How many passengers can it hold? Is the cruise line reputable? and more. CTQ tree consists of four elements as shown in Figure 2.6: need, drivers, requirements, and convert requirements into CTQs.

EXAMPLE 2.1

Process of defining customer needs for a finger rehab device: Stroke is one of the reasons that can cause fingers to malfunction or patients that break or suffer ligament damage to their joints, particularly in the index finger, need rehabilitation for recovery. There is a need to design and develop a home-based finger rehabilitation device to support the rehabilitation process. Consider redesigning a new finger rehab device that would rehabilitate the proper motion in the finger in a safe and passive way.

BACKGROUND

To design a new finger rehab device (see Figure 2.7), the following positive and negative survey questions were sent to a group of customers to define their needs. The survey questions were as follows:[a]

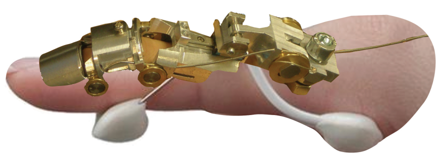

Figure 2.7: Finger rehab device.

Positive Questions (functional):

1. How would you feel if the rehabilitation device function (flexion & extension) is automated?
2. How would you feel if the rehabilitation device is designed for patient comfort?
3. How would you feel if the rehabilitation device is lightweight?
4. How would you feel about the rehabilitation device's low cost?
5. How do you feel about the rehabilitation device is controlled by an app?
6. How do you feel about the battery being rechargeable?
7. How do you feel about the rehabilitation device with concealed wires?
8. How do you feel about the rehabilitation device is portable/robust?

9 How do you feel if the product prevents swelling?

10. How do you feel if the device has continuous passive motion?

11 How do you feel if the device meets the medical device regulations.

12 How do you feel if the device supports user activity.

EXAMPLE 2.1 (continued)

Negative Questions (dysfunctional):

1. How would you feel if the rehabilitation device (flexion & extension) is not automated?
2. How would you feel if the rehabilitation device is not designed for patient comfort?
3. How would you feel if the rehabilitation device is not lightweight?
4. How would you feel about the rehabilitation device is not low cost?
5. How do you feel about the rehabilitation device is not controlled by an app?
6. How do you feel about the battery not being rechargeable?
7. How do you feel if the rehabilitation device has exposed wires?
8. How do you feel about the rehabilitation device is not portable/robust?
9. How do you feel if the rehabilitation device doesn't prevent swelling?
10. How do you feel if the device doesn't have continuous passive motion.
11. How do you feel if the device doesn't meet the medical device regulations.
12. How do you feel if the device doesn't support user activity.

KANO ANALYSIS

The survey was sent to approximately 40 people and 30 responses were received. Raw data from customer responses were analyzed and customers' need statements were extracted from each response. Using survey results and Figure 2.5, each positive question was compared against each negative question for every respondent to determine the appropriate letters shown in Table 2.4.

Table 2.4: Kano analysis results for 30 responses.

Features ↓	**E**	**L**	**M**	**I**	**R**	**Q**
Automated	10	6	7	3	0	4
Comfort	14	8	4	3	0	1
Light weight	9	9	9	0	0	0
Low cost	4	10	8	4	0	4
Device controlled by an app	13	5	5	4	0	3
Device with rechargeable battery	5	10	9	4	0	2
Device with concealed wires	6	6	14	2	1	1
Portable/robust	5	12	6	4	0	3
Device prevents swelling	6	6	14	2	0	2
Device has continuous passive motion	4	9	10	4	0	3
Meets regulations	2	9	12	4	0	3
Support user activity	4	8	11	4	0	3

EXAMPLE 2.1 (continued)

From the Kano analysis results, we can define the most important design categories to include in the final customer needs and engineering characteristics (requirements). To develop a set of customer requirements, qualitative data collected from customers is used to build the KJ diagram shown in Figure 2.8.

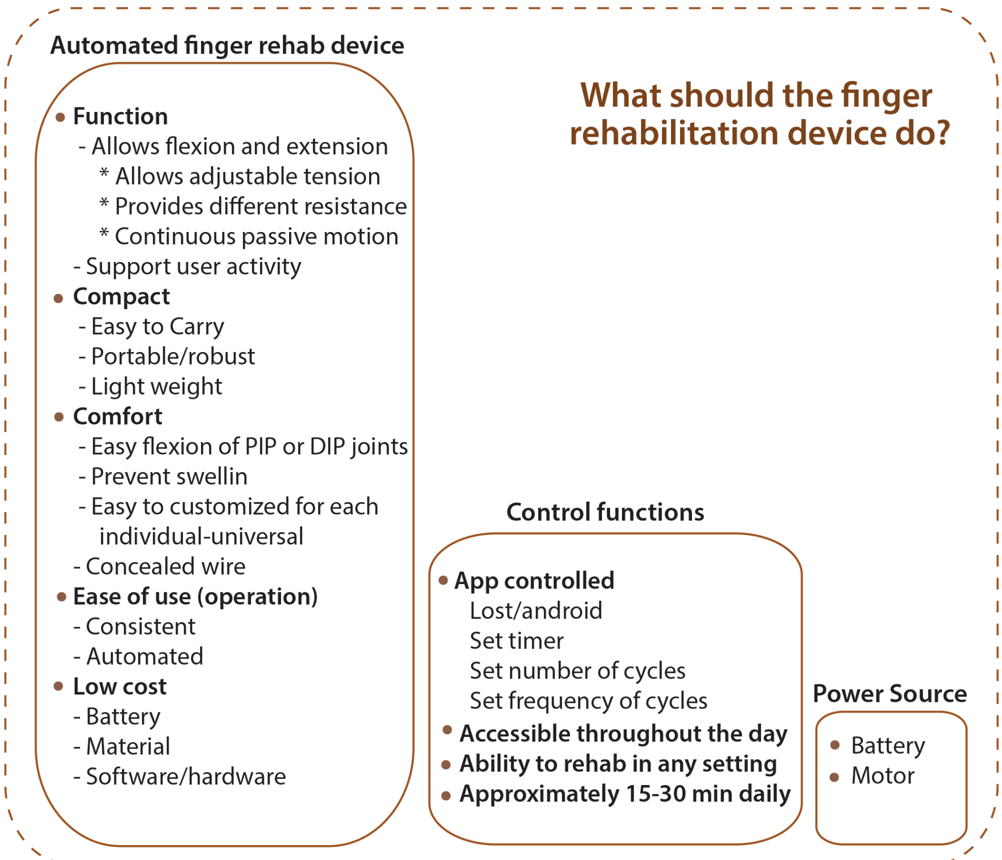

Figure 2.8: KJ diagram of finger rehabilitation device.

After forming the KJ diagram, customer data can easily be translated into quantitative terms to develop the CTQ tree, shown in Figure 2.9. In Figure 2.9, the driving design categories are expanded more in a rehab device CTQ tree to allow a more specific idea of what is needed for the design requirements to be developed.

[a] This example problem was adapted from the design class project. Raymon Garza Isaiah Marquez, Abdul Hamed, Alejandro Procel, Jesus Rongel, Yeung Hun Choi, (May 2020). "Automated Rehab Finger."

EXAMPLE 2.1 (continued)

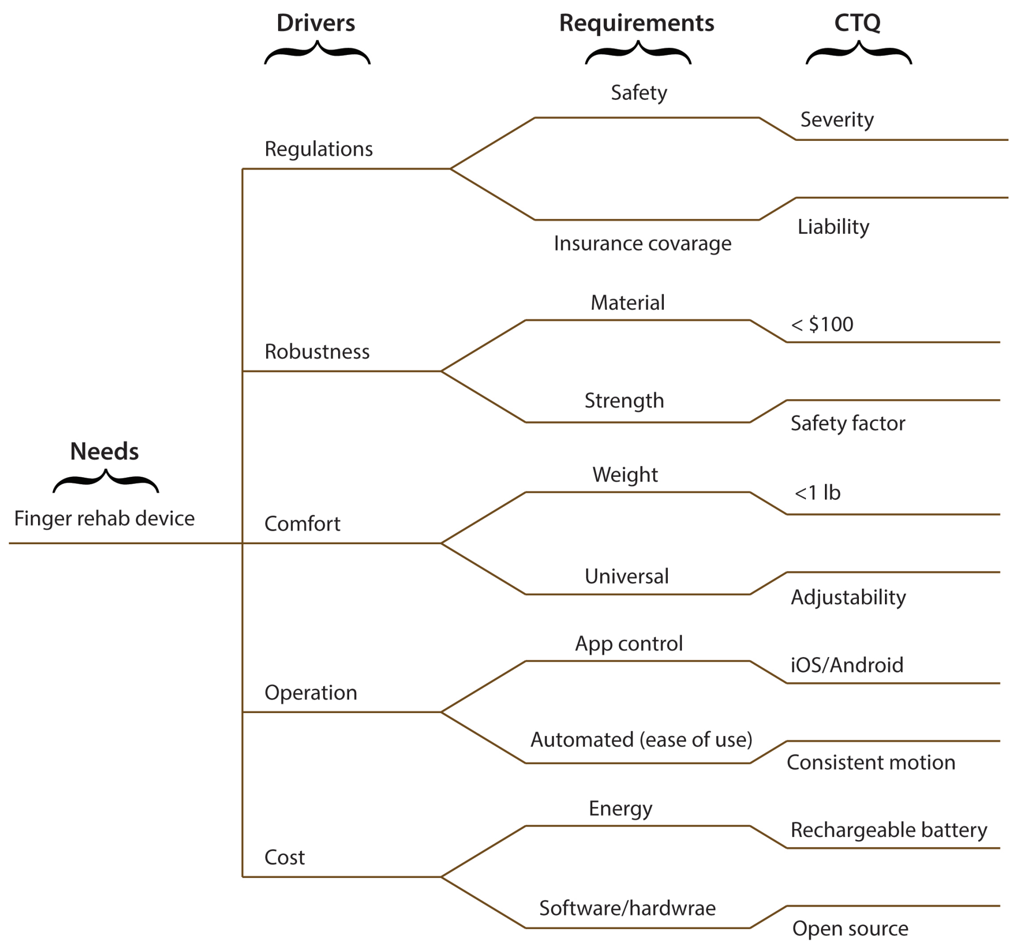

Figure 2.9: CTQ tree for finger rehabilitation device.

2.4 Quality Function Deployment: Requirement Prioritization Method

Quality Function Deployment (QFD) was developed in Japan in the early 1970s and has been effectively used in the United States since the 1980s. QFD is a planning process and management approach for product and service development to reflect the voice of the customer – to weigh or prioritize customer requirements and correlate customer desires (WHATs) to system features

(HOWs). It is a method for identifying customer needs and making sure that the voice of the customer is included in a design process for product/service development. QFD provides a systematic design process that allows an enterprise to go beyond CTQ characteristics.

The five stages of the QFD chart are shown in Figure 2.10. The steps for documenting information in this chart is as follows:

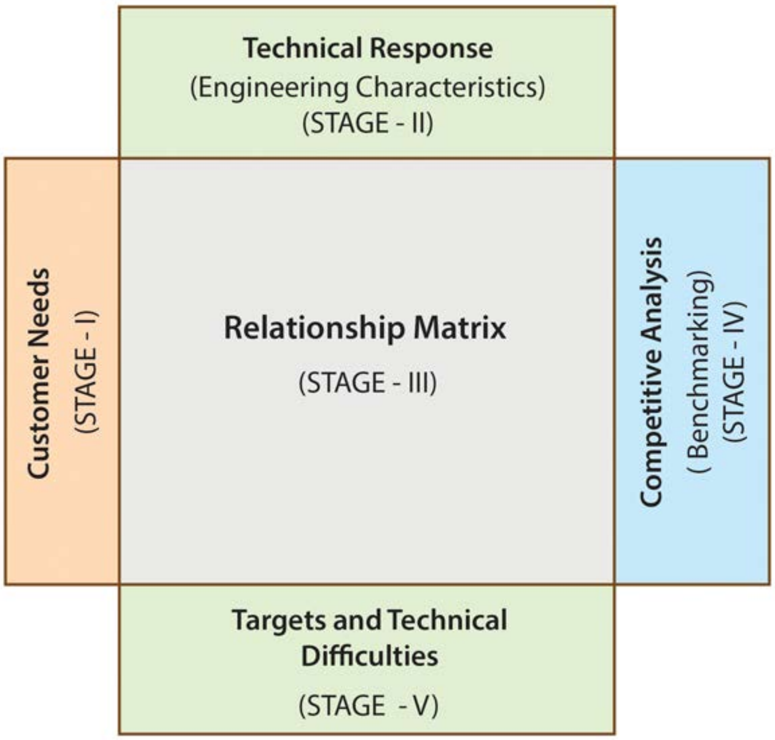

Figure 2.10: QFD matrix.

- *Stage 1*: includes customer needs. Customer needs are product characteristics desired or needed by the customer. However, understanding poor and incomplete information on customer needs is not an easy task. Five important concerns to understanding customer needs are:

  1. Customer may have unknown needs that they don't even know they have,
  2. Customers may have a hard time expressing their needs,
  3. Customers' needs may change in time,
  4. Customers may not realize what they want until they see it, and
  5. It is difficult to know all of the customers' needs.

  Note that, after filtering and translating customer needs into engineering terms, customer needs become customer requirements. The practice of collecting the voice of customers and converting them into engineering characteristics is an important initial part of the project execution.

- *Stage 2*: includes the list of engineering characteristics. The customer's subjective and non-technical requirements are translated into measurable engineering language. These requirements are developed by design engineers to satisfy the customer's needs.

  The customer needs to tell us what to do and the engineering characteristics tell us how to do what customers want.

- *Stage 3*: involves developing matrix relationships between engineering design characteristics and customer needs. This relationship matrix is used to verify and improve the dependability of the translation of customer needs into measurable engineering characteristics. By ranking the relationship between customer needs and engineering characteristics as strong, medium, or weak, the requirements are identified in quantifiable terms.

- *Stage 4*: the product design is compared with competitors' products through what is referred to as competition benchmarking. Other product design attributes are compared with the list of customer needs to identify the best optimal design solution. The process of benchmarking provides the following benefits[4]:

  1. eliminating the trial and error process,
  2. stimulation the improvements process,
  3. improving the efficiency of the company in developing innovative ideas.

  It is important to note that the selected benchmarking products should have similar functions and applications to be comparable. Benchmarking can be scaled between 1 and 5, with 1 being not satisfied and 5 being completely satisfied.

- *Stage 5*: In this stage, the technical difficulty of each engineering design characteristic is scaled between 1 and 5, with 1 being easy and 5 being most difficult to achieve. Also, target values of each engineering characteristic are set.

[4]C. E. Bogan and M. J. English, (1994).*Benchmarking for best practices: winning through innovative adaptation,* vol. 1. McGraw-Hill New York.

EXAMPLE 2.2

Using Kano analysis results, KJ (given in Figure 2.8), and CTQ diagram (given in Figure 2.9), develop Quality Function Deployment for the finger rehab device.

The purpose of the Kano, KJ, and CTQ analysis is to help construct and define engineering characteristics to better achieve customer needs. Using the results of Kano, KJ, and CTQ, the student research team developed the following customer needs.

Universal: The design of the finger rehab device will be usable by all people, to the greatest extent possible.

Portable: The next customer need is " the device must be portable" - lightweight, compact, and small enough to fit on a finger.

Automated: Automation is an important aspect of this design. The purpose of designing an automated device is to mobilize the finger in a safe and repetitive way so that users achieve their highest level of recovery.

Controlled by app: One of the most unique features of this design is providing users with a programmed mobile application that allows users to control the device to their convenience. The application will provide users with a variety of options to better control the motion of the finger. These features include speed, deflection, timing, and sensitivity.

Concealed Wires: As opposed to the previously described requirements, customers were not satisfied with having exposed wires.

Rechargeable Battery: A rechargeable battery will provide a variety of benefits to users which include convenience, battery efficiency, performance, earth-friendly, and money-saving.

Inexpensive: Customers would like to have a good quality product at an affordable price. Cost is one of the driving factors for this product.

Light weight: Customers would like to have a device with lightweight.

Figure 2.11 shows simplified eight customer requirements developed by the design team used for the Quality Function Deployment to provide a structured way of designing quality into the finger rehab device while establishing engineering characteristics – thus integrating the voice of the customer into the design process.

EXAMPLE 2.2 (continued)

Ranking Key		
Strong Relationship	⦿	9
Medium Relationship	○	3
Weak Relationship	△	1

Customer Requirements (What?)	Minimum cost	Weight	Strength	Support user activity	Reliability	Power & energy	Flexion & extension	Customer Score	Proposed Product	Competitor 1	Competitor 2
	Engineering Characteristics (EC) (How?)								**Benchmarks (1-low, 5 high)**		
Universal	⦿	○					△	13	3	1	2
Portable	△	⦿	○			△	○	17	5	2	4
Automated	⦿	△		⦿	⦿	⦿	○	40	5	4	3
Controlled by app	⦿			⦿				18	5	3	4
Concealed wires		△			△			2	5	4	4
Rechargeable battery	○				○	⦿		15	5	5	5
Inexpensive	⦿	⦿	○	○	○	△	△	29	5	4	3
Light weight	○	⦿	○		○	△	△	20	4	3	3
(EC) Score	43	32	9	21	19	21	9				
Unit	$	lb	psi		%						
Target Value	<90	<1	400		99%						
Technical Difficulty (1-Easy, 5-Most Difficult)	3	3	4	4	4	2	3				
	Product Targets and Benchmarks										

Figure 2.11: Quality Function Deployment (QFD).

As shown in Figure 2.11, the customer's requirements are listed as the row of the matrix, and the engineering characteristics are listed as the columns of the matrix. Engineering characteristics are what you control, performance criteria are what your customer cares about. A 'target value" refers to the planned value for an "engineering characteristic" in the final design that you have certain control over. For example, weight, size, shape, speed, cost, etc. Engineering characteristics may have an effect on certain performance criteria – for example, the engineering characteristics of the weight of a system may have an effect on the performance criteria of cost. By grading the relationships as strong, medium, and weak between the customer's requirements and engineering characteristics we identify those areas in need of improvement and focus. If the relation cells are blank, that indicates there is no correlation between customer requirements and engineering characteristics.

EXAMPLE 2.2 (continued)

As shown in Figure 2.11, automation (40), inexpensive (29), and lightweight (20) scored the highest for the customer's requirement. Minimum cost (49) and weight (32) scored the highest for the engineering characteristics. For customer satisfaction, design effort will focus on improvement in those areas that were scored high. It is clear that the cost of the finger rehab device production is the driving factor for this product to survive in the market.

To understand the market position of the finger rehab device, benchmarks for each competitor's values are also shown in Figure 2.11. The degree to which competitors satisfy the requirements was evaluated by rating them on a 3-point scale. Finally, the target value of each engineering characteristic is defined and target difficulties are shown in the figure. Each engineering characteristic was evaluated for satisfaction criteria. If the criteria could be measured, a unit of measure was defined and a target value specified. For example, the target cost of production was determined to be less than $90.

From this QFD analysis, designers can make a decision on the critical areas and potential failure points for the final product design.

Bridging customer needs, engineering characteristics, and design requirements is an important step to develop design requirements. Normally, we collect our customer needs first, then filter and translate those into engineering terms as long as we are getting those needs from actual users. Then, we carefully decide on engineering characteristics to meet the customer requirements. This will provide us to develop a QFD to understand how customer requirements and engineering characteristics are correlated. These customer requirements and engineering characteristics become parts of the design requirements for the product (see Figure 2.12).

Customer Requirements (What?)	Engineering Characteristics (EC) (How?): Minimum cost	Weight	Strength	Support user activity	Reliability	Power & energy	Flexion & extension
Universal	⊙	○					△
Portable	△	⊙	○			△	○
Automated	⊙	△		⊙	⊙	⊙	○
Controlled by app	⊙			⊙			
Concealed wires		△			△		
Rechargeable battery	○				○	⊙	
Inexpensive	⊙	⊙	○	○	○	△	△
Light weight	○	⊙	○		○	△	△

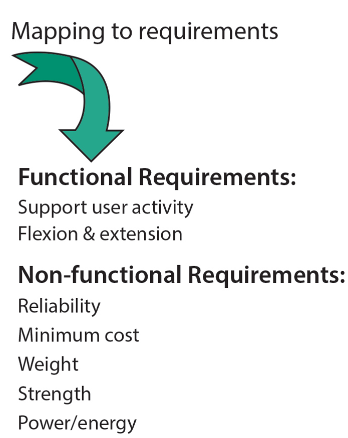

Figure 2.12: Mapping to requirements.

2.4.1 Design Requirement Categories

There are three main requirement categories.

a) **Functional/Non-functional Requirements.** A functional requirement (FR) describes ***"what"*** the system/product must do without describing them in quantitative terms. For example, "the finger rehab device shall be capable of flexing and extending the hand fingers, repetitively." Non-functional requirements (NFR) serve as constraints or restrictions on the design of a system. For example, security, reliability, maintainability, weight, strength, etc.

b) **Performance Requirements.**

Performance requirements describe ***"how well"*** the system/product must perform certain functions under specific conditions. They are quantitative requirements and are verifiable. For example, "the finger rehab device shall be capable of exerting 3-axis forces at each fingertip with output force ranges up to 3.5 N, having 0.5 second response time during each cycle, in order to open the fingers." As seen from this example, there is more than one performance requirement associated with a single functional requirement.

c) **Design Constraints.** Constraints determine the performance limits of the system/product such as acceptable range of frequency, temperature range, operation range, weight, size, etc. – what is expected of the product. For example, "the finger rehab device weight shall not exceed 0.5 lb". Categories of some examples of constraints are shown in Table 2.5.

Table 2.5: Categories of some examples of constraints.

Technical	**Social**	**Environmental**	**Economical**
Physical	Legal/Ethical	Ecological	Ergonomic design
Functional/performance	Political	Operational	Cybernetic design
Laws and regulations	Health	Regulations	Microeconomic factors
Standards and guidelines	Security	Storage	Affordability constraints
Policies and procedures	Public and & international laws	Reuse and reusability	Budget
Codes	Safety		

2.4.1.1 How to Write Good Requirement

As mentioned before, writing good requirements is not an easy task.

As mentioned by Albert Einstein, *"When you are out to describe the truth, leave elegance to the tailor."* This quote tells us that an elegant and entertaining requirement writing style is not necessary – don't use buzzwords.

Followings are the summary of essential points to write a good requirements:[3]

- Define requirements as clear as possible – uncertainty leads to confusion and unhappiness.
- Define one requirement one at a time - each requirement should be short. To avoid confusion try not to use conjunctions like and, or, also, with, and the like.
- If extensive conjunctions are necessary for clarity, the sentence should be decomposed to a shorter sentence.
- Each requirement should have a complete sentence with no buzzwords or acronyms.
- Don't use vague and unverifiable terms. For example user-friendly, versatile, robust, approximately, minimal impact, easy, sufficient, flexible, adequate, fast, large, small, etc. This will cause difficulties to define their test cases.
- Each statement that defines a requirement must contain the word "SHALL". Use positive statements such as "the system shall...", instead of "the system shall not..."
  - Examples using correct terms:
    * The finger rehab device shall be capable of exerting 3-axis forces at each fingertip with output force ranges up to 3.5 N.
    * The buildings shall withstand wind loads of 150 mph.
    * The scooter shall have a maximum speed of 10 mph.
- "Will" should be used only for statements that provide information, and "Should" be used to represent a goal to be achieved.
- Requirements must be realistic and allow acceptable solutions (what not how). Requirements should state WHAT is needed, not HOW to provide it.
- Requirements must be quantifiable, testable, and verifiable.
- Do not use "To Be Determined" (TBD) and "To Be Resolved" (TBR). Use the current best estimate within brackets [value] in the requirement and state your basis for why the value is still an estimate.
- State tolerances for qualitative values. For example, less than; greater than or equal to; plus or minus; root mean squares.

2.4.1.2 Check Requirements Reliability & Correctness

- Is each requirement correct and as clear as possible?
- Are the requirements technically feasible and realistic?
- Are the requirements measurable, testable, and verifiable?
- Are the reliability requirements specified?

Rationale statements are useful for reducing ambiguity in the requirements documents. It is an additional statement to simplify and support design requirements. For example, consider NASA's ISS Crew Transportation and Services Requirement Document. 3.8.5.1.5 Operable by Single Crewmember. The spacecraft shall be operable by a single crew member for operations that require crew control [R.CTS.135].

Rationale: "...The vehicle must be designed so that mission events can be completed by a single crew member. In addition, vehicle design for single crew member operations drives operations simplicity and contributes to operations affordability. This requirement results from lessons learned from the Shuttle cockpit, which had critical switches that are out of the operator's reach zone and software that requires more than one crew member to perform a nominal operation..."[5]

2.4.1.3 Requirement Decomposition

Requirement decomposition is a complex system engineering task. When developing large systems, it is important that the requirement decomposition process is performed. Because not all requirements of the system are equally important they can be arranged hierarchically. Higher-level requirements may be abstract and should be decomposed into a number of sub-requirements. Figure 2.13 shows a requirement decomposition of a new start-up company.

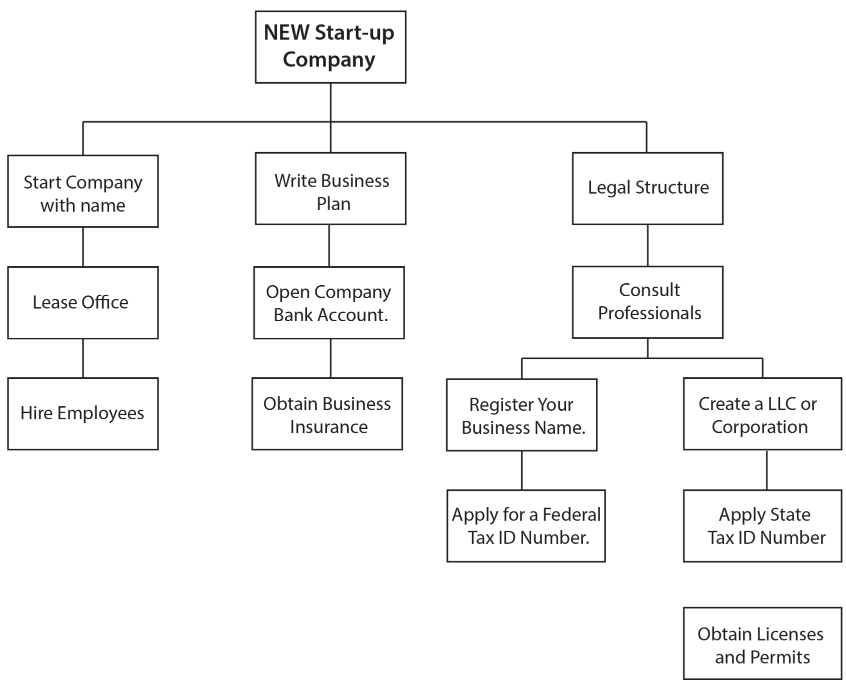

Figure 2.13: Requirement decomposition of a new start-up company.

[5]Source: https://qracorp.com/write-clear-requirements-document/

2.4.2 House of Quality

Afterward, Toyota improved the QFD and introduced the House of Quality (HOQ). The house of quality is a transdisciplinary design tool that has been used successfully by Japanese manufacturers of consumer electronics, home appliances, clothing, integrated circuits, synthetic rubber, construction equipment, and agricultural engines, etc.

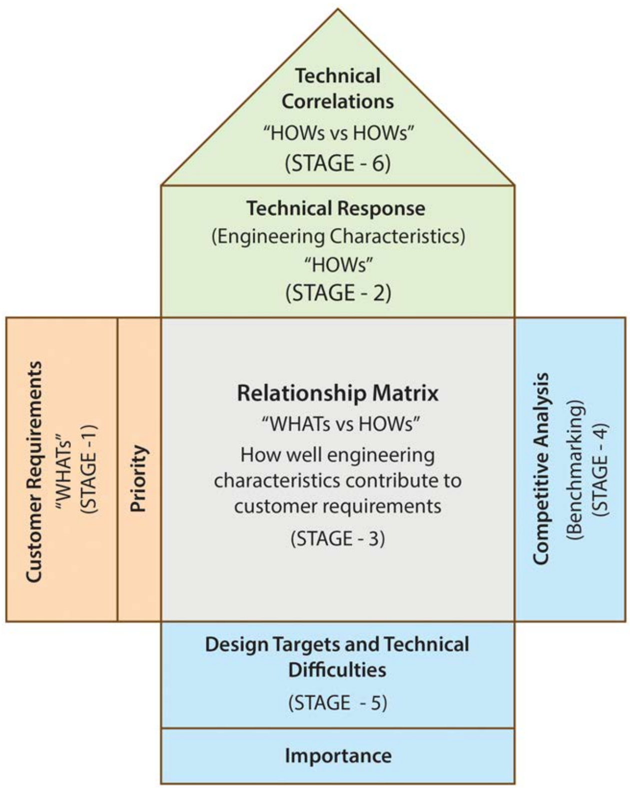

Figure 2.14: *textnormalHouse of Quality (HOQ).*

As shown in Figure 2.14, the HOQ matrix has the shape of a house with a *correlation matrix* as its roof – Like the QFD, it uses a relationship matrix to relate what the customer wants to how a production company is going to meet those wants. There are several advantages of HOQ: (a) reduces the time involved for planning, (b) reduces design changes, (c) improves quality, (d) reduces design and manufacture costs, (e) reduces time to market, (f) helps in prioritizing different design parameters, (g) improves customer satisfaction.

The finger rehab HOQ example shown in Figure 2.15 gives a straightforward overview of the intended use of a HOQ.

EXAMPLE 2.2

HOQ example for the finger rehab device.

Design team prepared an orthogonal array (House of Quality) for the finger rehab device design as shown in Figure 2.15.

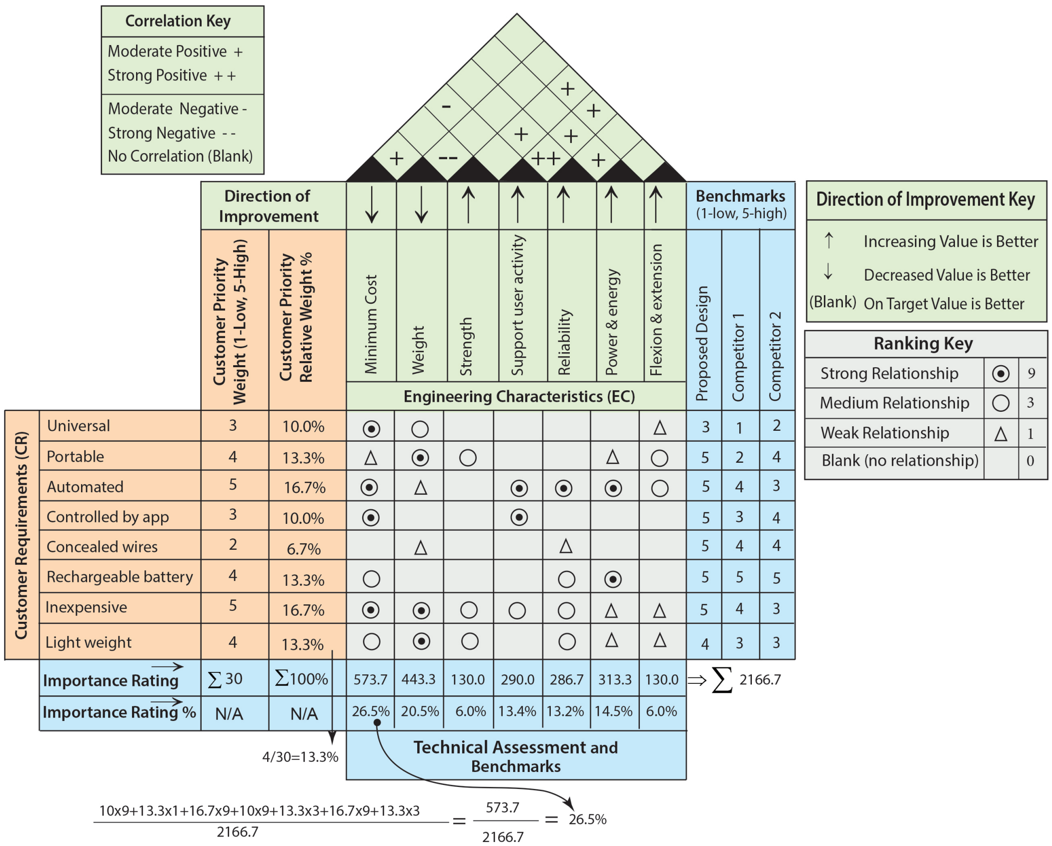

Figure 2.15: HOQ for the finger rehab device.

EXAMPLE 2.3 (continued)

$$\begin{aligned}\text{Importance Rating} &= \sum \text{Priority relative weight } \% \times \text{Relationship ranking}\\ &= +10 \times 9 + 13.3 \times 1 + 16.7 \times 9 + 10 \times 9 +\\ &\quad +13.3 \times 3 + 16.7 \times 9 + 13.3 \times 3\\ &= 573.7\end{aligned}$$

Importance rating % row is completed by dividing individual importance rating by the total importance rating of 2166.7. For the "minimum cost" requirement, this number is 573.7/2166.7= 26.5 % (note that, since it is rounded to one decimal place, you may have a round of error).

The proposed finger rehab device design is compared with two other competitors' similar product designs through what is referred to as competition benchmarking. Benchmark design features are compared with the list of customer requirements scaled between 1 and 5, with 1 being not satisfied and 5 being completely satisfied.

The direction of Improvement is shown in Figure 2.15. For example, if we keep all the other engineering characteristics constant, lower weight is better for the finger rehab device design. From the HOQ analysis, it is clear that weight and the cost of production have the highest importance rating. These critical design points should receive concentrated effort in the design process.

The engineering characteristics may often conflict with each other. As shown in Figure 2.15, the correlation matrix is used to identify where engineering characteristics support or conflict with each other in the design of the finger rehab device. For example, Figure 2.15 shows that a finger rehab device with lightweight requires lower-cost production – affects each other positively. Similarly, support user activity and reliability affect each other strongly positively. But lightweight and strength have a strongly negative impact on them – the finger rehab device gets stronger (improvement: good), but the weight increases (worsening: bad). This situation involves a trade-off between different engineering characteristics (parameters) – how much one design parameter can be optimized without sacrificing other parameters. Or, the design must be repeated or discussed with the customer until the negative impact can be designed out. Another option to eliminate the conflict is the use of "Theory of Inventive Problem Solving (TRIZ)". This subject will be covered in Chapter 3.

2.4.3 Concept Development

The importance rating of engineering characteristics from HOQ analysis can be used for concept development. If the importance ratings are not available then engineering judgment can be used for the importance ratings.

For example, consider that we have two-finger rehab design concepts and one of them will be selected for further analysis. For the selection process, the concept selection matrix shown in Figure 2.16 can be used to quantitatively decide which conceptual design would be a better option. The following engineering characteristics from HOQ are used to measure the effectiveness of each concept: Cost of Production, Weight, Strength, Software, Reliability, and Power & Energy.

Criteria (Engineering Characteristics)	Importance Rating, % (IR)	Concept A (IR)x(R)	Concept B (IR)x(R)
Minimum cost	26.5	⊙ = 132.5	○ = 79.5
Weight	20.5	○ = 61.5	⊙ = 102.5
Streght	6.00	⊙ = 30.0	○ = 18.0
Support User Activity	13.4	○ = 40.2	▲ = 13.4
Reliability	13.2	▲ = 13.2	○ = 39.6
Power & Energy	14.5	○ = 43.5	○ = 43.5
Flexion & extension	6.0	○ = 18.0	○ = 18.0
		338.9	**314.5**

Ranking (R)		
Strong Relationship	⊙	5
Medium Relationship	○	3
Weak Relationship	▲	1

Figure 2.16: Concept selection matrix.

As shown in Figure 2.16, importance ratings of each engineering characteristic were determined and used in the concept selection matrix. As shown in this figure, a three-point ranking is used for the relationships between the engineering characteristics and each concept. Related ranking numbers for each concept and importance ratings are multiplied together to determine the concept score.

In Figure 2.16, results show that concept A has the higher total sum of 338.46. Thus, Concept A will be chosen as a basis for the final design analysis.

2.4.4 Cascading QFD Analysis

Usually, one QFD may not be sufficient to explain the customer requirements down to actual production. As shown in Figure 2.17 there are four phase processes to develop a product which include four cascaded House of Qualities (HoQ). This figure shows that QFD is an integrative process for connecting customer requirements to production – HOWs are refined until the detailed level of production requirements is reached. As seen from this figure, the HOWs of phase-I become the WHATs of phase-II. For example, in phase-I, taking the customer requirements and defining engineering characteristics that are carried on to phase- II to establish the basis for the component requirements. This process will continue until the manufacturing operations are defined. The cascaded HOQ phases translate the customer requirements to a set of process parameters to be controlled.

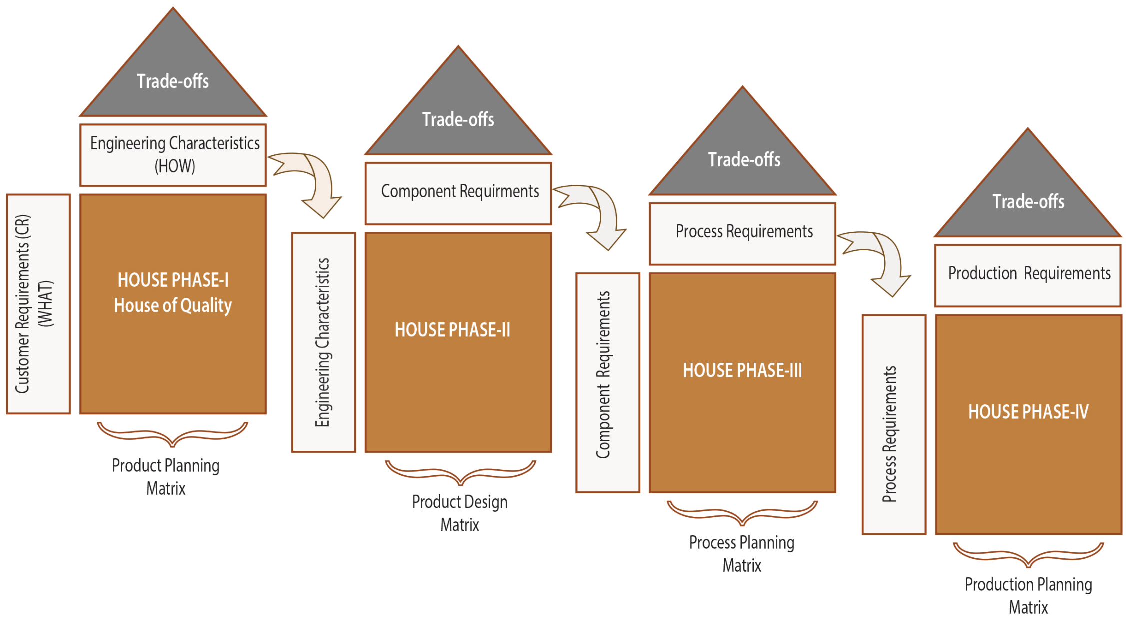

Figure 2.17: Connecting customer requirements to production.