How to Better Take User Needs into Account in the CK Theory Using QFD

by

Sina SALIMI

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In 2020, I lost my best friend, Dr. Pouria Badali, who was like my brother. He was very kind and passionate about science. He loved exploring different academic fields to increase his knowledge and share it with everyone. Also, he was waiting for my thesis to read and learn about my research. Therefore, I dedicate this work to him with love and miss.

COMMENT MIEUX PRENDRE EN COMPTE LES BESOINS DE L'UTILISATEUR DANS LA THÉORIE CK EN UTILISANT LE DFQ

Sina SALIMI

RESUME

En conséquence des besoins humains, les produits portent un rôle essentiel dans leur vie. Pour cette raison, plusieurs produits sont inventés et utilisés quotidiennement. Avec le développement de la technologie et l'accroissement des besoins humains, les concepteurs utilisent des méthodologies de conception qui prennent en compte la créativité et l'innovation, afin d'obtenir plus de produits innovants pour le succès du marché. Ainsi, plusieurs méthodologies de conception ont été conçues et créées. Parmi celles-ci, la théorie C-K et TRIZ. Ces méthodologies sont centrées sur la création et l'innovation.

Il y a plusieurs entreprises qui mettent en application les désirs de l'utilisateur à leur produit pour approcher la demande du marché et augmenter le succès commercial. Éventuellement, différentes méthodologies comme le Déploiement des Fonctions Qualités (DFQ) ont été créées pour comprendre les besoins du consommateur et traduire leur voix pour la conception d'éléments. Les théories comme celle de C-K prennent en considération les attentes des utilisateurs et leurs résultats. Par conséquent, cette recherche combine la théorie C-K et DFQ pour développer une méthodologie afin d'éliminer le manque de la demande à la clientèle.

Avec cette nouvelle méthodologie, il est possible d'extraire les demandes des clients à partir du DFQ et de les transférer à l'espace K de la théorie C-K. Par la suite, en utilisant les besoins des utilisateurs comme concepts initiaux dans l'espace C de la théorie C-K, les résultats de cette théorie vont être transféré à l'DFQ afin d'obtenir les résultats axés sur le client pour de nouveaux produits.

Dans cette recherche, un appareil de réhabilitation utilisé pour le membre inférieur a été conçu dans une étude de cas avec la méthodologie proposés et basée sur les besoins des utilisateurs.

Ainsi, la méthodologie démontre que les demandes des utilisateurs sont utilisées depuis la première étape de conception jusqu' à la dernière étape.

Mots clés : Théorie C-K, déploiement des fonctions qualités (DFQ), méthodologie de conception, demandes des clients, innovation du produit.

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ABSTRACT

Due to human needs, products play a vital role in our life. For this reason, various products are invented and used for daily needs. With the development of technology and the increment of human needs, researchers found it essential to have design methodologies that consider creativity and innovation to achieve more innovative products for customer satisfaction and market success. So, different design methodologies have been designed and created. For instance, the Concept & knowledge theory (C-K theory) and TRIZ are two methodologies that contain creativity and innovation at their core. Besides, different companies concluded that they need to consider and apply user desires to their product to approach market demand and increase user satisfaction. Eventually, different methodologies like the quality function deployment have been created to understand customer needs and translate their voice to design elements. However, the design theories like the C-K theory have the limitation of considering user expectations in its structure.

Accordingly, this research tends to integrate the C-K theory and the QFD to develop a new methodology in order to use customer demand in the structure of C-K theory thanks to QFD.

The new methodology extracts customer demands from the QFD and transfers them to the structure of the C-K theory. Then, the results of the C-K theory are transferred to the QFD to get the customer-based outcomes for new products.

In this research, a home-use lover limb rehabilitation device has been designed as a case study with the proposed methodology based on user needs.

Therefore, the methodology demonstrates that user demands are used from the first design step to the last step.

Keywords: CK theory, QFD, Design methodology, Customer demands, Product innovation

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LIST OF ABREVIATIONS

C-K	Concept & Knowledge theory
DFQ	Déploiement des Fonctions Qualités
QFD	Quality Function Deployment
SBP	Science Based Products
CBP	Creativity Based Products
DP	Design Parameters
FR	Functional Requirements
DCL	Design/ Creativity Loop
HOQ	House of Quality
SD	Systematic Design
TRIZ	Theory of Inventive Problem Solving
C	Concept(s)
K	Knowledge
GDT	General Design Theory
AD	Axiomatic Design
CDP	Coupled Design Process
ID	Infused Design
NPD	New Product Development
NPS	New Product Success
CA	Customer Attribute(s)
EC	Engineering Characteristic(s)

CR	Customer Requirement(s)
HAL	Hybrid Assistive Limb
BWSS	Body Weight Support System
GPS	Global Positioning System

INTRODUCTION

Due to human needs, products have essential roles in our lives, from food supplies to daily needs. Hence, experts attempt to design and develop different products. By increment of design technology and knowledge, different design theories have been made. However, there are challenges with these theories in product design and innovation. One of these design theories is called the concept and knowledge theory (the C-K theory).

According to Hatchuel and Weil (2003), the C-K theory can be used to address several problems that may arise from an ongoing innovative design process. Hatchuel and Weil further argue that the theory provides a precise and clear definition of the "design," having a robust theoretical foundation linked to the well-recognized issues in logic. Besides, the theory provides the opportunity for innovation and creative thinking that is not external to the design theory, but rather part of its central core functions (Hatchuel, & Weil, 2003).

Previous studies have illustrated how C-K theory can overcome classical views and present the assumptions through a case study design. As a result, C-K theory can support reasoning and organize different planning techniques in every innovative activity. Also, it enables to characterize different types of innovative aspects that need specific reasoning, which are Science-Based Product (SBP), Creativity-Based Products (CBP) and presents distinctive design methods (Hatchuel, & Weil, 2003).

This research tends to develop a methodology to integrate the C-K theory and Quality Function Deployment (QFD) to use customer needs as data during the design process for ideas and concepts generation based. The research comprehensively illustrates all the designing steps besides integrating the quality function deployment with the C-K theory to address the customers' needs. The developed methodology allows product designers to substitute the lack of customer desire consideration in the C-K theory structure. As a case study, an over-ground gate trainer device at a low price and non-expert requirements for home use has been designed.

This work is subdivided into four chapters. Chapter one aims to clarify the definition of the design and creativity, and necessity of design theories. Also it illustrates design/creativity loop and creative problem solving process to address design theories place which, indicated in the chapter's conclusion part. chapter two demonstrates the literature review, including past design theories, an introduction and description of the CK theory, designing a chair with different design theories and the CK theory with results comparison of the design methodologies, description of the QFD and the house of quality, customer needs role in product innovation, advantages and drawbacks of the CK theory and the QFD, and a conclusion which contains problem statement and research question. Chapter three presents the research methodology with illustration of each step and finally, chapter four demonstrates research process involved in applying C-K theory with QFD in the design process, and a conclusion part after chapter four.

Furthermore, the story of this work backs to a medical invention invented in 2013 by the author. The invention won 2 international prizes at a competition in Germany and was approved by the orthopedic faculty of Urmia university of medical sciences. After that, the author tried to improve the invention and develop it by using its users' feedback to allow patients to use the invention in their homes. Then, he got familiar with several design methodologies and the CK theory but could not find the method he wanted to use for his purpose. So he decided to do research by studying for a master's degree to develop a customer-based methodology and utilize it to develop his invention. Finally, by developing the new methodology and re-inventing his previous product, the new invention has more features and is user-friendly. Besides, its structure changed and developed for safety and comfort reasons. The new product will be used for launching a startup company in the near future.

CHAPTER 1

INTRODUCTION TO THE DESIGN & CREATIVITY

1.1 The design & creativity definitions

The body of literature of design has various ideas in common with the literature of creativity. In its own right, the design has been described as a methodology that contains creativity. Thus, design and creativity are concerned with the imagination and comprehension of new things or objects (Clinton & Hokanson, 2011). Also, we can say that design is a creative process (Hatchuel, Le Masson,& Weil, 2017).

Creativity has many definitions. Many researchers stated creativity with different points of view. For example, Chiu and Salustri (2010) believe creativity is the essential part of success in design, and design contains creativity at its core undoubtedly (Hatchuel & Weil, 2008). Additionally, they indicated creativity must be essential in engineering fields and students' outcomes. Besides, integration of high creativity skills with academic knowledge implementation enhances design quality and improves its innovativeness (Chiu & Salustri, 2010).

Han, Forbes and Schaefer (2019) investigated literature of design definition and identified various statements of different researchers. Some of these definitions are stated below:

Creativity is humans' brainpower with fundamental characteristics (Cross, 2011). The four main factors of creativity are environment, process, product and creative people (Couger et al., 1993; Rhodes, 1961; Thompson and Lordan, 1999).

As Gero (2011) stated, creativity can be in at least one of the following sections: the design, the evaluator of design, the process of design, designer, the interplay between customer and designer, in the community, which design lies, and the relation of all elements mentioned above (Gero, 2011).

Over the years, design methodologies have been improved, and different scholars have proposed new ones. The reason is that past design theories could not provide answers for some creativity issues (Dorst, 2006). Then, the creativity issues were identified as items that limit creativity and analyzed as different fixation forms. An investigation of these fixations may help identify creativity issues that were recognized during the last two centuries. As an achievement, researchers found that recent design methodologies make structured knowledge that aims to boost the creativity of design (Hatchuel, Le Masson, Reich & Weil., 2011) (Le Masson, Hatchuel & Weil, 2011).

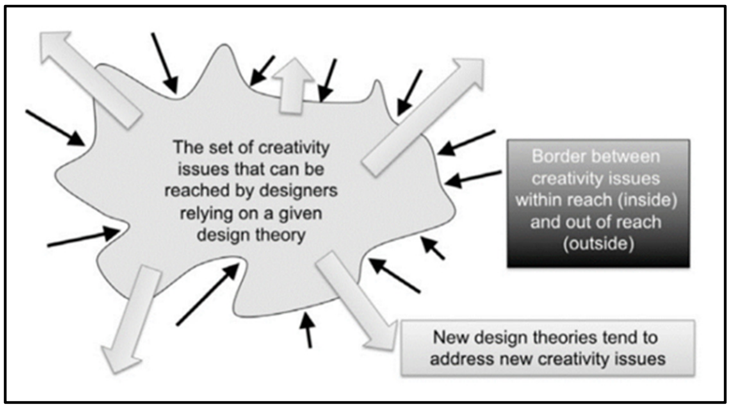

Figure 1.1. Interplay between creativity issues
and design theory
Taken from Le Masson et al. (2011)

Engineering design theories indicate the importance of depending on knowledge and capabilities. Knowledge can support, although limit design competences. Also, new design theories try to overcome current design fixations. But they can create new fixations, which will be defined by creativity studies (Le Masson et al., 2011). Hence, different design methodologies have been created to increase the support of knowledge on design and decrease its specific limitations in other design theories.

1.2 Design/Creativity loop

Some researchers, such as Gero & McNeill (1998), and Akin & Lin (1995), stated designing as a repetitive process that is fast, ongoing and iterative succession of analysis, combination and evaluation, or investigation and cycle. This cycle then improved as a creative cycle, pointing necessary ideas that are novel and useful, which is called the design/creativity loop (DCL). It must take it into consideration that the cycle doesn't illuminate all the kind of iteration or case (Clinton & Hokanson, 2011).

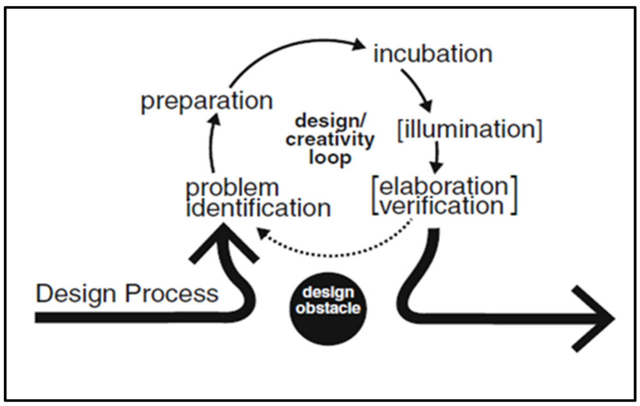

Figure 1.2. Design/Creativity Loop
Taken from Clinton & Hokanson (2011)

1.3 The creative problem solving process

According to Timbadia and Khavekar (2017), problems are created when a human decides to design a new product or service. In order to solve these problems, a decision should be made by the designer. The following eight elements are the base of the creative problem solving process (Higgins, 1994); (Timbadia & Khavekar, 2017):

1- environment consideration.
2- problem investigation.
3- problem identification.
4- making assumptions.

5- creating alternatives.

6- decision making between alternatives.

7- selected solution implementation.

8- control.

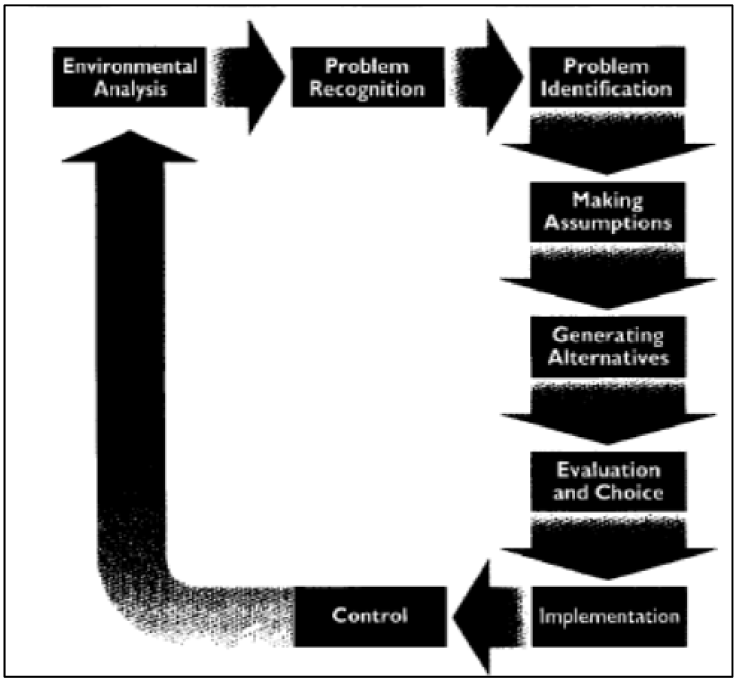

Figure 1.3. The creative problem solving process
Taken from Timbadia & Khavekar (2017)

As an outcome, following seven items can be highlighted (Timbadia & Khavekar, 2017):

1- process ideas innovation and novel product.

2- product or service enhancements on a constant basis.

3- productivity increment.

4- enhancing efficiency.

5- Flexibility and speed.

6- products and service quality improvement.

7- high performance.

1.4 Conclusion

In this chapter, various definitions of design and creativity are stated. The necessity of different design theories is discussed. Furthermore, design/creativity loop and creative problem-solving process are explained. Creativity and design are two inseparable elements for creating new products based on the contents. As a result, we can understand that different design theories are a part of design/creativity loop and creative problem-solving process. This is because design theories are used after problem identification and before the evaluation/verification process. Also, as mentioned before, the goal of design theories development is to decrease design fixation and allow designers to have different perspectives for solving problems. In the next chapter, a comparison between several design theories demonstrates how design theories enhance designers' points of view and decrease design fixation.

CHAPTER 2

A REVIEW OF THE LITERATURE

This chapter aims to cover description and literature review of design methodologies, the CK theory including a sample of a product design process and a comparison between other design theories and the CK theory using a chair design case study. Then it highlights importance of customer desires roles on product innovation in the design process. After, it describes the quality function deployment (QFD) with the process of house of quality (HOQ) matrix structuring. After the QFD definitions, advantages and drawbacks of both the CK theory and QFD are described. At the end, a statement of research problem and question has been made in the conclusion part.

2.1 Design methodologies

2.1.1 Two models of past and historical design theories

2.1.1.1 The ratio method

The first engineering design theory is assigned to Redtenbacher (Redtenbacher, 1852a; Konig, 1999). The method addressed two following fixations: 1- it suggested combination models of existing objects called 'object models.' 2- it suggested a methodology to utilize these combined models to design, particularly unknown objects. As a case study, he designed water wheels. First, he did a state-of-art review of wheels and available theories. At that time, because of a lack of knowledge about the wheels' equation (only diameter and width were available) and limitations of the model, he couldn't use scientific knowledge. After the first step, he went to the second step, concluded that the performance of the wheels depends on the condition of construction. Then, the client's conditions are identified through a dialogue, which was budget to allow the designer to choose material for the wheel to design it by the best size of each material because of performance effection. After material selection and wheel designing, he made a chart that shows the best wheel for the different scales of flow and fall height. Later he recognized his method comes from architecture. (Konig, 1999, P. 24) mentioned that earlier than Redtenbacher, a similar methodology had been utilized by German & English mechanics. This method contains many fixations and a lack of innovation. In 1884 when Watts steam water was more than 60 years old, Redtenbacher was working on waterwheels! (Le Masson et al., 2011).

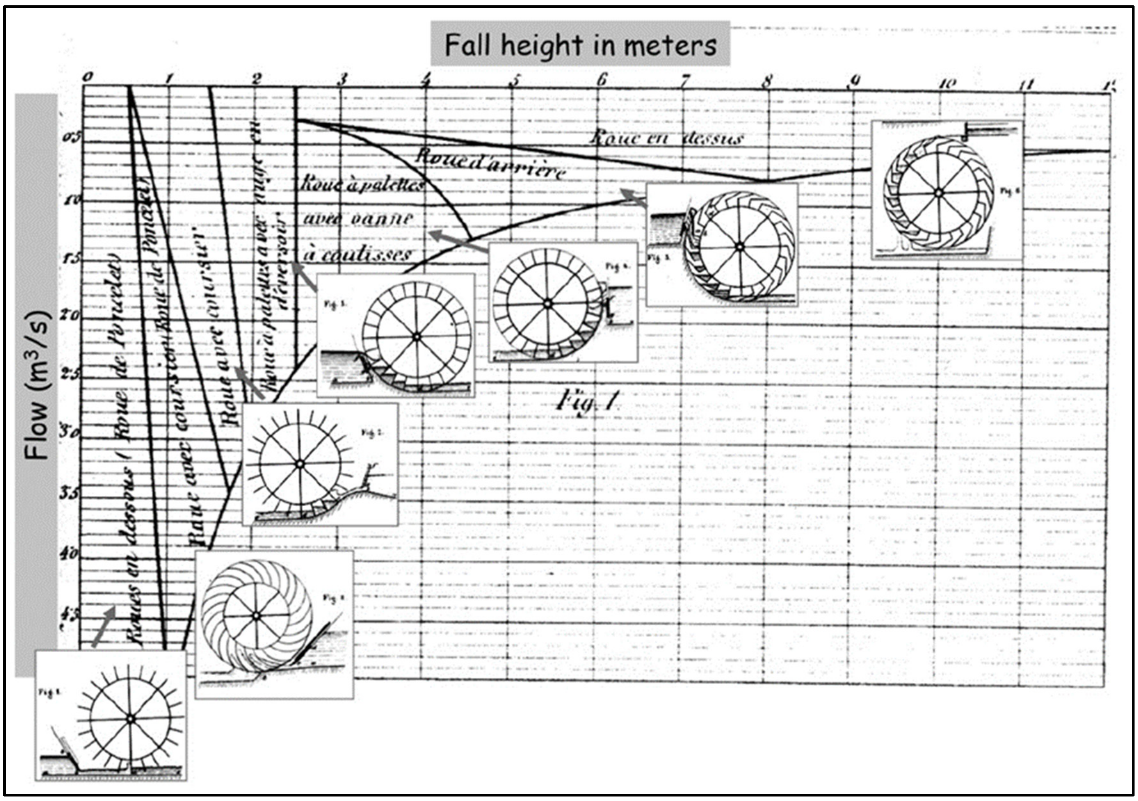

Figure 2.1 Chart of waterwheel, depending on size, flow and fall height
Taken from Le Masson et al. (2011)

2.1.1.1 Systematic Design (SD)

One of the well-known methods of engineering design is systematic design (SD). It is also most commonly used for engineering projects. This method has four sections, including the initial step to clarify the task, conceptual design, visualization, and detailed design. The age of the method and its development backs to between 1900-1960. SD tries to address two major criticisms: 1- The ratio model was unable to consider regular progress because of increased capacity for creating knowledge which, increased critical fixations due to outdated and abolished design rules reuse by designers. 2- designers tried to utilize existing machine elements to design complex assemblies. SD can create new spaces for creativity and new knowledge exploration on technical principles powerfully and efficiently (Le Masson et al., 2011).

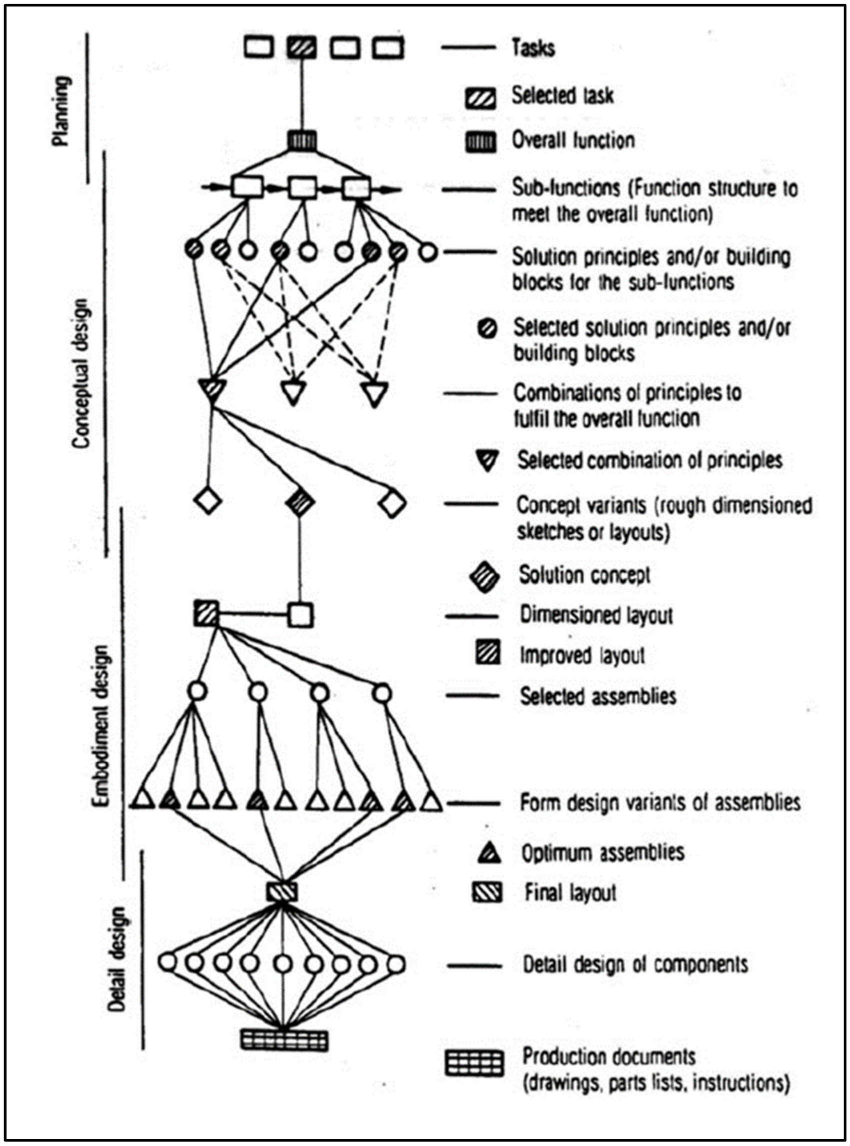

Figure 2.2. SD according to Pahl and Beitz (1977)
Taken from Le Masson et al. (2011)

Opposite of the ratio method, which needs knowledge of particular for ratios of each object, SD is widely independent of objects; however, in 1980, experimental studies showed that designers used the formal framework of SD rarely, and scholars claimed that the formal framework of SD so fixed. Also, no one even has an understanding or perspective about it anymore (Le Masson et al., 2011).

2.1.2 Current design theories

There are several design fixations that recent studies show. These fixations are based on the representation of things, using knowledge, emotions, illustrations and analogies, and fixation by organizational and social connections in enterprises that are not professionals in creativity. Novel design theories try to overcome these fixations and extend generative creativity. A couple of these theories are TRIZ, C-K theory, infused design. TRIZ tries to reduce fixation caused by relying on common solutions to a problem. It suggests a large database and an intelligent explorer, the matrix of contradictions, to find creative solution elements to problems. C-K theory aims to decrease fixation by the representation of items and support the reconsideration of object identities through the dual expansion of concepts and knowledge. The infused design supports the tough relationship between various scientific things and helps to recognize knowledge gaps and fill these gaps by utilizing complementary knowledge for design. New design theories try to motivate and support new design structure forms for innovation (Le Masson et al., 2011). In the further sections, five current design theories and their comparisons will be presented.

2.2 The C-K Theory

C-K theory is one of the strongest design theories that can help designers achieve their goals. It offers novel notions: "concept undecidability," "knowledge independence," "generic expansions," and "Knowledge reordering." The K space of the theory clarifies the missing history of any accomplished creative process. It performs various roles: a reference space or a resource space and an output space converted during the creative process. In this methodology, fixing concepts produce new knowledge, more original ideas, and the value of design is extracted from the continuous use of this new knowledge (Hatchuel et al., 2017).

2.2.1 The CK theory's purpose and origins

C-K theory is an innovative design theory with two spaces in its structure. The first one is concept space (C) and the second one is knowledge spaces (K). Main proposition of the C-K is a formal distinction between these two spaces. The theory suggests a precise and straightforward explanation of 'design,' free of any domain. (Hatchuel, Le Masson & Weil, 2004).

2.2.2 Industrial Issues in Design

Regarding the previous studies, the C-K theory presented practical difficulties within the scientific contexts. It has been developed to guide different groups' work engaged in extremely innovative projects in various industries. These industries followed systematic principles but did not adopt them due to fundamental technological changes and the short evolution of consumers' expectations (Weiss & Hari, 2015).

2.2.3 The Principles of the C-K theory

According to Hatchuel et al. (2004), Agogué, Hooge, Aenoux & Brown (2014), and Motyl & Filippi (2014) The theory is comprised of the interdependent propositions as follows:

2.2.3.1 Basic Assumptions and Definition of Design in the CK theory

- Knowledge space named 'K' is an informational area, the extent of concepts with rational designer status. This area is usually neglected within the previous literature; however, it is difficult to define styles without referring to space (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

- A proposition's logical status is called an attribute that determines the degree of trust D assigned to a proposal. The normal logic propositions can be correct or incorrect. In non-standard logic, propositions might also be valid, invalid, undecidable or have an unclear value. Designers may use many logics. However, the most important concept is that each of the propositions of K has a logical status. For keeping it simple, we will assume that designers have got a regular true or false logic in the K (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
- Construct is referred to as a proposition or a set of propositions with logical status in K because the K produces all the other parts used in creating the construct proposition. Hence, when a concept is created, it cannot be confirmed as a proposition of K. In design, a concept normally defines a group of properties qualifying one or numerous entities (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
- The meaning of the design: Here design is outlined as the method by which a concept brings out different concepts or reworking into knowledge that is propositions in K. The prior assumptions enable the description of 'concept-sets' and 'concept-expansions (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

2.2.3.2 The Concept space: Properties and Expansions

- Concepts have specific sets: Like in the previous model, a construct C is a proposition with no logical status during a space K (i. e., incorrect or correct in K). It means that an entity (or a group of entities) confirms a group of properties Pn. This description is corresponding to defining a collection associated with C. This set is also known as C (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
- Concepts are outlined in the set theory and special sets from which we tend not to extract one feature. This property of concept-sets issues a well-known elementary issue in set theory: it is a matter of the choice axiom. Therefore, based on Cohen (1963), the selection axiom is independent of set theory's other axioms. Thus, we will utilize all primary sets for concepts

whereas leaving the selection axiom (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

- Concepts will only be divided or included, not searched, nor explored. If we add further properties, then we shall partition the set-in subsets; if we subtract properties, we have the collection in a set that includes it. Hence, nothing else may be done (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
- By adding or removing properties, we adjust the level of concepts: whenever we tend to create an operation like these, we return to K's proposition (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

2.2.3.3 The Design Reasoning Process with Disjunctions and Conjunctions

- The method of adding and removing properties to concepts or propositions is that the main mechanism of style changes propositions of K in concepts C and the opposite true for otherwise. We name disjunction the method of re-modelling or re-designing propositions toward concepts (going from K→C); and that we call conjunction the reverse operation or function (going from C→K), which ends up in the additional technical definition of design (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
- Definition 2: Design refers to the process of generating and expanding the K→C disjunctions to achieve C→K conjunctions. Expansion is done through partitioning of including the disjunctions (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
- The tree structure of the space of concepts: notion of extended partitions: an area of concepts is essentially tree-structured. This is because the only allowed operation is partitioning., inclusions, and initial disjunctions. Therefore, it is important to differentiate between two sorts of partitions: restrictive and extensive partitions. If the effects we add to a concept are already known in K as a property of one of the entities involved, we get a limiting partition. On the other hand, if the property we include is unknown in K as a property of one of the entities concerned within the concept definition, we get an extended (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

- Creativity and innovation result from extended partitions of concepts: the concepts will be freely expanded within the space of concepts, given that expansive properties are obtainable. These properties just come from K's existing knowledge and from which we get to draw all the features required to present the design method, which provides the formulation of C-K theory (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

2.2.4 The Design Square with the Four C-K Operators:

The design will be described as a method developing the two areas' co-expansion: space of concepts 'C' and the space of knowledge 'K'. However, this distinction may disappear or may simply be reduced to only computation or improvement. Therefore, the design method is nothing over the operators that permit these two spaces to expand, where every space helps the other expand. There are essentially four different types of operators in this context: the external ones (C→K, K→C); the internal ones (C→C, K→K), which provide some indications to everyone. The four types of operators are called 'square design' (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

2.2.4.1 External Operators

K→C: This administrator includes or remove properties from K to concepts in C. It makes disjunctions once it changes a recommendation into a concept. This corresponds to what is typically known as the 'generation of alternatives'. However, concepts are not choices whereas they are possible sources for alternatives. This operator expands the area C with components from the K (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

C→K: This operator aims for properties in K that could be added or removed to achieve propositions with a logical position.; It forms conjunctions that might be taken as 'finished styles.' It is equal to validations or confirmation in classical design: doing a test, an experimental setup, a model, and a moC-K-up are C→K operators' samples (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

2.2.4.2 Internal Operators

C→C: This operator is the classical rule in the set theory that deals with management partition or inclusion. It is often enriched to provide set theory axioms (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).
K→K: This operator is at least the classical and propositional logic rule that permits a knowledgeable area to expand on its own (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

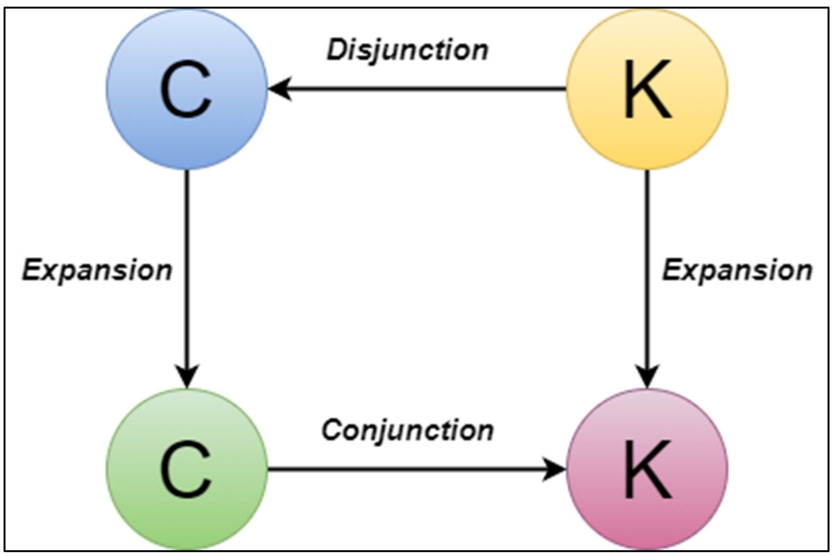

Figure 2.3. The design square

2.2.5 The Design Square and C-K Dynamics

Figure 2.3 shows the design square. It provides the fundamental structure of the design method. It also shows the importance of defining the model both in terms of concepts and knowledge. Another demonstration of the C-K dynamics is shown in Fig 2.4. Variation is acknowledged in the tree structure in C, and the structure in K. The mentioned figures also show that any expansion in C depends on K, and the reverse is true. Expansion in C is considered to be Kdependent. Conversely, any creation in K moves through C. Styles starts with a disjunction and can be done simply if some conjunction exists and is often seen as 'an appropriate answer' (Hatchuel et al., 2004), (Agogué et al., 2014), (Motyl & Filippi, 2014).

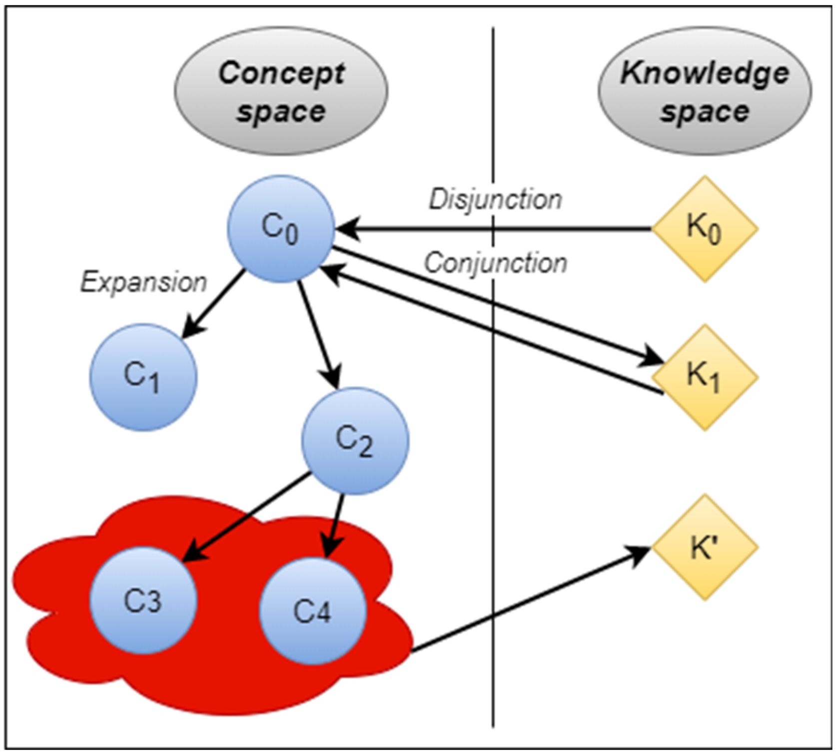

Figure 2.4. C-K Dynamics

2.2.6 Designing nail holder

This product had been produced and positioned in a start-up company. The first product was designed as a nail holder that avoids hurt hands during hammering. The managers then decided to keep the nail holder's creative level and generate new concepts as a new product. For this reason, they started designing with the goal of "safe knocking nail." The whole design process is in two phases. The first phase is divided into two parts. A concept had been generated in the first part of the first phase with C-K theory modelling "safe knocking nail with a hammer that left-hand holds the nail." The concept is identified as the source of accidents in traditional hammering. After phase one-part one, the second part was completed. The second phase started with the goal of functional improvements and increasing marketing by collecting "do it yourself" products' as a part of the knowledge space (Hatchuel et al., 2004).

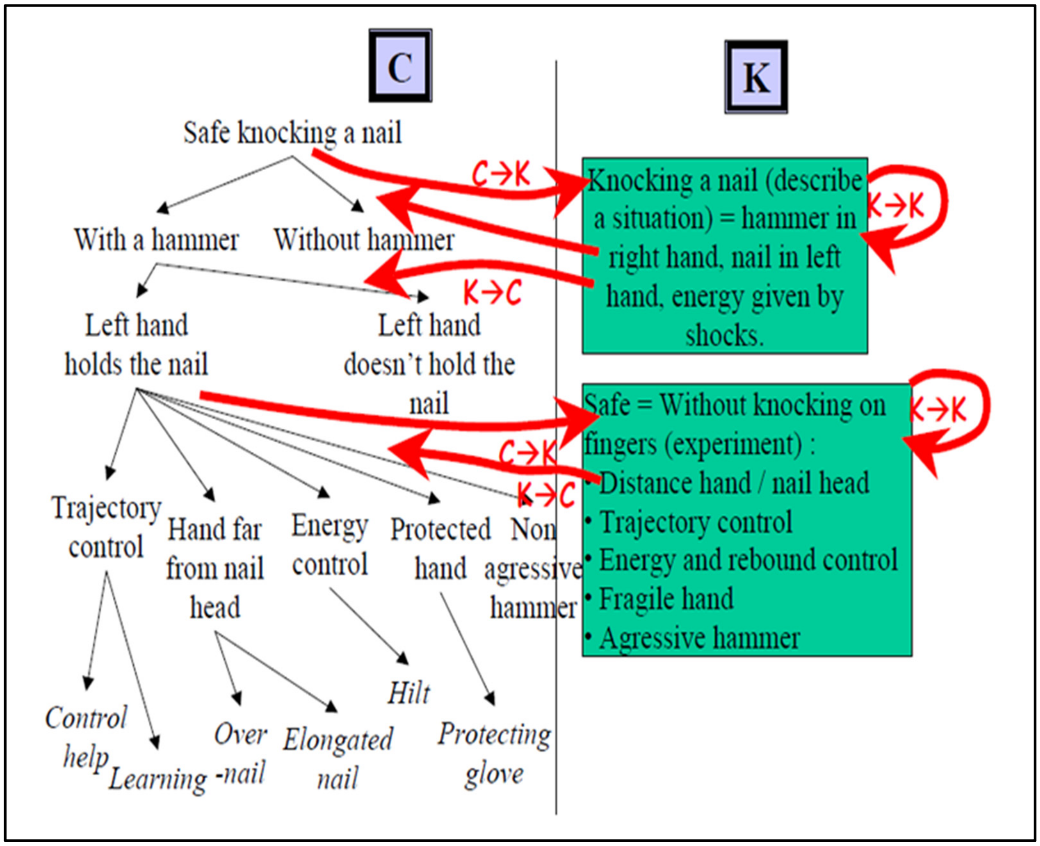

Figure 2.5. Phase 1, part 1

Taken from Hatchuel et al. (2004)

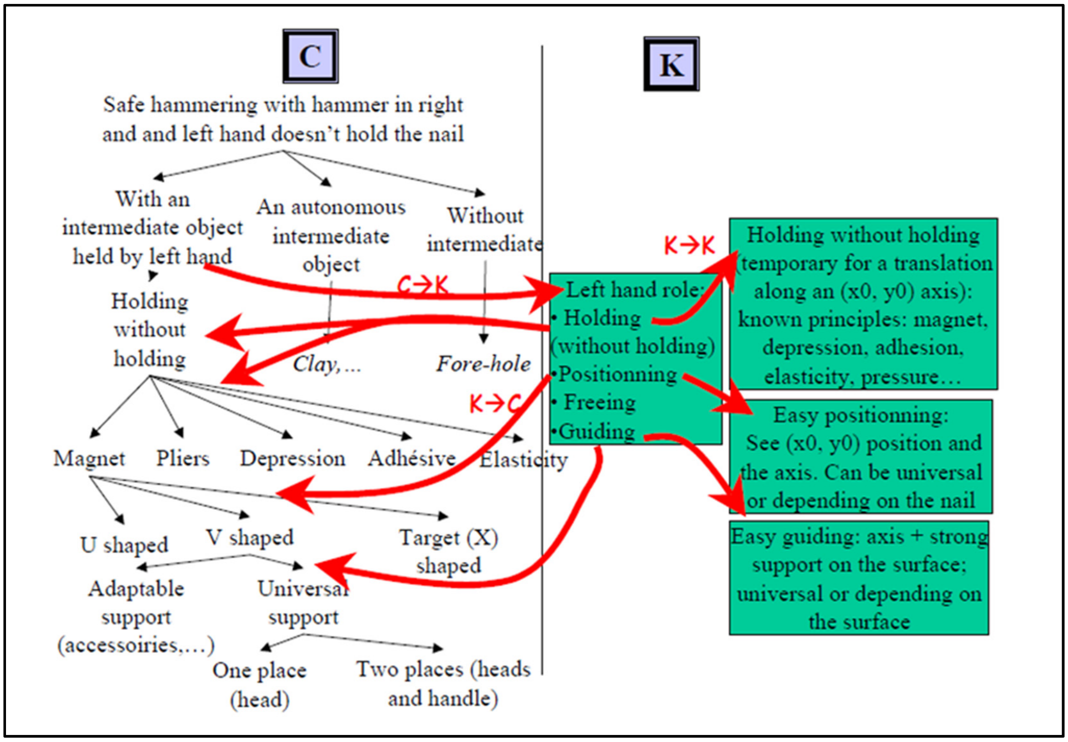

Figure 2.6. Phase 1, part 2

Taken from (Hatchuel et al. (2004)

Figure 2.7. AVANTI nail holder

Taken from Hatchuel et al. (2004)

2.3 Five formal design theories and their comparison

This section shows a comparison between the five design theories by analyzing their generativeness and Robustness. A case study of camping chair design is the evaluation of the design theories based on the above parameters. Generativeness is defined as the capacity of a design theory to generate new solutions. Also, Robustness is described as the capacity of design theory to help the designer achieve a robust design. The five design theories selected for the comparison are General Design Theory (GDT) by Yoshikawa & Tomiyama, Axiomatic Design (AD) by Suh, Braha & Reich's Coupled Design Process (CDP), Shai & Reich's Infused Design (ID), and Concept & Knowledge Theory (CK) by Hatchuel & Weil (Hatchuel et al., 2011).

2.3.1 General Design Theory (GDT)

GDT depends on a huge number of axioms and origins. Nevertheless, the central notion of the theory is its definition of existence sets. An existence set S is defined as the set of all true things that exist, existed or will exist. GDT differentiates among two sections: 1- Ideal knowledge. 2- Real knowledge. The basic description for design with GDT is to linking an entity based on functions for the section of "Real Knowledge" there is a topology as shown below. The entities are described by a finite number of attributes and models connecting a function to its related attributes. To design a new chair with GDT, a designer starts the process with some attributes and functions. Then she links every function to one or more attributes. In the next step, she selects one subset of entities that possess all needed functions except one. Conclusively, she utilizes one last model for the missing function to add one attribute, which is different from the K existing ones. In the logic of GDT, this chair is new (Hatchuel et al., 2011).

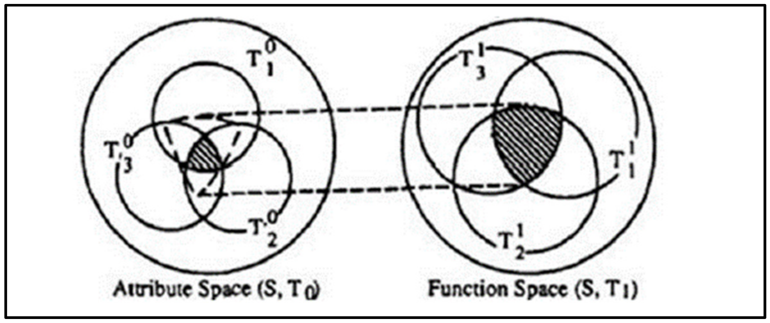

Figure 2.8. GDT: most suitable fit of design among
set of functions and attributes
Taken from Hatchuel et al. (2011)

Entity sets and topology fix the generativeness of GDT. Consequently, it is limited by the list of attributes and functions that are supposed to be known in advance. Also, the design's Robustness relies on entities' structure (Hatchuel et al., 2011).

2.3.2 Axiomatic Design (AD)

AD describes the design as a mapping among Design Parameters (DPs) and Functional Requirements (FRs). AD's central mathematical models are: 1- defining a design as a matrix algebra between DPs and FRs. 2- a theory of the quantity of information associated with the change of the FRs. The theory stated that a design must be decoupled. It should implement one-to-one communication between DPs and FRs. AD also states that a decoupled design should also accompany the lowest information principle for the user. Hence, the user should not change any design parameter to benefit from the system's functions. The meaning of user in AD can be as the product engineer who wants simple and true manufacturing or as the user that demands simple product usage. In AD, generativeness starts after some design has already been made. Yet, AD's knowledge history and its potential development are not specified (Hatchuel et al., 2011).

2.3.3 Coupled Design Process (CDP)

CDP can be recognized as a direct generalization of GDT that enhances design generativeness. CDP considers that design is a process where functions and design parameters evolve together. Opposite of GDT, in CDP, there is no static fit among a fixed list of functions and attributes. Also. In CDP, new functions and attributes can be added to explain new design conditions and problems. Additionally, CDP covers learning and discovery as an inseparable part of the design process. Braha and Reich illustrated that GDT is a specific case of CDP. However, the generativeness and Robustness of CDP are stronger than GDT. It relies on the dynamic structure of its knowledge and the explanation of the design process as a rise close space. Also, compared to AD, the generativeness of CDP is more strong than in AD because it is created in the design process itself, and the knowledge history of AD is not defined. For Robustness, AD can be applied in CDP to guide filtration and synthesis processes (Hatchuel et al., 2011).

2.3.4 Infused Design (ID)

ID introduces the effect of the transformations of the knowledge history in the design process formally. Such dynamics were missing in GDT and only implied in CDP and AD. Furthermore, ID characterizes a specific class of knowledge transformations that is of direct guidance for the designer. In the ID structure, a design problem mapped out in one area's language can be perfectly translated into another area where it can be solved more easily. Moreover, by reusing existing solutions, ID could lead to innovative solutions in one field. The generative ability of ID arises from connecting knowledge references that previously were recognized to be distinguished and become a piece of a single part of knowledge through ID. Additionally, Robustness is built into ID through the mathematical foundation that guarantees the solutions' validity translated from another field. The Robustness of these solutions is as the Robustness of the reused solutions (Hatchuel et al., 2011).

2.3.5 The C-K Theory

In the C-K theory, like ID, a designer cannot reach a proposition without developing its knowledge. Hence, the existence of a design solution automatically requires knowledge expansion in the structure of the CK theory. Also, reaching various solutions with expanding knowledge space is the most surprising thing that happens during the design process. These aspects raise one step further the generativeness of design. Regarding Robustness, C-K theory creates C branches' family that corresponds to a general and close area of K. this enables finding near similar designs in case of context changes (Hatchuel et al., 2011).

2.3.6 A comparison between different design theories & the CK theory

This section provides the results of designing a Camping chair with the five design methods. The design theories for this comparison are: General Design Theory (GDT), Axiomatic Design (AD), Coupled Design Process (CDP), Infused Design (ID) and the CK theory. The case study for this process (chair) should have three specifications: a) easy to transport and pack. b) As light as possible. c) Comfortable. The results are shown in the figure 2.9 (Hatchuel et al., 2011):

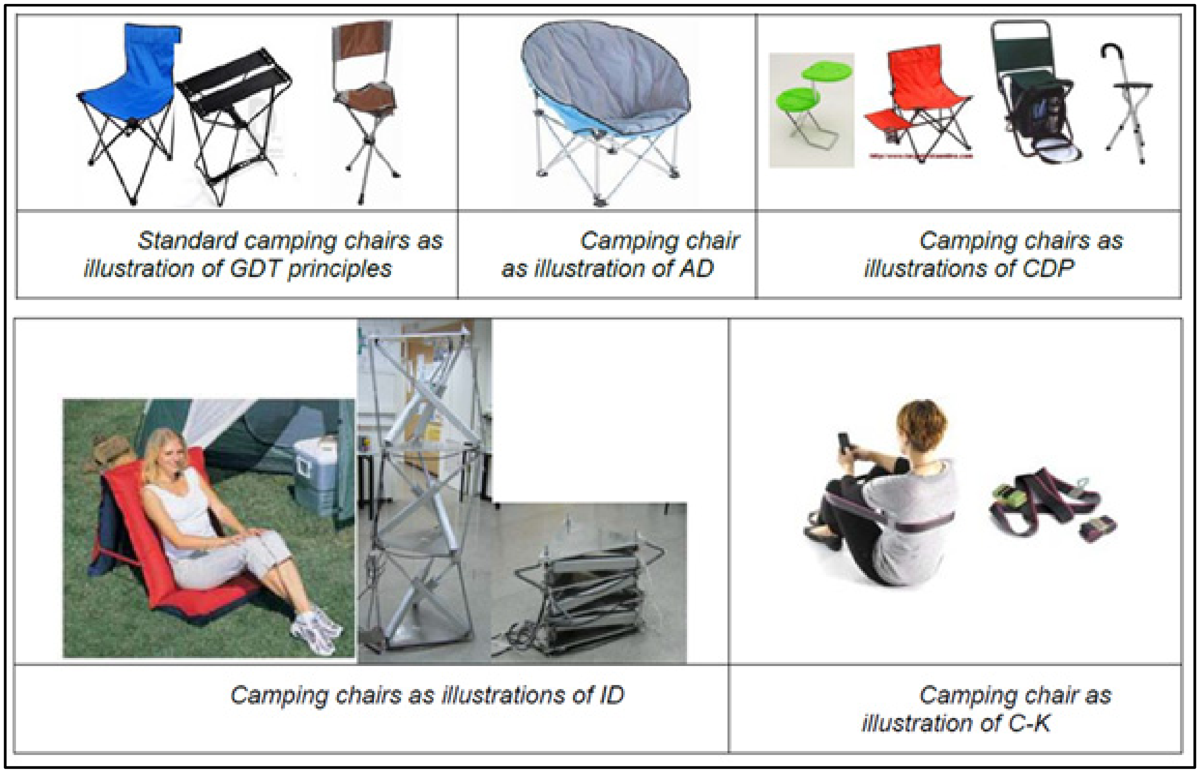

Figure 2.9. Designed camping chair with the five design theories
Taken from Hatchuel et al. (2011)

Results: The different ideas achieved by GDT, CDP, and ID clearly would arise as partitions in C obtained by different knowledge about supporting structures. Consequently, a complementary undecidable concept would be created in C: "a camping chair with no supporting structure." The concept is surprising, but it illustrates the generativeness of the C-K theory (Hatchuel et al., 2011). Also, the results illustrate that the design fixation in CK theory is less than other mentioned theories as the final results of each theory can be part of concepts in the C space of the CK theory.

2.4 Customer demands & product innovation

Due to the increment of product variety and market competition, the development of innovative products can be risky and costly. Analysis has shown that only one out of four New Product

Development (NPD) projects is successful. Thus, factors like product advantage and its market strategy are significant drivers of New Product Success (NPS) (Evanschitzky, Eisend, Calantone & Jiang, 2012). Demand and need are the essential and primary factor of innovative products design (Gang Wang, Courtright & Colbert, 2011). Hence, the methodologies like QFD have been designed and applied to the design of various products. These types of methods aim to deliver customer voice to designers for influencing the designer in order to consider and apply customer needs in the design process and product.

2.5 Quality function deployment (QFD)

QFD refers to the product development strategy that 'deploys' the customers' voice throughout the process of product development (Hauser, Griffin, Klein, Katz & Gaskin, 2010). In this regard, the cross-functional teams usually use QFD by forming a series of matrices, the initial one being referred to as the House of Quality (HOQ). This series of matrices associate customer needs and wants to various sets of product features. Accordingly, a set of matrices is often developed to measure how perfect product features can meet the customers' needs. The specifications of the product design are identified and prioritized (Hauser et al., 2010).

QFD enables the general product development team to prioritize their improvement actions systematically. According to Hauser et al. (2010), the facilitation by QFD enables the development team to collaborate and achieve a common objective concerning product design and customer needs. Additionally, it offers an 'audit trail' that reminds individuals, both old and new, to a given project, as to the reasons why the past decisions were created in a particular manner. The process of QFD usually improves the thinking capacity of the product development teams on the activities that are most crucial to the creation of a succeeding product or service. Moreover, it enhances communication between the product development team members. Consequently, the outcome is a product that is thoughtfully designed directly from the start and cut down the requirements for later reworking and reducing the development costs and time (Hauser et al., 2010). QFD is used before the design phase, during the design stage, or even after the design process. it aimed only at ensuring customer satisfaction throughout the growth of business process, additionally, it is the only comprehensive quality system that consider the customer voice for the development of the business process. Many famous companies utilize QFD like Toyota, Ford Motor Company, Procter, 3M Corporation, Gamble, AT&T, Hewlett Packard, Digital Equipment Corporation, etc.

2.5.1 House of Quality

The QFD product/service development procedure or method is based on building a series of matrices known as 'House of Quality (Bernal, Byrnes, Dornberger & Suvelza et, 2009). Clausing and Hauser (1988) described the 'house of quality' (HOQ) as the main design mechanism of the managing process known as QFD. According to Clausing and Hauser (1988), the HOQ is a kind of conceptual map that presents the standards for inter-functional planning and communications during the service or product development cycle. The authors noted that this would allow individuals with different responsibilities and hold different views to "thrash out design priorities while referring to patterns of evidence" on the matrices or HOQ's grid. Besides, according to Kim and Park (1998), HOQ is a QFD tool that is used to identify customer requirements and to establish priorities of design requirements to satisfy customer needs. QFD involves four stages of HOQ to incorporate customers' informative necessities (Clausing & Hauser, 1988; Hauser, 1993). Specifically, HOQ is used to understand the customers' needs and translate into the designer's language so that the voice of the customer can be integrated into product/service features, key process operations, and production requirements (Hauser, 1993). Bernal et al. (2009) suggest that it can be utilized to estimate benchmarking index, prioritization index, and quality advancement index (Johnson, Muller, Sieck & Tapke, n.d), which can be used to guide management practices in public organizations (Basri, 2015). The HOQ is demonstrated in the figure 2.10.

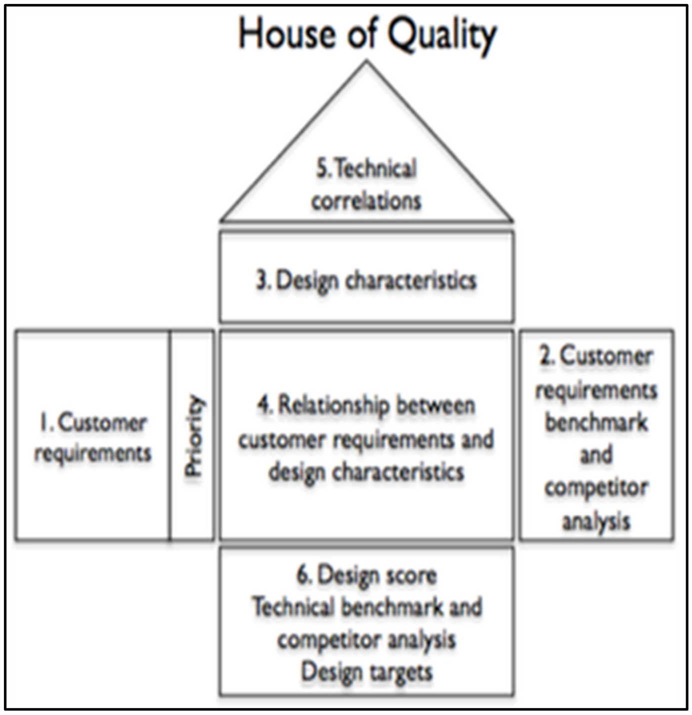

Figure 2.10. House of Quality

Taken from Hauser et al. (2010)

2.5.1.1 Calculation process of HOQ matrix

Before taking the calculation process into account, it is important to mention that, the customer desires are attributes (CA) that they want from products, and the design characteristics refer to engineering characteristics (EC). During the data collection from customers, they are asked to weight the CAs to know how much each of them are important for the product. After the weighting process, designers make a list of ECs to set the relations between CAs and ECs in HOQ matrix. These relations can be such as: strong relation-normal relation-weak relation. After completion of relation matrix process, designers make calculation to choose the suitable ECs in order to design the product based on them. In different products, ECs may have relation with each other that can affect the product negatively or positively based on CAs. These relations are shown in the roof part of HOQ. According to the figure 2.11, ECs & CAs with the relation matrix are illustrated. In this illustration, five ECs and five CAs are selected to clarify the calculation process based on these five ECs and five CAs. (Shin, Kim & Jeya Chandra, 2002)

Importance relation	
○	1
●	3
▲	6

	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6
CA_1		●	○		○	
CA_2	○		●	▲		
CA_3	▲					○
CA_4	●			○		●
CA_5			○	○	▲	
Total EC weight	Weight of EC_1	Weight of EC_2	Weight of EC_3	Weight of EC_4	Weight of EC_5	Weight of EC_6

Figure 2.11. The HOQ relations

The results are calculated based on formula below:

$$\boldsymbol{total\ weight\ of\ EC}(\mathbf{1}) = \sum[(\mathbf{WCA1} \times \mathbf{RWEC1}) + \cdots + (\boldsymbol{WCA}\mathbf{5}\ \times \boldsymbol{RWEC}\mathbf{1})]$$

WCA: Weight of Customer Attributes

RWEC: Relation Weight of Engineering Characteristics

2.6 Advantages and drawbacks of the CK theory & QFD

2.6.1 The CK theory

Various advantages of the CK theory are mentioned in previous sections indirectly (literature review of the CK theory). However, in this section some of its advantages and drawbacks are illustrated directly.

CK theory seems very useful for designing new products because of its innovation and concept generation process. The concepts can be really close to designers' targets and new products (Choulier, Coatane'a & Forest, 2010).

The structure of the CK theory is very unique and innovative. It enables to design various concepts of new products based on knowledge which, makes every stage of design logical and innovative (Choulier et al., 2010). In a comparison between other design theories which mentioned in the CK theory literature, the results of other theories can be concepts in the CK theory which, means the d. Another advantage of the theory is the knowledge expansion by new concepts generation which, can help designers in design of future products. Besides, various concepts during the design process can be new products or solutions for various needs and requirements.

For representing of drawbacks of the CK theory, various content can be mentioned such as:

In the CK theory, Design is studied and evaluated at the designer level, more specifically at the designer reasoning level. The theory can lead and guide the design process, and therefore the innovation process, however this does not imply that the design process' outcome can be predicted. Furthermore, there is no evidence about the theory that can successfully regulate and steer the innovation process. Provided examples of the CK theory by its authors are very basic without enough description about its usage of cognitive mechanism which, used by designers to assure that creative outcome is the actual results of the CK theory usage (Choulier et al., 2010).

2.6.2 QFD

QFD is a strong method that integrates user needs to design data in order to develop products for enhancing market success and meet customers' requirement.

It has been used by organizations all over the world and has been applied in nearly each area. Thanks to QFD, the voice of customer is successfully heard throughout the organization which helps to improve clients' satisfaction. Additionally, companies maintain direct touch with clients, and it also enhances internal connections between and within the firm's numerous departments. QFD assists businesses in remaining competitive by developing product design and lowering the amount of adjustments to a product. By using QFD, Designers may identify major production requirements in advance, and reducing upfront costs. Its functions have been used in different field such as timing and costing, design, planning, decision making, engineering, management, teamwork, etc. (Olewnik & Lewis, 2008). In production line, QFD can help to use strategic planning. Also, it gives data to know weaknesses and advantages of company in comparison with others (Wolniak, 2018).

Despite the methodology has many advantages, it also has limitations such as:

The QFD matrix might become complex piece, making it time consuming and requiring a huge amount of work from the user (Olewnik & Lewis, 2008). The complexness also causes difficulties to analyze and data extraction (Wolniak, 2018). The methodology is mostly qualitative; it can be difficult for designers to sort and categorize the customer needs due to their uncertainty and fuzzy nature of customer data. Besides, linking of customer data and engineering characteristics are very difficult and this can cause decrease the quality of products. QFD usage is very difficult because it needs high skills and a lot of knowledge to run (Wolniak, 2018).

2.6.3 Conclusion

Regarding the previous sections, there are different limitations and drawbacks in QFD and the CK theory, which need various research and investigations.

Based on the literature review of the CK theory, in the current structure of the theory, concepts are being designed based on designers' skills, creativity, and knowledge. The CK theory does not consider user demands in its structure to help designers provide concepts that are integrated with customer desires. However, designers may consider customer needs in their concept generation process but, it will not be reflected in design process with the CK theory. Consequently, it may arise problems such as hardening design, not considering user needs in every design process. Referring to section 2.4, with the current form of the CK theory, outcomes may not meet the market demand and cause failure. Besides, it may increase the design process period and repetition. As we studied in previous sections, one of the most important issues for product design and innovation is increasing market success and approaching market needs that come from using user needs consideration. This limitation seems to be a major element affecting product development, market success, and companies' growth.

Furthermore, QFD gets the customer needs data early in product design and development. It provides a solid and organized structure to help companies and designers match engineering characteristics with customers' needs. Although it has drawbacks, it is a strong tool to integrate user ideas and desires with design elements, and its outcomes are appropriate for companies and designers.

For this reason, this research tries to answer the following question: is it possible to eliminate the lack of customer needs integration during the design process with the CK theory by using QFD?

CHAPTER 3

METHODOLOGY OF THE RESEARCH

According to the research question and problem which is provided in the section 2.6.3, a methodology has been proposed in this chapter. Also, for testing the methodology, a new medical product has been designed which, its information is provided in the chapter 4. This chapter aims to clarify the research methodology by identifying how the CK theory and QFD can improve design considering customer demands from the first step of the design process. For this reason, the methodology process is clarified, and every process of the methodology is described step by step. The proposed methodology has been designed based on qualitative data which come from both QFD and the CK theory literature review and functions that are mentioned in chapter two. As qualitative data is used for developing a methodology, the research is based on interpretivist research philosophy. For testing the methodology, the qualitative data of the background of the case study has been studied. Then for designing a new product using the proposed methodology, it is needed to collect customer desires and their importance weight data for QFD. Consequently, both qualitative and quantitative data have been collected, which is considered as mixed-method data.

Additionally, the proposed methodology results will be divided into two parts. The first part is the results of the CK theory, which are new ideas as qualitative data. The second part is the results of the HOQ, which contains both quantitative and qualitative data as the HOQ matrix calculates quantitative data to generate final ECs, which are qualitative data. In the next parts, it is demonstrated how the data collected.

3.1 Combination of the CK theory and QFD

As QFD starts with processing customer demands to choose the most suitable options among the engineering items, the new methodology starts with customers' data collection for the HOQ matrix to understand customer needs and their point of view. It is essential to mention that the customer desires can be considered as concepts or attributes that customers seek in the products. Thus, we consider customer demands as initial concepts in the C space of the CK theory. This is because the process of design should be completed based on the demands that directly come from customers. Furthermore, lack of customer requirement utilization eliminated in the design process. After the concept generation process by the CK theory, for adding engineering specifications and features, a new space is defined as “ideas space.” In this space, concepts are integrated with engineering elements specifically designed to be applied directly to products. In addition, the integrated concepts developed with the designers' creativity skills to use engineering items in the products innovatively. So, we name these types of propositions as “Ideas” in this work. As it said before, customer demands can be considered as concepts, based on this statement, we can conclude that concepts also can be evaluated in the HOQ matrix to get the most suitable EC's for our product. For this reason, the new ideas will be transferred to HOQ to be completed with the right materials in order to get the final results. In this research, new ideas can also be considered as transformed customer requirements that describe user needs by engineering elements. This is because their source concepts come from customers. Figure 3.1 describes the research process at a glance, and the next paragraphs describe the research process.

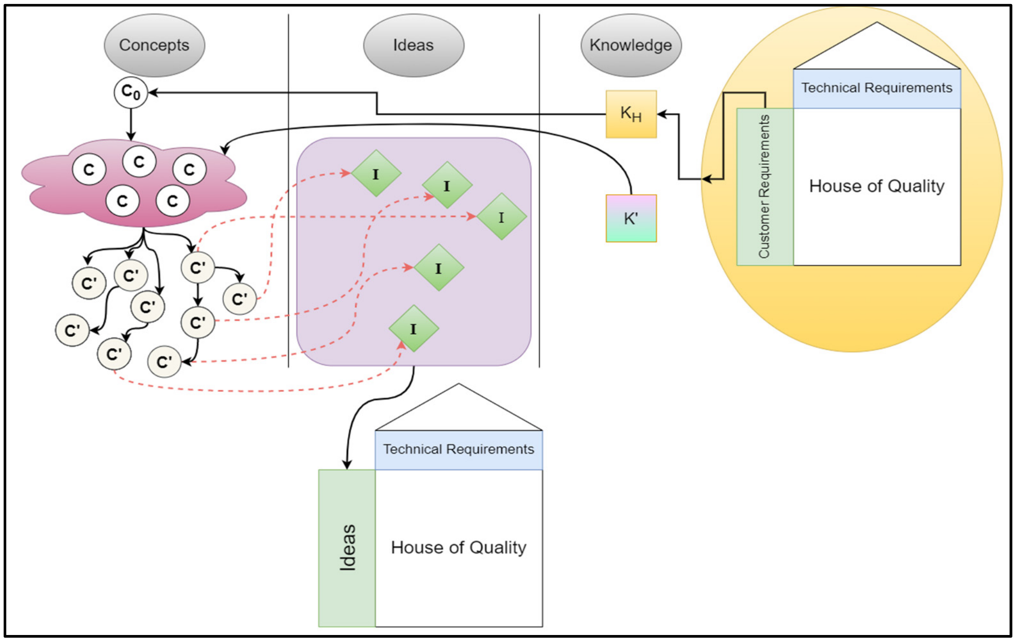

Figure 3.1. The Research process

3.2 Methodology flowchart

According to the figure3.2, the research process is illustrated in 8 steps which, are discussed in the next parts.

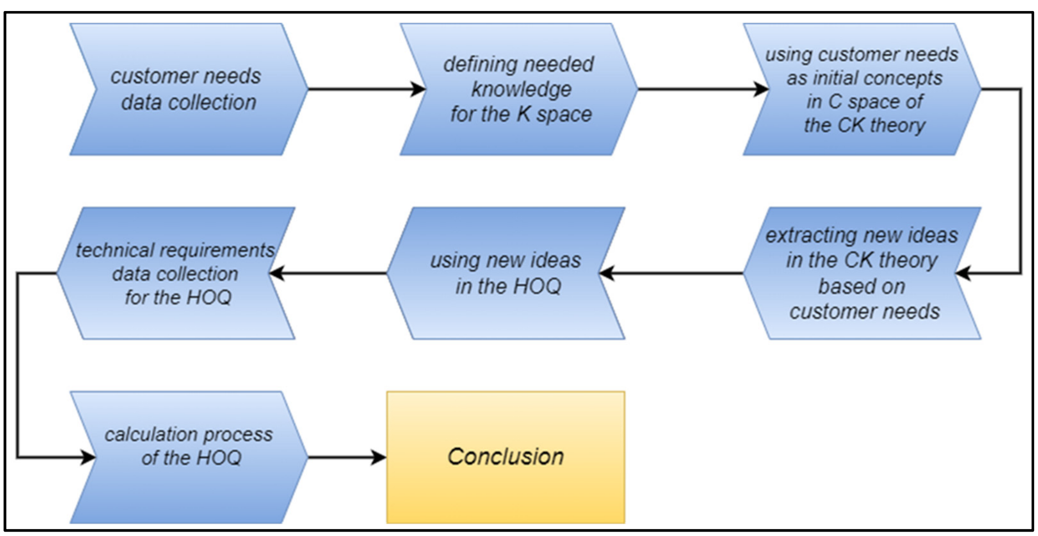

Figure 3.2. Methodology flowchart

3.2.1 Customer needs data collection

The first step of the research process starts with collecting customer desires data. Here, for our sample product, user demands collected from five physicians who do research in rehabilitation areas. After collecting data from the physicians, they were sorted to eliminate the same or similar concepts. Then, it is asked the participants to weight sorted concepts based on their importance which is one of the main rules of QFD.

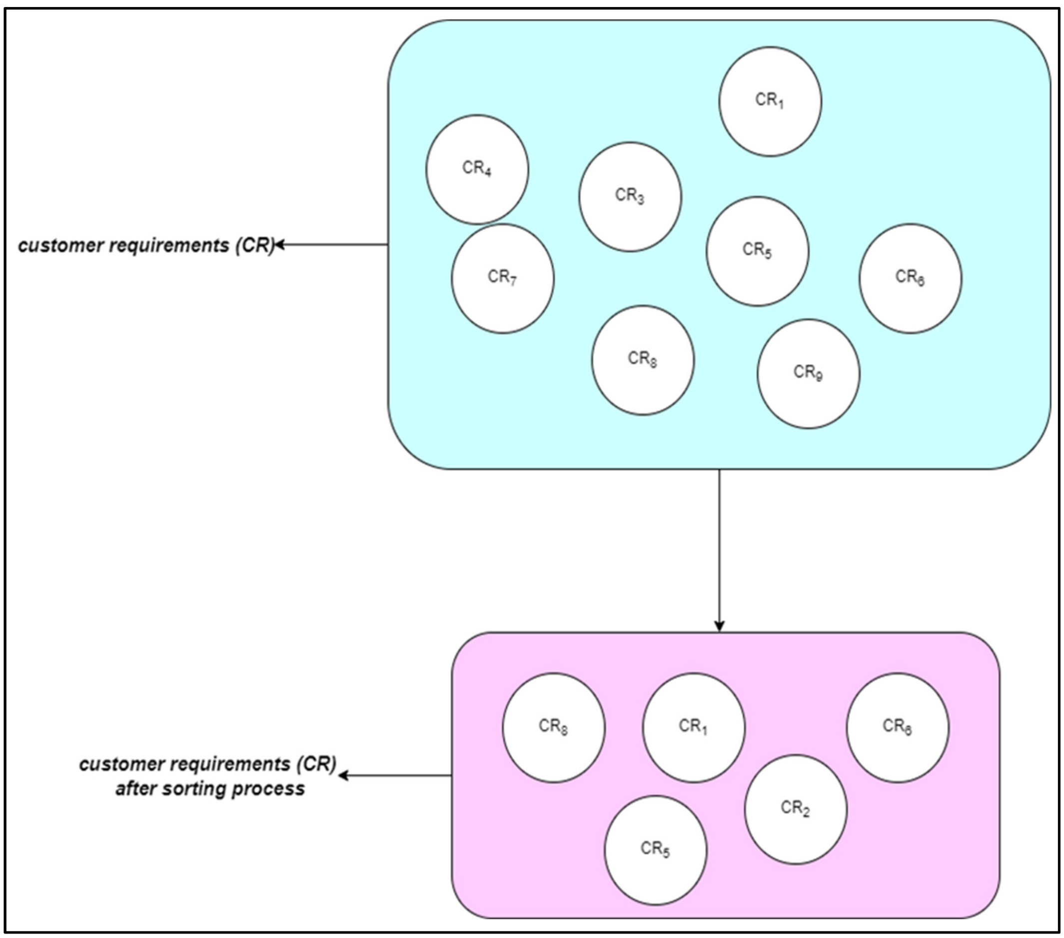

Figure 3.3. Customer requirements

3.2.2 Defining needed knowledge for the K space

According to the initial concepts which come from the HOQ, for further concepts generation, it is essential to define adequate knowledge. Also, the new knowledge will help to extract new ideas from concept space.

3.2.3 Customer needs transfer to the CK theory

After the first step, in the second step, customer demands are considered in the knowledge space in the K space of the CK theory. This is because we already have the customer desires in the first step of the design process with the CK theory. So by using the K→C operation, we have customer needs as concepts in the C space of the CK theory.

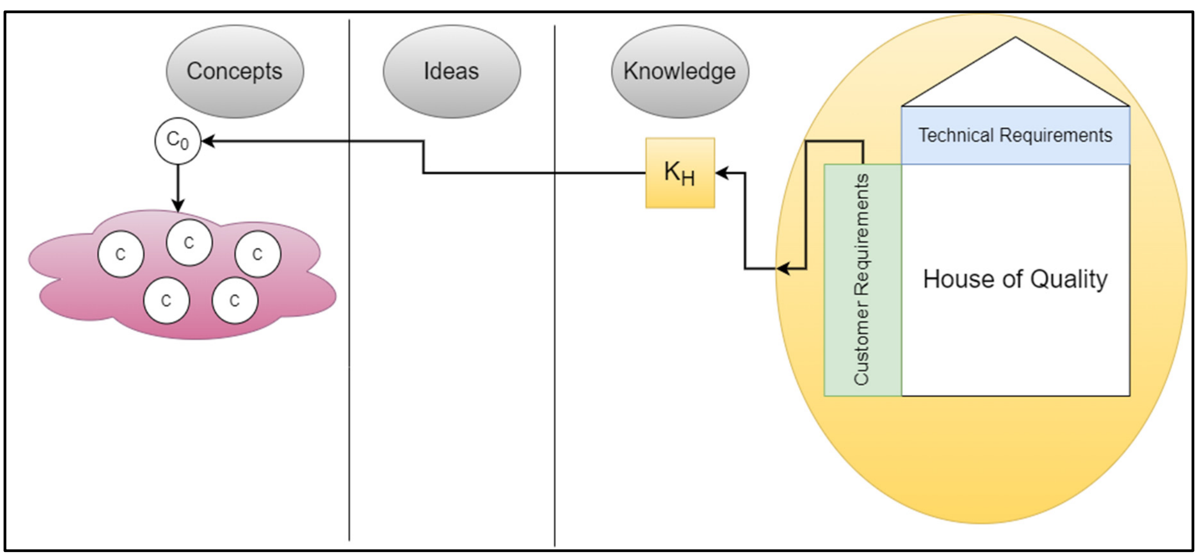

Figure 3.4. Knowledge from the HOQ

3.2.4 Design process with the CK theory

In this step, the design process continued with the rules of the CK theory. After conceptualization, ideas are extracted from the concepts. Ideas generated to be used as product specifications and in the HOQ customer desires section. For designing different products, designers can use and choose the ideas by their goals. Nevertheless, in this research, all extracted ideas have been used in the designed product as well as in the HOQ diagram.

3.2.5 New ideas extraction and their utilization in HOQ

In the structure of the CK theory, after the conceptualization process, new ideas have been extracted from the concepts. These ideas have different engineering specifications based on customer requirements. Designers can select the suitable ones for their products in the next design steps if required. Since customer desires are considered concepts, then the ideas which are concepts with engineering elements will be transferred to the HOQ structure for further steps of the research.

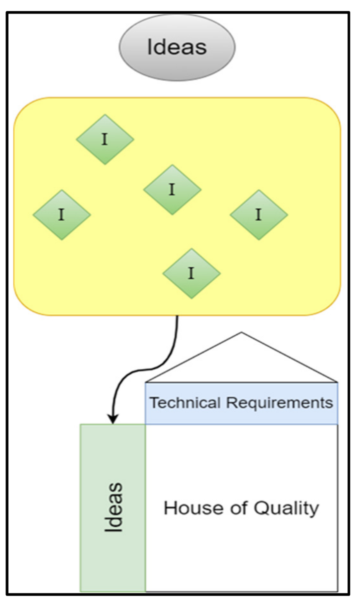

Figure 3.5. Ideas transfer to the HOQ

3.2.6 Technical requirements data collection for the HOQ

In this research, the data collection methodology for the part of the technical requirements follows the main rules of the HOQ and all technical part's data is collected based on the ideas requirements.

3.2.7 Calculation process of the HOQ

In this step of the research, it is essential to use importance weighting data in order to be able to complete the calculation process of the HOQ. According to our research, we do not have importance weight for the ideas that we added on the HOQ, and we only have the weighting data of the initial concepts, which are customer needs data. For adding importance weight, designers can consider different methods, but here importance weight of initial concepts (customer requirements) is used for related ideas. For instance, if we consider A as an initial concept with an importance weight of 4 and A' as an idea extracted from A, the importance weight for A' is considered 4. Additionally, if an idea has more than one source concept, we consider the total weight of source concepts. After adding these data to the structure of the HOQ, the calculation process follows, as it is demonstrated in chapter two, the section of the QFD.

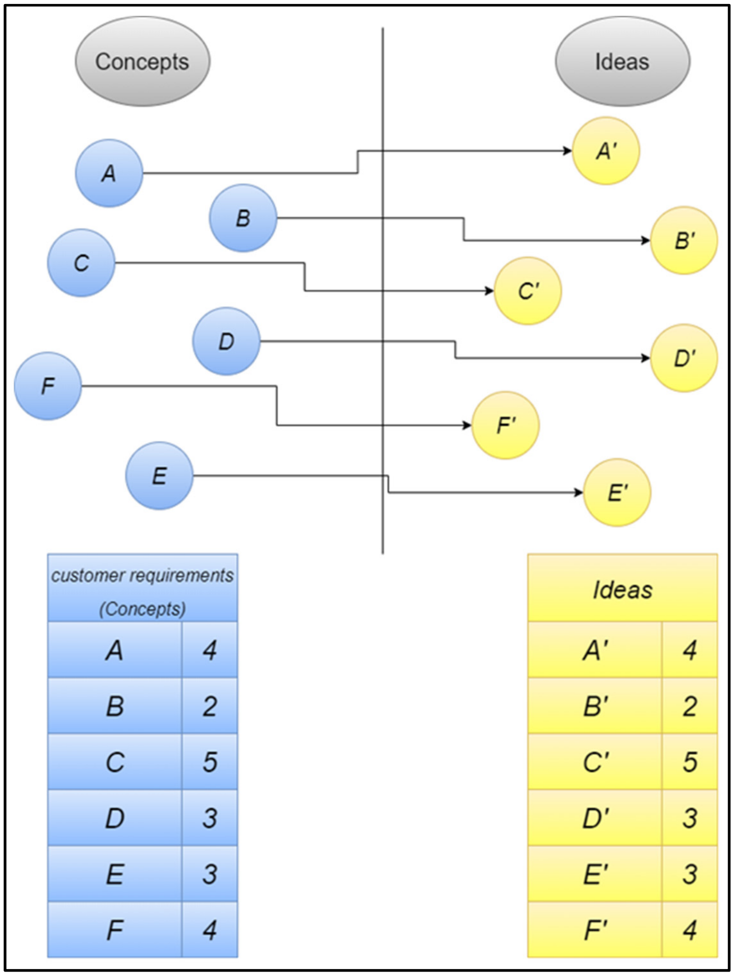

Figure 3.6. Ideas weighting process

3.3 Conclusion

In this chapter, all steps of the proposed methodology are described and reasons behind of each step of the methodology are explained. Furthermore, for designing a product, it is shown that how the needed data will be collected. In the next chapter real data are applied to the methodology to get the results and discuss the outcomes.

CHAPTER 4

RESEARCH PROCESS & RESULTS

4.1 Case study background and limitations

As a case study for this research, a lower-limb over-ground gait trainer rehabilitation device is taken into account. The design aims to provide a home-use overground gait trainer device without needing an expert while users utilize it. For this reason, literature on the lower-limb rehabilitation devices is stated with stating limitations at the end.

4.1.1 Mechatronic Systems for Lower-Limb Rehabilitation

Over the past years, several lower-limb rehabilitation robots have been presented to improve rehabilitation process and quality more than before. Díaz, Gil, & Sanchez (2011) categorized robotic systems under the rehabilitation principle, as shown in the figure 4.1. The categories are a) treadmill gait trainers; b) foot-plate-based gait trainers; c) over-ground gait trainers; d) stationary gait & ankle trainer systems; and e) active foot orthoses.

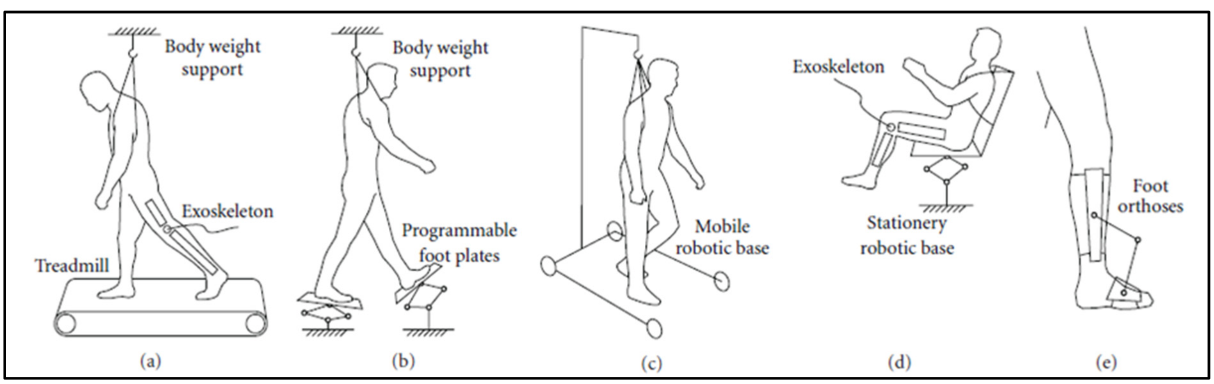

Figure 4.1. Robotic system types for lower-limb rehabilitation
Taken from Díaz et al. (2011)

4.1.2 Over-ground Gait Trainers

Over-ground gate trainers permit patients to move under their control instead of forcing them through predetermined movement practices. It is quite obvious that almost all tested systems have been commercialized. The KineAssist is a robotic tool produced by Kinea Design, LLC, for balance and gait exercise. It consists of a custom-designed torso and pelvis harness affixed to a mobile robotic base. The robot is handled according to the issue's forces by the load cells placed in the pelvic harness (Díaz et al, 2011). Besides, Díaz et al. (2011) conducted a clinical trial to evaluate over-ground walking acceleration & speed changes utilizing the KineAssist system.

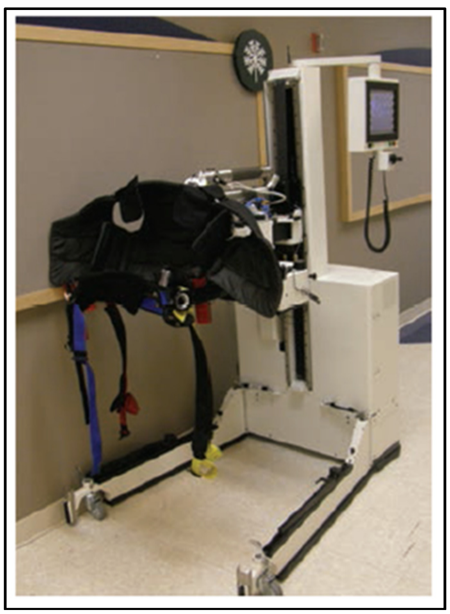

Figure 4.2. KineAssist robotic Device
Taken from Díaz et al. (2011)

A Walk-Trainer (Swortec SA) is a robotic rehabilitation system comprising de-ambulatory, pelvis orthosis, bodyweight support, two leg orthoses, and a real-time controlled electro stimulator (Meng et al., 2015). It is an over-ground walking re-education de-ambulatory with the corporation between the pelvic and the leg orthoses. The device is being used for the first clinical trials.

A ReWalk is a wearable, motorized quasi-robotic suit from ARGO Medical Technologies Ltd. that can be utilized for therapeutic needs and exercises. (Díaz et al., 2011), as shown in figure 4.3 ReWalk comprises a light wearable brace support system, which links the joints with DC motors, rechargeable batteries, various sensors, and a computer-based control system. The upper-body exercises of the patients are noticed and utilized to form and keep walking and stepping processes.

Hybrid Assistive Limb (HAL) is a wearable robot developed for multiple benefits, going from rehabilitation to serious work aid, and many built-in performances (full body version and two-leg version) (Díaz et al., 2011). The current version 5 is being used in clinical tests' conduction (Díaz et al., 2011). A single-leg version of HAL has also been designed to help the walking of patients with hemiplegia. The walking support process was once assessed with a hemiplegic matter who could not bend his right knee (Díaz et al., 2011).

Figure 4.3. ReWalk wearable system
Taken from Díaz et al. (2011)

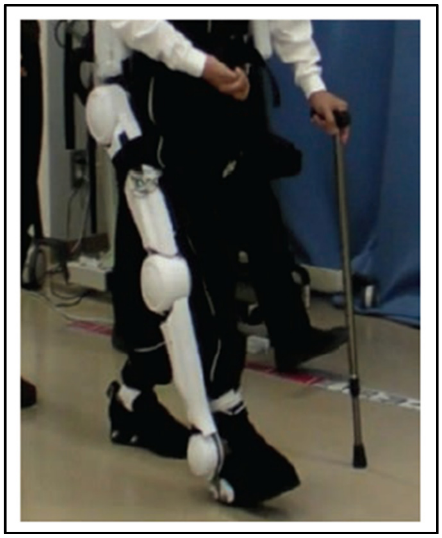

Figure 4.4. Single-leg version
of HAL robot
Taken from Díaz et al. (2011)

According to Lee et al. (2021), BWSS is another type of rehabilitation device that its structure made by two linear actuator modules, loadcell weight sensors, two arm supports, and harness. As it is shown in the figure 4.5, the two linear actuator modules connected to the harness which, signals can be send to the main system using the loadcell sensors. By using the arm supports and the harness it provides body control and safety to users (Lee, Li & Liang, 2021).

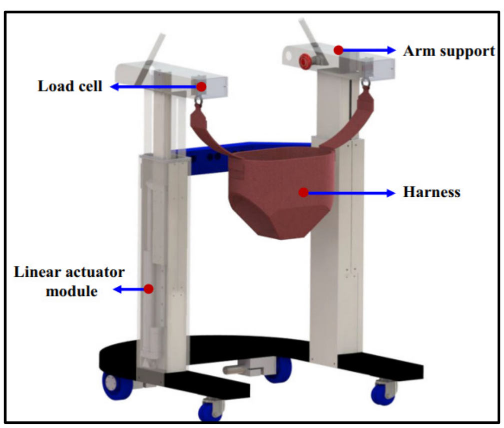

Figure 4.5. The BWSS
Taken from Lee et al. (2021)

4.1.3 Challenges and limitations

According to Meng et al., (2015), Dzahir and Yamamoto (2014), and Lee et al. (2021), most of the rehabilitation devices are used in clinical centers and need experts to run them. Besides, there is no information about robotic devices specifically designed for home use.

It is important to mention that new clinical devices decrease health problems for patients and improve their recovery period. But, patients still face many problems like high costs and expenses using these devices, long schedules that cause recovery period increment, and transportation issues when they have to be present at rehabilitation centers.

Consequently, the existence of a home-use device that doesn’t need an expert to help patients while they use the device can provide advantages that decrease the recovery period and eliminate device utilization waiting lists and transportation problems.

4.2 Design process

Before starting the design process, the figure 4.6 presents all steps of the designing home-use lower limb rehabilitation device using the proposed methodology.

To start the design process, it is important to mention that the case study selected for this research is a sample model of the real one. Due to patenting rules, it is not possible to illustrate the full version of the designed device in this research.

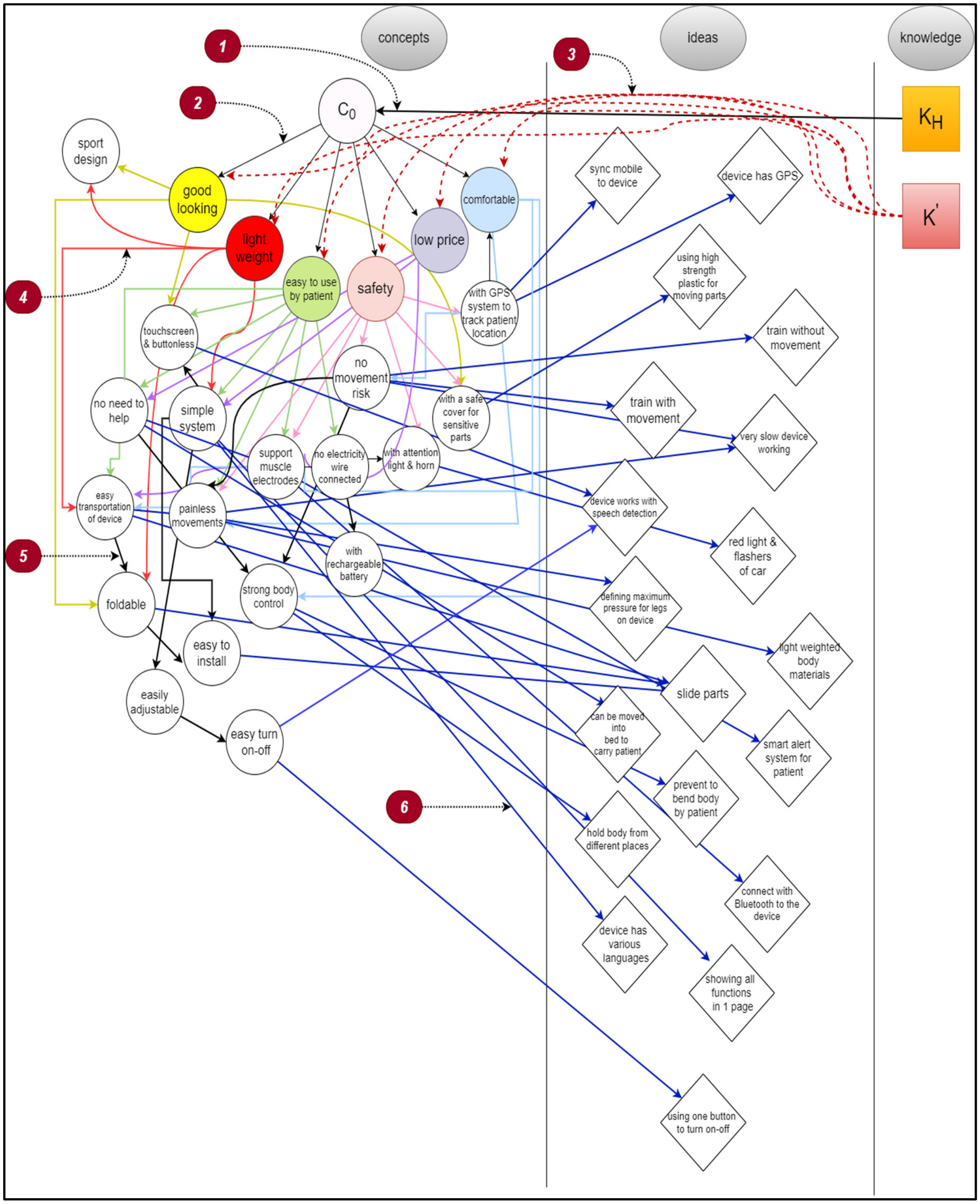

Figure 4.6. The case study design process

4.2.1 Customer needs data collection

According to the contents above, a part of the customer desires data with their weights have been determined. As previously mentioned, the data was collected from five physicians who work in the rehabilitation field. This is because they are in contact with patients who use these types of rehabilitation devices. In the first step of the data collection process, participants were interviewed and described the new device's purpose, which is the home-use rehabilitation device. The participants are then asked to give their desires concerning the new device. In the second step, a list of customer desires is made and categorized to eliminate desires stated similarly but are worded differently, for example, "easy to use everywhere" and "can be used in different places." In the third and last step, participants were asked to weight the sorted and categorized data based on their importance from one to ten. In the table below, the final data with their weights have been demonstrated:

Table 4.1. Customer desires
with their importance weights

Customer desires	**weight**
Comfortable	9
Low price	9
Safety	5
Easy to use by patients	10
Lightweight	7
Good looking	3

4.2.2 User demands transfer to the CK theory

Since the customer desires in HOQ are concepts that provided by users, and we have this information as knowledge so that we can use them in knowledge space, by K→C disjunction operation to the main concept, we have customer demands as initial concepts according to the figure4.7.

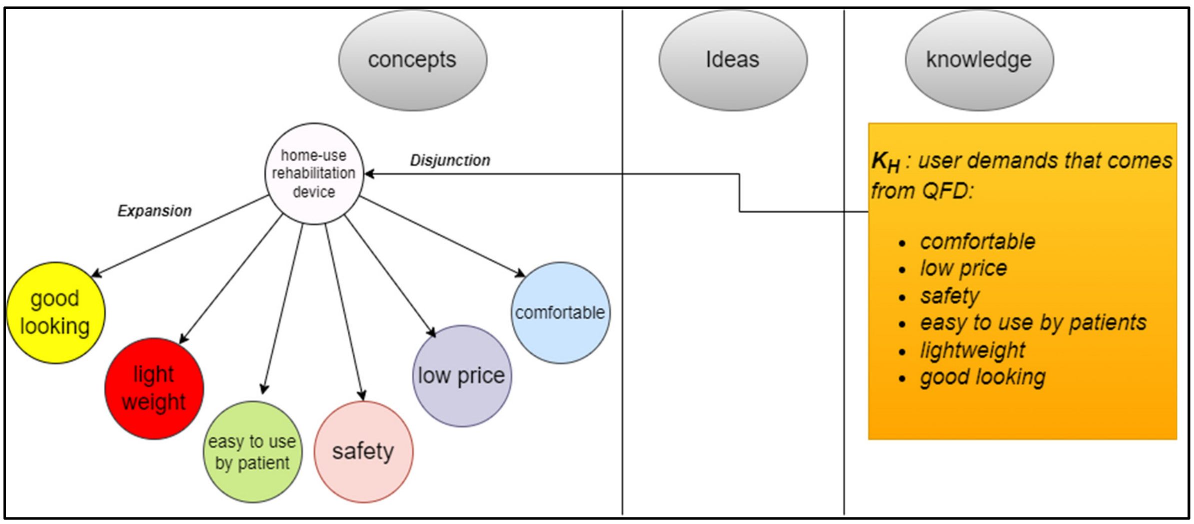

Figure 4.7. User demands utilization in the CK theory

According to the figure above, we have:

The main concept as C_0: home-use rehabilitation device

KH as the knowledge that comes from HOQ customer desires section

We have $K_H \rightarrow C_0$ as disjunction and $C_0 \rightarrow C_1$, $C_0 \rightarrow C_2$, $C_0 \rightarrow C_3$, $C_0 \rightarrow C_4$, $C_0 \rightarrow C_5$ and

C0 → C6 as expansions.

C_1, C_2, C_3, C_4, C_5 and C_6 are initial concepts which defined as C_1= comfortable home-use rehabilitation device, C_2= home-use rehabilitation device at a low price, C_3= home-use rehabilitation device with high safety, C_4= home-use rehabilitation device which is easy to use by patients, C_5= light-weighted home-use rehabilitation device and C_6= home-use rehabilitation device with good looking.

4.2.3 Defining needed knowledge for the K space

For further concept generation by the CK theory, we need to have the essential knowledge. For this reason, following part of knowledge added to the K space as K':

K': based on our experience in life, we have used different products and were in contact with numerous people who have had experiences in different situations of their life. Consequently, we can say:

A comfortable device can be a device that puts minimum pressure on the patients' body during usage and easily and safely can be moved.

A cheap or low-price device can be a device that does not require experts to use it, does not have a complex system, and can be moved without special conditions requirement.

A safe device can have the minimum risk for patients during usage, its body does not harm users in all situations, and it can prevent danger in all conditions. For instance, tracking users' conditions can increase safety. This is about tracking location and body condition. For tracking location nowadays, people use GPS technology. For the body condition tracking, like blood pressure and muscular pressure, can be tracked by blood pressure monitors or devices, and muscle pressure can be tracked by muscle electrodes and devices (B. Armstrong, 2019).

An easily usable device can be a device that has a simple system, it does not require experts to help the user during utilization, and it is also safe.

A light-weighted device can be determined as a device with low-weighted materials.

A device that looks good can have a good shape, or it can look like a sports product and take less space.

4.2.4 Expanding initial concepts to new concepts

Regarding the CK theory operations, and the figure 4.8, by using K→C disjunction and C→C' expansion, we have the following concepts in the next step of the design:

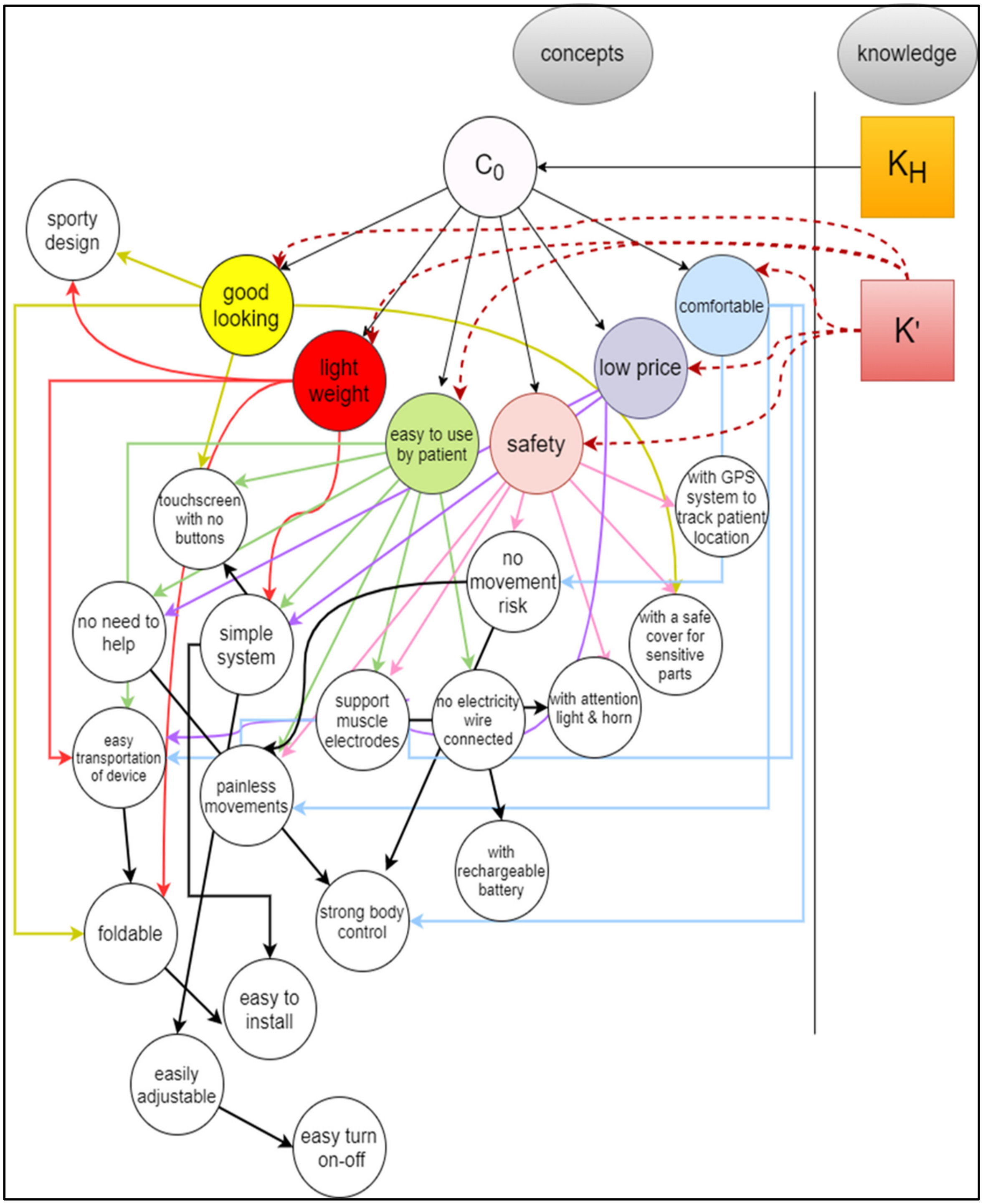

Figure 4.8. C expansion

Concepts that extracted by using K→C disjunction:

Table 4.2. Extracted concepts

Initial concepts	**Extracted concepts**
C_1	1- Rehabilitation device with no movement risk. 2- Rehabilitation device with easy transportation. 3- Rehabilitation device with painless movement. 4 -Rehabilitation device that gives users strong body control.
C_2	1- Rehabilitation device with easy transportation. 2- Rehabilitation device with simple system. 3- Rehabilitation device with no need to help for utilizing.
C_3	1- Rehabilitation device with GPS to track patient's location. 2- Rehabilitation device with safe cover for sensitive parts. 3- Rehabilitation device with attention light & horn. 4- Rehabilitation device with no movement risk. 5- Rehabilitation device that supports muscle electrodes. 6- Rehabilitation device with painless movement.
C_4	1- Rehabilitation device with a touchscreen with no buttons. 2- Rehabilitation device with simple system. 3- Rehabilitation device with easy transportation. 4- Rehabilitation device with no need to help for utilizing. 5- Rehabilitation device with painless movement. 6- Rehabilitation device that supports muscle electrodes. 7- Rehabilitation device that has no electricity wire connected.
C_5	1- Rehabilitation device with simple system. 2- Rehabilitation device that is foldable.
C_6	1- Rehabilitation device that is foldable. 2- Rehabilitation device that has a sporty design. 3- Rehabilitation device with safe cover for sensitive parts. 4- Rehabilitation device with a touchscreen with no buttons.

Besides, we have concepts that come from C→C' expansion:

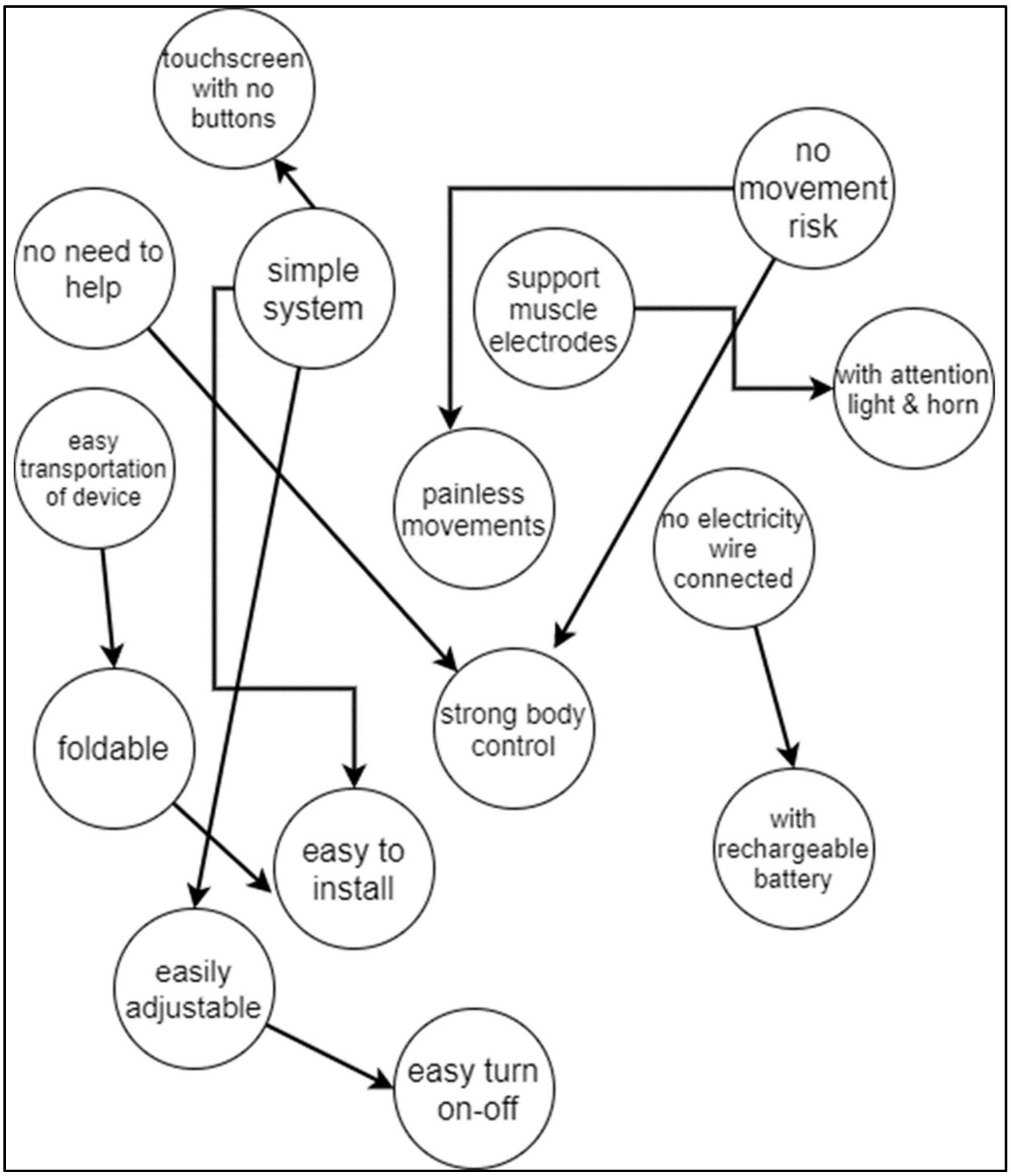

Figure 4.9. Expanded concepts & their sources

As illustrated in the figure 4.9, we have the following concepts:

Table 4.3. Expanded concepts

Concepts (C)	**Further concepts by expansion operation (C')**
Rehabilitation device with no movement risk	1- Rehabilitation device with painless movement. 2- Rehabilitation device with strong body control ability.
Rehabilitation device that supports muscle electrodes	1- Rehabilitation device with attention light & horn.
Rehabilitation device that has no electricity wire connected	1- Rehabilitation device with a rechargeable battery.
Rehabilitation device with simple system	1- Rehabilitation device with a touchscreen with no buttons. 2- Rehabilitation device that is easy to install. 3- Rehabilitation device that is easily adjustable.
Rehabilitation device with easy transportation	1- Rehabilitation device that is foldable.
Rehabilitation device with no need to help	1- Rehabilitation device with strong body control ability.
Rehabilitation device that is foldable	1- Rehabilitation device that is easy to install.
Rehabilitation device that is easily adjustable	1- Rehabilitation device that is easy to turn it on or off.

4.2.5 New ideas resulted from final concepts & their usage in HOQ

4.2.5.1 Ideas extraction

After the conceptualization process, new ideas are generated based on the last concepts extracted using K→C and C→C' operations. These ideas are specifications that can be used in the new device, which came from customer needs data. In the first part of this section, new ideas are demonstrated then moved to the 'customer desires section of the house of quality. The figure 4.10 shows the process:

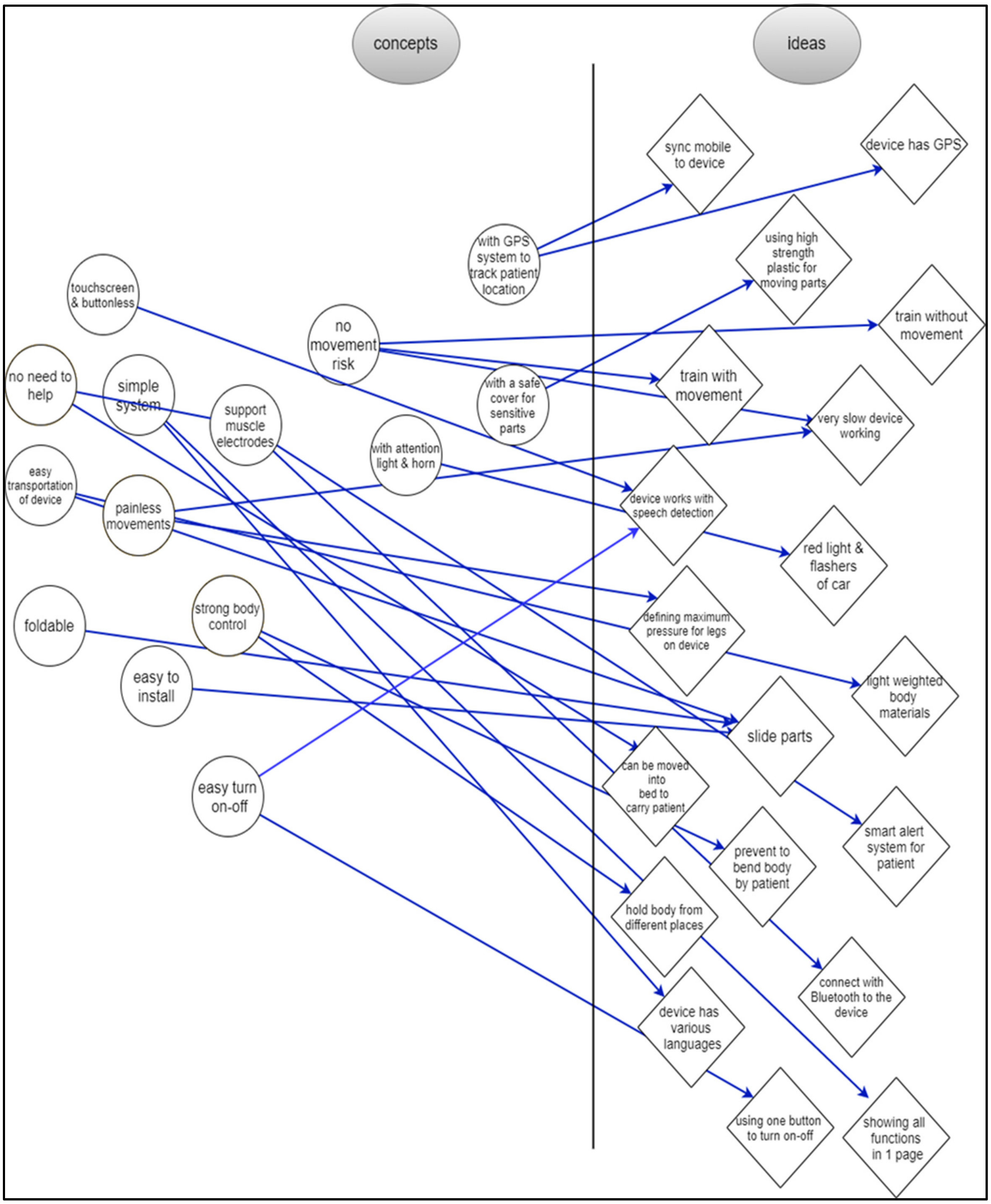

Figure 4.10. Ideas & their sources

Table 4.4. Extracted ideas

Concepts	Ideas
Rehabilitation device with GPS to track patient's location	1- Sync mobile to the rehabilitation device. 2- Rehabilitation device has GPS.
Rehabilitation device with painless movement	1- Rehabilitation device trains patients without movement. 2- Rehabilitation device trains patients with movement. 3- Rehabilitation device that works very slow.
Rehabilitation device with safe cover for sensitive parts	1- Rehabilitation device has high strength plastic for moving parts.
Rehabilitation device with attention light & horn	1- Rehabilitation device has red light & flashers of car.
Rehabilitation device with a touchscreen with no buttons	1- Rehabilitation device works with speech detection.
Rehabilitation device with simple system	1- Rehabilitation device has various languages in its system. 2- Rehabilitation device shows all functions on one page.
Rehabilitation device that supports muscle electrodes	1- Rehabilitation device has smart alert system for patients. 2- Rehabilitation device allows to connect with Bluetooth to its main system.
Rehabilitation device with no need to help for utilizing	1- Rehabilitation device has smart alert system for patients. 2- Rehabilitation device can be moved into bed to carry patient.
Rehabilitation device with painless movement	1- Rehabilitation device that works very slow. 2- Rehabilitation device that allows defining maximum pressure for legs on the device.
Rehabilitation device with easy transportation	1- Rehabilitation device has light-weighted body materials. 2- Rehabilitation device has slide parts.
Rehabilitation device with strong body control ability	1- Rehabilitation device prevents to bend body by the patient. 2- Rehabilitation device holds body from different places.
Rehabilitation device that is foldable	1- Rehabilitation device has slide parts.
Rehabilitation device that is easy to install	1- Rehabilitation device has slide parts.
Rehabilitation device that is easy to turn on or off	1- Rehabilitation device works with speech detection. 2- Rehabilitation device has one button to turn on-off

4.2.5.2 Ideas utilization in HOQ

In this part, the ideas take place in HOQ in the customer requirement section.

Table 4.5. Ideas quantity

Quantity	Ideas
1	Sync mobile to the rehabilitation device
2	Rehabilitation device has GPS
3	Rehabilitation device trains patients without movement
4	Rehabilitation device trains patients with movement
5	Rehabilitation device that works very slow
6	Rehabilitation device has high strength plastic for moving parts
7	Rehabilitation device has red light & flashers of car
8	Rehabilitation device works with speech detection
9	Rehabilitation device has various languages in its system
10	Rehabilitation device shows all functions in one page
11	Rehabilitation device has smart alert system for patients
12	Rehabilitation device allows connecting with Bluetooth to its main system
13	Rehabilitation device that allows defining maximum pressure for legs on the device
14	Rehabilitation device has light-weighted body materials
15	Rehabilitation device has slide parts
16	Rehabilitation device prevents to bend body by patient
17	Rehabilitation device holds body from different places
18	Rehabilitation device has one button to turn on-off
19	Rehabilitation device can be moved into bed to carry patient.

In order to fit the ideas better in the HOQ diagram, alphabet letters were replaced for the description of each idea which, have been shown in the following table:

Table 4.6. Ideas in alphabet letters

No.	Ideas
1	A
2	B
3	C
4	D
5	E
6	F
7	G
8	H
9	I
10	J
11	K
12	L
13	M
14	N
15	O
16	P
17	Q
18	R
19	S

4.2.6 Calculation process of the HOQ

4.2.6.1 Ideas with their assigned importance weight

Referring to section 3.2.6, in order to continue ideas utilization in the HOQ, importance weight for each idea is assigned based on their source customer desire data. Before the demonstration of the results, the table 7 in below shows the source concepts of each idea:

Table 4.7. Source concepts of ideas

Ideas	Source concept(s)
A	safety
B	safety
C	Comfortable-safety
D	Comfortable-safety
E	Comfortable-safety-easy to use by patients
F	Safety-good looking
G	safety
H	Low price-easy to use-good looking
I	Low price-easy to use-light weight
J	Low price-easy to use-light weight
K	Easy to use-safety
L	Easy to use-safety
M	Easy to use-safety-comfortable
N	Easy to use-light weight-comfortable-low price
O	Easy to use-light weight-comfortable-low price-safety-good looking
P	Easy to use-safety-comfortable-low price
Q	Easy to use-safety-comfortable-low price
R	Low price-easy to use-light weight
S	Low price-easy to use

According to the above table, we have more than one source concept for some ideas, so the importance weight for the ideas is considered the total weight of their source concepts. Consequently, the following table illustrates the importance weight of each idea:

Table 4.8. Importance weight of ideas

Ideas	Importance weight	Ideas	Importance weight
A	5	K	15
B	5	L	15
C	14	M	24
D	14	N	35
E	24	O	43
F	8	P	33
G	5	Q	33
H	22	R	26
I	26	S	19
J	26		

4.2.6.2 Technical requirements data

In this sub-section, all required engineering requirements for the product have been presented. According to the different parts of the product, the following elements collected to be calculated in the HOQ diagram in order to select the most suitable ones, for each need, their usage and information are described as well:

For lifting patients by the device, it is possible to lift every person from their armpit. However, they should not have an injury from the arms and armpit areas. Additionally, Clinical devices can lift patients from axilla, groin or both. Lifting patients from both axilla and groin makes weight division of the body and gives good control for their balance (Aliman, Ramli & Haris, 2017; Duncan et al., 2011). So, we have four types of lifting types that take place in the engineering section of the HOQ, which are: lifting patients from armpit- lifting patients from groin- lifting patients from axilla- lifting patients from axilla & groin.

For movement needs, Jacks have many functions. Many sectors use jacks to lift heavy items, such as lifting cars in garages and trains to repair them. Jacks are also used in gait trainers to lift patients. There are different types of jacks, depending on the amount of weight to be lifted, movement speed, and accuracy. Jacks can be considered in two types: 1- mechanical jacks. 2- Electrical jacks. Electrical jacks are also divided into three types: 1- pneumatic jacks. 2- electro-mechanical jacks. 3- Hydraulic jacks.

Figure 4.11. Windhoff Lifting Jacks
Taken from imtram.com

For measuring the carried weight of patients by device, the next step aims to determine what facilities can measure the lifted weight during the device usage. Also, lifted weight by legs should be identified for medical purposes. Currently, different devices use similar methods to measure peoples' weight. The main item to measure the weight is weight sensors. Different sensors are designed for several purposes. They are designed to measure different weights; for example, some take bottom or top measurements separately, and therefore, designed to be used in different positions in different systems. An example is the bodyweight measuring system that a person stands on it to measure their weight.

Another example is the bascule weight measuring system. An item is hung on the bascule system, and its weight is read from the machine. Such systems have weight sensors that convert the weight to digital data and send it to a processor. In turn, the prossessor converts the digital data to the weight that the users read. Besides, connecting these sensors to Bluetooth boards is possible to send and receive data from processors (Yuen, Park & Friedman, 2013). There are many types of weight measurement sensors; for this project, four models are considered as SB6 Beam Load Cell (20 - 204kg), MHT force transducer (1-200kg), SB8 Beam Load Cell (10 - 500kg), and Asixx s type high precision load cell 300kg. These sensors and boards measure weight in a microsecond (Aykac, Kalkan, Aykac, Karahan & Kayar, 2013; Warner et al., 1993).

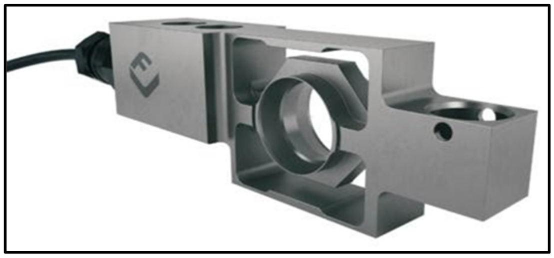

Figure 4.12. SB6 Beam Load Cell

Taken from flintec.com

Figure 4.13. SB8 Beam Load Cell

Taken from flintec.com

Figure 4.14. MHT1 Force transducer

Taken from flintec.com

Figure 4.15. S-type Beam Load Cell

Taken from amazon.com

The next step of the design process is to determine how the device's system can read the weight data and decrease and increase the patient's lifted weight by the device. It is essential to use a processor to measure and illustrate the weight by sensors and show them on LCD. Also, for speech detection and the alert system needed processor must be high-tech and have speed. There are processor boards that can perform many actions depending on the programming applied. Also, there should be a system for jack's movements to do movement commands by sending movement signals like up, down, and stop, which will be requested by the users (Yuen, Park & Friedman, 2013). Such boards are available in several kinds, including very accurate, quick, and low-priced. For example, the ESP8266, ESP32, Arduino Uno, and Arduino Nano are very famous besides being very accurate and quick. For LCD, it is only needed the basic coloured one; for this purpose, the most suitable screen is the Adafruit TFT LCD touch screen, which also allows users to do commands by its touch panel as the button (Plaza, Sancristobal, Carro, Castro & Ruiz, 2018).

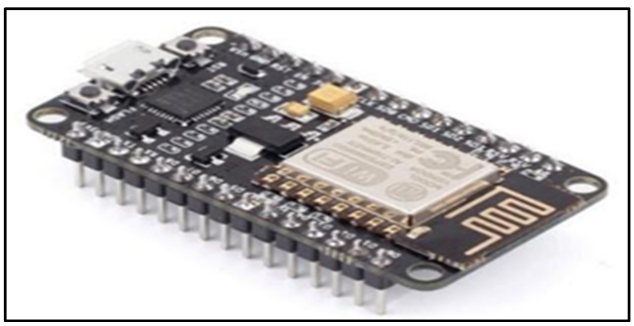

Figure 4.16. Nodemcu V2 - Esp8266 Kit

Taken from antratek.com

Figure 4.17. ESP32-DEV

KIT-32UE

Taken from digikey.ca

Figure 4.18. ARDUINO UNO
Taken from elmwoodelectronics.ca

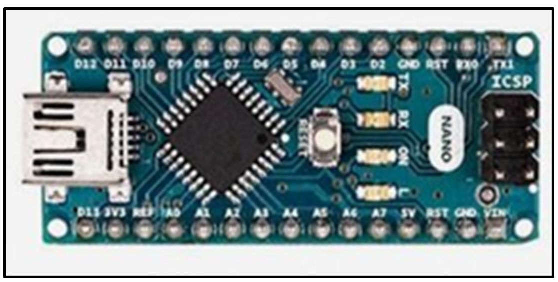

Figure 4.19. ARDUINO NANO
Taken from store.arduino.cc

Additionally, five types are considered for the body materials: steel- plastic- ferrite- aluminum-cast iron. Besides, for the device size 3 different sizes are designed based on the product's specifications as: length: 2m- 2.2m- 2.4m. Width: 0.8m- 1m- 1.2m.

4.2.6.3 The HOQ

After data collection for the engineering requirements section of HOQ, the final step in this section provides a full HOQ matrix with details and results based on previously mentioned information. The figure 4.20 illustrates the full HOQ diagram for this research:

relation weight	
○	1
●	3
◆	6

Importance weight	Ideas \ Technical Requirements	Lifting types				Movement				Weight sensors				Processors				Lentgh size			Width size			Body material				
		Axilla	Groin	Armpit	Axilla & Groin	Mechanical jack	Electro-mechanical jack	Pneumatic jack	Hydraulic jack	SB6 Beam Load Cell	MHT force transducer	SB8 Beam Load Cell	Asixx s type	ESP8266	ESP32	Arduino Uno	Arduino Nano	2 m	2.2 m	2.4 m	0.8 m	1 m	1.2 m	Steel	Plastic	Ferrite	Aluminum	Cast Iron
5	A													◆	◆	●	●											
5	B													◆	◆	●	●											
14	C					○	◆	◆	●																			
14	D					○	◆	◆	●																			
24	E					○	◆	●	○					◆	◆	○	○											
8	F																							○	◆	○	○	○
5	G													◆	◆	◆	◆											
22	H													◆	◆	●	●											
26	I													◆	◆	◆	◆											
26	J													◆	●	●	●											
15	K									●	●	◆	○	◆	●	○	○											
15	L													◆	◆	◆	◆											
24	M													◆	●	●	●											
35	N									○	○	◆	○											○	◆	○	●	○
43	O					○	◆	◆	○																			
33	P	●	○	●	◆													●	◆	●	●	●	◆					
33	Q	○	○	●	◆													○	●	◆	○	●	◆					
26	R													◆	◆	◆	◆											
19	S	●	○	●	●													○	●	●	○	●	◆	○	●	○	◆	○
	Total weight	189	85	255	453	95	570	498	151	80	80	300	80	1158	963	717	717	151	411	354	151	255	510	97	525	97	278	97

Figure 4.20. The HOQ diagram

As a result, technical needs for the product are selected based on the highest total weight for each EC.

For the lifting type “axilla & groin”, for the movement “electro-mechanical jack”, for the weight sensors “SB8 Beam Load Cell”, for the processors “ESP8266”, for the length size “2.2m”, for the width size “1.2m”, and for the body material part “plastic” got the highest weight and are selected to be used in the product. It is also important to mention that the technical correlation part of the HOQ is not utilized in this research because no relation is found between the engineering characteristics.

4.3 Conclusion

In chapter 4, the real product has been designed based on the proposed methodology. During the design process, 6 customer needs were collected and considered a part of knowledge in the structure of the CK theory. Then, they became 6 raw concepts in the C space using the CK theory operations. After the expansion process, 14 new concepts have been generated that don't have specific engineering elements. Later, 19 new ideas were added to the space of the ideas which, have engineering specifications. Based on the methodology, the ideas transferred to the HOQ structure and assigned with the total importance weight of their source concepts considered in the K space before starting the design process. In the next step, engineering materials are collected in order to complete the HOQ for starting the calculation process of the HOQ matrix. After the calculation process, the right materials are selected for the ideas in order to apply them directly to the product.

The results illustrate that, by using the methodology, customer demands are applied to the product directly with creative features and solutions. By having ideas, the collection of engineering characteristics becomes easier due to being aware of what types of materials should be applied to the product.

Furthermore, using customer demands decreased design fixation by adding different design perspectives, which helped to design different concepts and ideas by looking from the customers' point of view. Besides, doubts about using ideas and concepts decreased by knowing user demands during the design process. Also, there was no need to repeat a step or conceptualization for designing the product.

In conclusion, the new methodology eliminated the lack of user demand consideration in the structure of the CK theory. It increased the accuracy of the QFD outcomes by using Ideas instead of customer desires.

CONCLUSION

Regarding the research process and the methodology, the results are determined in the following statement:

According to the main purpose of this research, integration of the CK theory and the QFD helped the design process and the case study product be designed based on customer desires and points of view. The methodology used in this research allows us to extract the concepts and ideas from customer needs, which means the details of the product are designed based on user data. Besides, using ideas in the house of quality diagram helped define engineering needs according to the product specifications. Consequently, engineering requirements are selected regarding both product specifications and customer demands.

Additionally, considering user needs from the first step of the design decreased design process steps and eliminated design doubts at the time of the design. Using the methodology, the market success rate for the product is impacted positively due to customer needs utilization in each step of the design.

Although the methodology has advantages, it has limitations, as stated below:

Regarding the CK theory results, several ideas have been generated for a single need which may not be needed to apply all the related ideas to the new product. This means that the proposed methodology does not help the designers in the decision-making process of ideas, and designers should decide about the ideas based on their knowledge.

Also, the customer needs data could not be enough to address all the needs of users and causing designers to do not have an adequate understanding of consumers' needs, and the new product may not meet the customer satisfaction.

Besides, the designed product has not been tested in the market, so it is needed to test the product in the real market to get accurate results of the methodology.

In addition, it is highly recommended that researchers do research and investigate the methodology with a new product design, using feedback from consumers and the market success rate to discuss the results of this research. As a proposition, researchers can gather designers, make 3 to 5 groups, train them with the CK theory and the new methodology, assign different design projects to each team, and ask them to design their product with the CK theory and the proposed methodology. After the design process, the researchers can compare the products which came from the CK theory and the proposed methodology in order to evaluate the generativeness and impact of the new methodology on the products. Also, they can ask a group of users to test the products and do a survey to get their feedback to know if the results of the users demonstrate the success rate of the proposed methodology by the products that come from it.

As the last recommendation, researchers can research different species of design fixation, such as designing products for behaviour change. There is always a gap for many folks between what they want to do and what they actually do. This gap is called the intention-action gap. Sometimes humans utilize specific products and make bad decisions because of their behaviour that comes from life experiences. Besides, some products' goal is to help and limit the bad behaviours of their users. These types of products can be such as medical or educational products.

For this reason, understanding such problems can be difficult and is a type of design fixation. Since the new methodology studies user needs, it would be interesting to investigate behaviour change with it. But before taking behaviour change into account, it is highly recommended to refer to the book entitled "designing for behaviour change" by Wendel (2013) for a deep understanding of the fixation and his propositions regarding the actions that can help designers and researchers to get accurate results.

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