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Chapter 8
An Application of Quality Function Deployment and Axiomatic Design to the Conceptual Design of Temporary Housing

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Abstract

The interdisciplinary complexity of modern construction projects has made meeting customer needs and requirements a difficult task. Under the current model, decisions affecting the early stages of design when designers have the largest impact on the final cost and functionality of a given product are approached in an informal and non-homogeneous manner. This study proposes an alternative approach, combining Quality Function Deployment (QFD) and Axiomatic Design (AD) methodology as a systematic way to approach the conceptual design phase of construction projects; specific to temporary housing. This methodology would help to ensure the designer meets the customer’s needs and requirements, as well as satisfies the design objectives in a homogeneous manner. More precisely, the QFD-AD method proposed herein is considered novel because it combines two prevalent design methodologies in a way that allows a smooth transition from the translation of customer needs into a formal and methodical design approach. The method also allows for an effective framework to help evaluate and compare conceptual design decisions, including the complex process of material selection. The design of a refugee housing unit is presented as an illustrative case study of temporary housing.

Key-words: Quality Function Deployment (QFD), Axiomatic Design (AD), QFD-AD, refugee housing, civil engineering design.

8.1 Introduction

Construction projects are rapidly growing in complexity. Modern designers in the construction industry need to consider more encompassing view including the life-cycle issues (such as constructability, durability, life-cycle maintenance, energy efficiency, the cost of maintenance, environmental impact, and social-economic impact) and the more traditional concerns (such as aesthetics, structural integrity and initial cost) [1]. According to Marchesi et al. [2], the intricacy of modern architectural design demands a more rational approach to the design phase when decisions with fundamental and extensive effects on appearance, performance, and costs are made. This is perhaps even truer in the case of Temporary Housing (TH in the reminder of this text), which faces the broader challenges of a typical construction project as well as the need to satisfy a diverse range of stakeholders. To handle the growing complexity and find a more rational approach to design, many designers are looking outside of the traditional domain for solutions, particularly during the early design phase [1, 3-8]

Throughout a construction project timeline, the decisions impact decreases as the project progresses such that earlier decisions have greater importance. However, "rigorous analytical methods and optimization systems are used for decisions that impact project costs by plus or minus 7% (detailed design phase), while decisions that impact project costs plus or minus 30% (conceptual design phase) are internalized"[1]. Civil engineering and architectural work typically begins with a broad conceptual design performed by experienced experts who have received input from key stakeholders. However, the mounting intricacy of the conceptual design phase makes it difficult for even the most experienced engineer to effectively capture and understand the diverse range of customer demands, much less ensure all of their needs are met during preliminary design phase. Temporary housing, a field awash with different stakeholders, is even more liable to have trouble capturing the customer demands. Design of temporary housing is equally, if not more, complex as a traditional construction project, particularly given the diverse contexts, environments, and stakeholders they are subject to. Therefore, it is critical to have robust, rigorous, and methodical approaches to early conceptual design for said TH projects.

Traditional design methods typically include building to code, formal/informal discussions with the clients and/or iterative design stages; however, some find these methods lacking in their ability to capture client needs and requirements and so other methods not typically applied in construction design may be useful. "In the construction industry, usually the client needs and requirements are not treated systematically. Even if they are collected before the design phase, they tend to be disregarded and finally vanish as the construction phase goes on" [3]. This has forced the construction industry to turn to other fields for direction. Newer fields, like manufacturing engineering, have developed a number of methods to improve product design and development projects based on customer requirements. Literature has demonstrated that manufacturing new product development (NPD) and construction share a number of similarities [9]. Due to this similarity, methods used in NPD are easily adaptable to the construction industry. Two popular NPD mythologies are Quality Function Deployment (QFD) and Axiomatic Design (AD), both of which are used in this study.

AD was developed by Nam P. Suh in the 1980's and like QFD, has quickly grown in popularity because of its ability to improve the conceptual design stage of a variety of different products. It has been used to develop products as complex as an autobus or refrigerator, to simple products like an efficiently designed soda can or bottle opener [10, 11]. AD works by creating a systematic approach to decomposing the design in a series of steps that takes it from a high-level view to a low-level view, while simultaneously encouraging adaptability. While AD is a strong design methodology, currently it assumes that the designer has identified the users Functional Requirements "well" before beginning. In earlier works, AD was used specifically for Temporary Housing conceptual design [12, 13].

The QFD methodology was developed in Japan in the 1960's by Mitsubishi Heavy Industries to improve the design of ships in the Kobe shipyards. It was adopted by Toyota in the 1970's and since has been used by car manufacturers worldwide to increase customer satisfaction [6]. Over the past forty years, QFD has continued to grow in popularity and use in other industries as a means to systemically assure that customer needs and wants are clearly specified and drive the product design and production process [14]. QFD translates the difficult to understand customer requirements into measurable technical characteristics through a cascading series of relationship matrixes. The relationship matrix ensures that every customer need is addressed by at least one element in the design, and further helps designers better understand the most important design elements.

In light of the QFD's ability to capture the Voice of Customer (VoC) and map it into requirements, and the AD's ability to guide the design process from high-level requirements into a conceptual design, combining the two processes seems a beneficial match. While this idea has been explored in the past by Taglia and Campatelli [15] and El-Haik and Said [16], neither work strongly demonstrates how to use the two simultaneously. Also, unlike previous work, this paper proposes a slight change in the QFD method to allow it to seamlessly join with the AD process, thus taking the strengths of both methods and creating a new streamlined process.

This paper seeks to address the conceptual design of TH using a QFD-AD methodology where the two have been seamlessly connected. Refugee housing has many stakeholders that need a formal approach to address their needs. Since no formal methodologies exist in the construction industry to both assess customer requirements and systematically approach the conceptual design of a construction project, this methodology is well-suited to fill this gap and to improve the design of complex projects. The methodology is applied to a TH illustrated example but it has potential to find other construction project applications, or may possibly be utilized in entirely different fields.

The remainder of this paper will proceed as follows. Section 2 introduces the QFD and the AD inner workings, and explains how the use of QFD at the start of AD is beneficial to the conceptual design process. Section 3 presents a case study to demonstrate the application of this theory to the conceptual design of a temporary housing unit. Ultimately, Section 4 provides a discussion of the results and a conclusion and Section 5 provides a list of acronyms used in the paper.

8.2 A QFD-AD

MethodologyQuality Function Deployment (QFD) is a well-known methodology for mapping customer needs into technical requirements and determining the most important features to ensure customer satisfaction with a product. Section 2.1 provides a brief introduction into the theory and literature on QFD. Axiomatic Design (AD) is proposed as a methodology to develop a conceptual design for a civil engineering project. Section 2.2 briefly introduces the fundamental axioms that govern AD.

8.2.1 Quality Function Deployment (QFD) to ensure customer needs drive design

QFD is composed of a series of "quality tables" that move a design from the Voice of Customer (VoC) down to the detailed operations level. The House of Quality (HoQ) is the first phase and arguably the most important phase of the QFD process. In fact, most QFD studies focus almost exclusively on the HoQ phase of design [17]. The HoQ displays the VoC and translates them into Technical Requirements (TRs), using the importance of different customer needs values to help determine the most important TRs to ensure customer satisfaction with the product. Typically, QFD is used in product development, quality management, or customer needs analysis; however, in recent years it has been expanded into other fields of study like engineering, management, teamwork, planning, design, costing, timing and decision making [18].

The advantages of using the QFD process in the construction industry have been strongly presented in literature. Some researchers have discovered additional benefits beyond "creating a more enhanced customer orientation", "more effective product development", and "improved communications and teamwork" that are typically discussed in QFD literature [17, 19]. Kamera et al [16], and Griffin and Hauser [20] both found QFD to be extremely beneficial in improving communication in project teams, and subsequently the success or failure of a project. One company found the use of QFD has resulted in 30-50% reduction in engineering changes, 30-50% shorter design cycles, 20-60% lower start-up costs, and 20-50% fewer warranty claims [21]. Although the benefits of QFD are highly proven in the construction industry, with dozens of papers written on the matter, the methodology has still not gained hold in the field [3-8]. However, the trend is slowly changing.

In order to seamlessly integrate the QFD and AD design process, a few adjustments need to be made to the QFD matrix. The new process works by first filling in an adjusted house of quality like the one in Figure 1 below. The key difference between this QFD and a traditional QFD is the TRs and the roof of the house (boxes 5-13 in Figure 1). The Technical Requirements are split into Constraints (Cs), non-Functional Requirements (nFRs) and Functional Requirements (FRs), three of five essential elements of AD decomposition as highlighted by Thompson [22]. In this paper, Optimization Criteria (OCs) and Selection Criteria (SCs) are considered to be parts of constraints for simplicity. Projects that are more complicated may find it worthwhile to include these two items in addition to Cs, nFRs and FRs. The Functional Requirements should come from the second level decomposition. The roof of the house is done identically to a typical QFD by specifying the direction and strength of the relationship between the different TRs. However, the information provided in the roof will be used to guide the AD process. The roof provides the designer a compact and rapid view of the different Cs and nFRs that will affect the decomposition of the FRs in the AD zigzag design process. The QFD will provide the designers with important information, such as the most important FRs to ensure clients' satisfaction, and which Cs are most likely to hinder the realization of the project. From this information, designers can determine the most important areas to invest resources. When the QFD is completed, the designer moves to AD to complete the design.

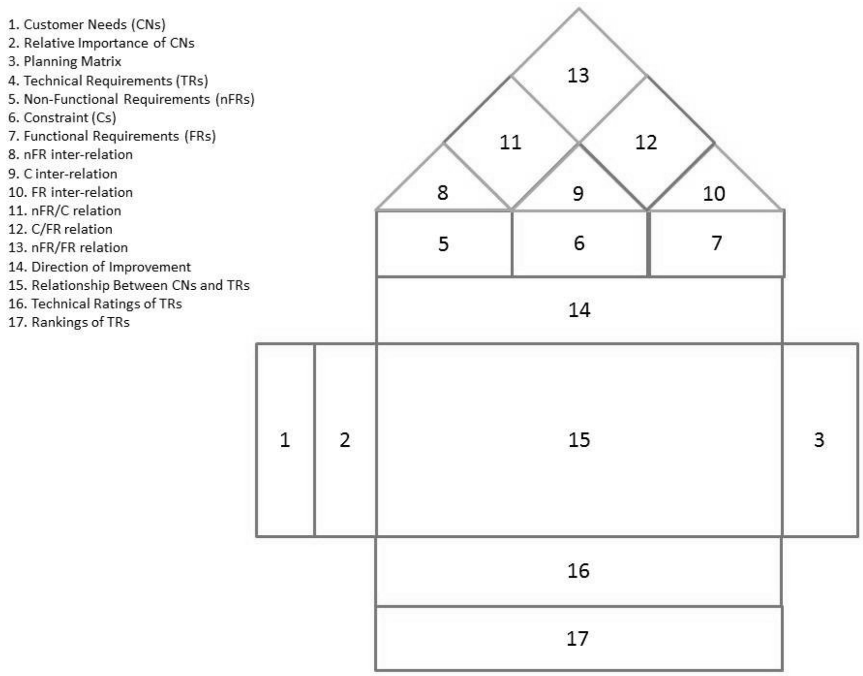

Figure 1 Modified QFD

8.2.2 Fundamental Concept of Axiomatic Design

Similar to QFD, AD is used to guide the design process from the VoC down to a final design and manufacturing technique. However, literature on AD usually focuses on the process of mapping and guiding the designs functional requirements (FRs) to Design Parameters (DPs) through the zigzag process. In addition, while Axiomatic Design does consider the customer needs, it does not have a methodical process of translating the customer needs into functional requirements.

The heart of AD is the two fundamental axioms upon which it is built, the independence axiom and the information axiom, where an axiom is a "truth that cannot be derived for which there are no counter examples or exceptions" [11]. These are formally stated by Suh [11]:

Axiom 1: The Independence axiom. Maintain the independence of the functional requirements.

Axiom 2: The information axiom. Minimize the information content of the design.

For additional information regarding either axiom, the reader should refer to [1, 10, 11].

AD is a rigorous design tool and has been applied in many areas. In its relatively short history, AD has been used in fields ranging from industrial design to aerospace engineering. It has even been used in the construction industry. It helps designers start with the statement of "what we want to achieve" and ends with a clear idea of "how we want to achieve it" AD was established to create a systematic, scientifically based process that would make "human designers more creative, reduce random search process, minimize iterative trial-and–error processes, and select the best designs among those proposed" [11].

Axiomatic Design has been applied in architecture by Marchesi et al. [2], structural engineering by Albano and Suh [1], and transportation engineering by Baca and Farid [23]. In earlier works, it was also applied to the design of a modular temporary housing unit, where it was found to be beneficial in making the design process more systematic and flexible to changes in requirements or resources [12, 13].

In this integrated methodology, very few changes were made to the AD process. The key difference was that QFD was used to capture the customer needs and transform them into functional requirements, nonfunctional requirements, and constraints which can then be used in the AD zigzag process, where the Cs and FRs from the QFD guide the decomposition of the FRs and DPs.

8.3 Case Study: Design of a Refugee House

In the following section, a case study is used to demonstrate the application of the combined QFD-AD methodology to the design of a refugee temporary housing unit. A brief introduction into refugee housing is provided in Section 3.1. While Section 3.2 demonstrates how the QFD can be used to capture customer needs and convert them into ranked FR's. Section 3.3 takes the TR's from section 3.2, and converts them into DPs using AD. Section 3.4 concludes the case study by demonstrating how the use of the AD information axiom helps assess and select the most appropriate solutions (DPs) to the given FR's. The case study focuses on one branch of the AD decomposition, a broader scope has been done in an earlier paper [12].

8.3.1 Case Study Brief

Every year, large numbers of people are forced to relocate from their homes due to wide spread violence, ethnic persecution, natural disaster, war, and other forms of political instability and natural disasters. According to National Geographic there are over 44 million forcibly displaced people in the world today [24]. Of these, "*15.4 million are refugees, 27.5 million are internally displaced persons (IDP's), and 800,000 are asylum-seekers hoping to achieve refugee status*" [24]. Many of these refugee's and IDP's end up living in camps, where they spend an average of 12 years waiting for conditions to improve in the area they are fleeing from, or a better option to open up. Many children spend their entire childhoods in these camps.

The Syrian conflict alone highlights the number of people who demand better access to temporary shelters. As of December 2013, the Syrian conflict has resulted in over 2 million refugees (1.8 million registered), and 4.25 million IDP's within Syria itself. Over a million of the refugees are children under the age of 18, and nearly three-quarters of a million are under the age of 11. Zaatari is the largest refugee camp in Jordan, the second largest in the world, and the fourth largest city in Jordan. Zaatari houses nearly 150,000 refugees and grows by up to 2,000 people daily. There are nearly 30,000 shelters in the camp, 1,700 administration buildings, and nearly 4,000 shops and restaurants. To stem the continued growth of Zaatari, another camp named Azraq, is being designed as an over flow camp. The majority of the buildings in the camp are tents provided by groups like United Nations High Commissioner for Refugees (UNHCR) [25]. There are no plans to make any of the buildings permanent, as the Jordanian government hopes all residents will return to their homes when the Syrian conflict is resolved. However, before it is resolved they will continue to experience large influxes of refugees into their country.

It is easy to contend that a safely built infrastructure and adequate housing conditions are among the most elemental human needs. Yet still a large proportion of refugees live in terrible and inhumane conditions [26]. The camps are often overcrowded, and housing within the camps filled beyond capacity [27]. Not only are the housing units overcrowded, they are poorly designed with little thought in mind for meeting the occupants needs. In a study of Sri Lankan Refugee camps, typical housing was found to be poorly ventilated, overcrowded, with no chimney to vent smoke from cooking with wood [4]. In another study of housing in the Palestinian refugee camp, Jalazonee, dampness was present in 72.5% of the houses, while 50.5% had mold, 37% had leaks, and only 41.5% were exposed to the sun [27]. In addition to the above problems, residents of many of these shelters have to deal with the constant threat of contagious diseases, especially Malaria.

Many organizations provide temporary housing for these refugees; however, the limited funds shift the focus to speed and quantity over quality and functionality. This typically involves the distribution of tents. In fact, currently more than 3.5 million people worldwide live in tents provided by agencies like UNHCR. The tents are compact, easy and cheap to manufacture, store, and ship. However, the technology behind the tents has not changed in years, and they provide little security and perform poorly in hot and cold conditions. Their inadequacy demonstrates a strong need for better designed housing options for refugees. Realizing this, the Ikea foundation and UNHCR recently joined in a collaborative project to design a new type of refuge shelter. The new design is built to have a lifetime of several years (compared to the current tent lifetime of 6 months), better thermal resistance, more privacy, and access to solar power for lighting. It is also designed to be compact for easy storage and transportation, and inexpensive to manufacture (expected cost of $1000 per unit). They are not alone, and a range of other groups have been founded to address this growing problem.

While the work done by Ikea foundation is a step towards improving the housing situation faced by refugees, there are still millions of refugees in need of better housing. Currently temporary housing camps are unsafe, thus it is essential to provide safe homes that are free of physical hazards. In a number of studies on the effect of poor housing on health conditions has found that crowded-cramped conditions in conjuncture with inadequate housing can lead to anxiety stress, high-blood pressure, acute respiratory infections, and poor mental health among children [26, 27]. If dampness and mold is present, these problems may expand to include aches and pains, digestive disorders, and respiratory tract infections [28]. The crowded conditions of the camps also encourage the spread of communicable and contagious diseases such as tuberculosis. New housing needs to address the health and safety issues of the refugees while simultaneously meeting the shipping, storage, manufacturing and cost requirements of agencies providing the structures. What is more, since the refugee's status is fundamentally temporary, their housing needs a temporary solution. However, it is clear that do to the tremendous heterogeneity and diversity of voices of stakeholders, an integrated one size fit all approach will not work.

8.3.2 Assessing Customer Needs

The first step of creating a QFD is obtaining the Voice of Customer (VoC). This information can be obtained from a range of sources including, but not limited to surveys, interviews, focus groups, and observation. Often customers are ambiguous with their description of needs, and may confuse a physical object for functional requirement. For example, a customer may specify they need an A/C unit (an object), however, what they mean is a way to regulate the internal temperature (a functional requirement). Customers may also provide vague (subjective) specifications, or provide very general ideas. Affinity trees and diagrams can help clarify and assist in the completion of the list of needs.

In this study, the Customer Needs (CNs) are determined from the open literature published on the subject. Table 1 shows the CNs found based on the work of Gilbert et al [13], Arnold [29] and Ballerino [20]. This was determined by first specifying the higher level CNs, and then determining the components that compose said high level needs. The importance of each low-level element to the user was determined and averaged to find the importance of the high-level elements to the customer. Note that unlike a typical VoC, the table gathers CNs from multiple stakeholders.

Table 1 High and Low-Level Customer Needs and Level of Importance

VOC				
Who it matters to	**High-level**	**Low-Level**	**Importance Low-Level (1-9)**	**Importance High-level (1-9)**
End User	Be Climatically Comfortable	Insulate from fluctuations in external temperature	9	7.00
		Insulate from external noise	4	
		Prevent penetration of precipitation	8	
		Resist incoming air-flow	7	
		Maintain internal humidity	7	
	Support Health and Safety	Resist rot and corrosion of materials	7	7.25
		Resist fire	9	
		Resist intruders	6	
		Prevent entrance of insects (mosquitos, etc.)	7	
	Support User Activity	Facilitate cultural specific activities	7	5.60
		Provide area for sleeping	8	
		Provide area for food prep	8	
		Provide area for work	3	
		Provide area for personal hygiene	5	
		Provide area for entertainment	2	
		Provide area for storage	4	
		Provide privacy	7	

		Provide access to electricity	7	
		Provide access to water	5	
	Be Aesthetically Pleasing	Have aesthetically pleasing interior	5	4.67
		Maximize natural light inside	7	
		Have aesthetically pleasing exterior	2	
End User/ Provider	Function and Performance	Last for 3+ years with minimal maintenance	8	8.25
		Be expandable/customizable	7	
		Resist local hazards	9	
		Meet international standards	9	
	Be Easy to Assemble	Need little or no experience to assemble	6	6.33
		Need minimal tools to assemble	6	
		Require little time to assemble	7	
Provider	Be Easy to Manufacture	Minimize shape complexity	7	5.67
		Use readily available materials	6	
		Use scalable process	4	
	Match Site	Accommodate high density	5	5.67
		Connect to available services	3	
		Function independent of infrastructure	9	
	Be Sustainable	Minimize embodied energy	5	6.00
		Ensure reusability of units or materials	7	
		Use local resources	5	

		Limit use of hazardous materials	8	
		Limit site disturbance	5	
	Minimize Cost	Minimize cost to store materials/units	9	8.00
		Minimize cost to manufacture	9	
		Minimize cost to ship	9	
		Support local economy	5	
	Be Easy to Transport and Store	Use minimal weight	9	8.50

Similar to the CNs, the TRs are determined from the literature, as well as an extensive review of the attributes highlighted by temporary housing as proposed on habitat.com, morethenshelters.org and the Ikea foundation home. Like with the customer needs, the higher-level TRs where further decomposed into the Cs, nFRs, FRs. Each of these three is then further decomposed into high-level TRs for the QFD, and low-level TRS to capture a more complete view. This is shown in Table 2 below.

Table 2 High and Low-Level Constraints (Cs), non-Functional Requirements (nFRs) and Functional Requirements (FRs)

Constraints	
High-Level	**Low-Level**
Environmental Impact	Minimize depletion of natural resources
	Minimize soil and land degradation
	Maximize recyclability/reusability
Volume During Transportation/storage	Minimize volume during transportation
	Minimize volume during storage
Number of Components	Minimize total number of components
Number of Materials	Minimize total materials used
Design/ Volume When Built	Maximize efficiency of layout
	Hit target area of built structure
	Hit target height for roof
Complexity of Assembly	Minimize required experience to assemble
	Minimize equipment required to assemble

	Minimize complexity of assembly
Complexity of manufacturing	Minimize required experience to manufacture
	Minimize equipment required to manufacture
Modularity	Make easy to customize
	Make modular connections possible
Material Physical Properties	Weight
	Thermal insulation properties
	Stability/expect lifetime
	Fire resistance
	Odor
	Chemical Activity
	Thermal exchange properties
	Moisture Resistance
	Corrosion Resistance
	Biological Resistance
	Deformation due to heat
	Absorption
	Embodied energy
	etc.
nFRs	
High-Level	**Low-Level**
Inexpensive	--
Lightweight	--
Aesthetically pleasing	--
Functional Requirements	
High-Level	**Low-Level**
Passively Protect and Maintain Internal Climate	All FRs are further decomposed in the AD zigzag process
Actively Protect and Maintain Internal Climate	
Maintain Structural Integrity	
Support User Activity	

The QFD in this case study is created around the VoC of the people who will purchase and provide the temporary structure (groups like UNHCR or the Red Cross and Red Crescent), not just the end users (IDPs and Refugees). This is different from a typical product designed using QFD. This is not to say the end users requirements are not taken into account, but rather, they are taken into account alongside the other tradeoffs made by the purchaser/owner. For example, the end user does not care about the amount of energy required to ship, store, and manufacture the shelter. However, they do care about the internal temperature of the shelter during the peak of summer. As can be seen in the list of CNs, both of these factors are acknowledged. This is due to the fact that from the provider's point of view, the end users comfort and the embodied energy of the structure are both important.

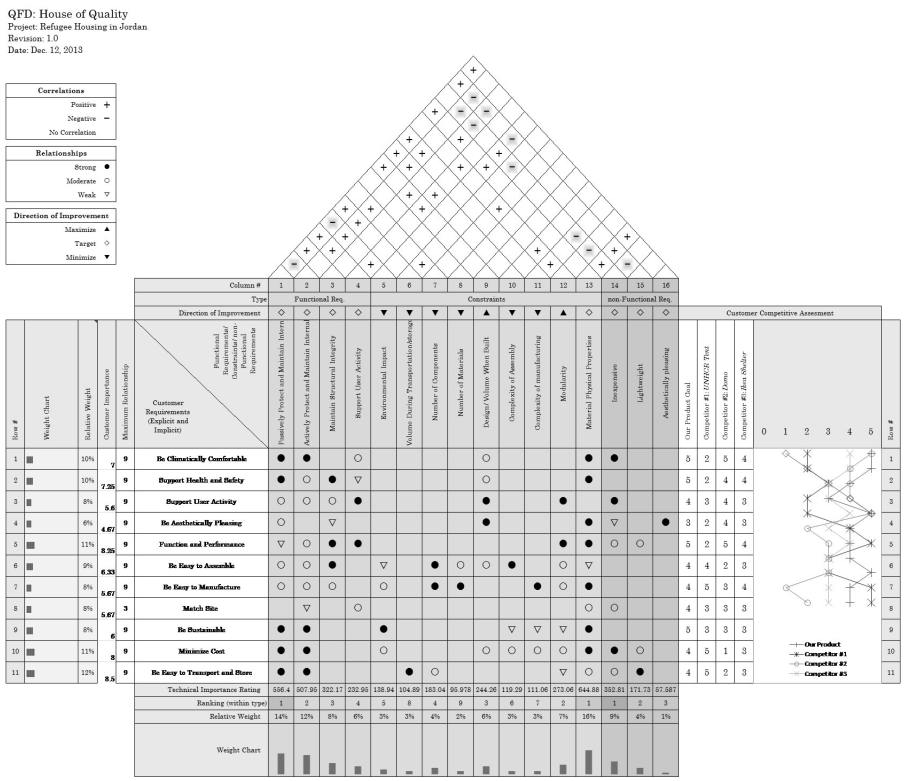

Figure 2 QFD for a temporary house

The displayed QFD in Figure 2 demonstrates that only the high-level CNs and TRs are used. The reasons to approach this from a high-level instead of leaf level (lowest level) view are twofold: improve clarity and eliminate unintentional bias towards high-level elements that have more leaf-elements. Projects of smaller scale do not require this top level decomposition, but projects as complex as construction projects do.

The QFD above also provides a benchmark analysis of 3 different existing and proposed temporary housing solutions. Specific information was not available for all aspects of the units, so ratings are based on literature about each unit. *UNHCR tents* are the units typically used for refugee housing today. As can be seen in the benchmark, they are inexpensive to produce, store and ship, however they are not very effective at addressing the comfort or activity needs of the users. UNHCR is looking at addressing this issues in the near future [30]. The second unit, *Domo*, was designed by a German group called More Than Shelter. It is a conceptual design that has been proposed to improve the quality of life of people living in refugee housing and slums by creating spaces to empower people. These units will be more expensive than a UNHCR tent, but are much more adept at meeting the user needs [31]. The final solution, the *IKEA shelter*, was unveiled in 2013, and is considered a promising solution to improve the quality of housing for refugees and IDPs [32]. Ikea seems to be a more middle of the road solution between the UNHCR tent and the Domo, providing less versatility then the Domo, but better at meeting user needs then the UNHCR tent. Using these different units as benchmarks helps to recognize where opportunities exist, and can help designers to better understand how other designers address, or don't address, the VoC.

8.3.3 Decomposition of a Refugee shelter

After the customer needs were used to highlight the high-level FR's, nFRs and Cs of the system, the design of the temporary housing system was done using the AD zigzag methodology.

As can be seen in the QFD, the high-level FRs are:

- FR1= Passively Protect and Maintain Internal Climate
- FR2= Actively Maintain Internal Environment
- FR3= Maintain Structural Integrity (against static and dynamic loading)
- FR4= Support User Activities (for up to 5±2 people)

Which are constrained by:

- C1= Environmental Impact
- C2= Volume During Transportation/Storage
- C3= Number of Components
- C4= Design/Volume When Built
- C5= Complexity of Assembly
- C6= Complexity of Manufacturing
- C7= Modularity
- C8= Material Physical Properties

Using the nFRs and Cs from the QFD, the design parameters (DPs) selected to fulfill each of these FRs are:

- DP1= Building Envelope System
- DP2= Mechanical System
- DP3= Structural System
- DP4= Building Interior and Layout

The DPs that are selected to fulfill the high-level FRs provide insights about the form of the shelter. The selected DPs may also change depending on designer's point of view and previous experiences. For example, designers more comfortable working with Structural Insulated Panels (SIPs) may have chosen to combine the Structural and Envelope System into a single DP. In short, the decomposition of the same system by two different designers will nearly always be different. This is considered an advantage, because it highlights that the methodology does not impede creativity in the design process.

During the AD design process, the conceptual design should start to take form in the designers mind. Each continuous step of the zigzag process and expansion of the Design Matrix (DM) will further develop the shelter form. A design matrix, like the one displayed in equation 6 below, needs to be formulated for each level of the decomposition to avoid violating the Independence Axiom. In this case, the choice of a building envelope system will have an effect on the mechanical system used, and the choice of a structural system. For example, if the building envelope is designed as to be load bearing, it will be part of the structural system; likewise, if the building has high-thermal resistance, the demand for a mechanical system to ensure the air is properly tempered will be lessened.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (1)$$

Equation 6 shows that the design is decoupled at the highest level and the independence axiom is not violated. Next, each the FRs will be further decomposed. For brevity, only FR1s decomposition will be shown, however the other FRs will follow a similar decomposition format. FR1 was chosen because it provides the primary function a refugee house needs to afford based on the Maslow hierarchy of needs [33]. The other three FRs all provide secondary, albeit important, functions for the users.

The building envelope system is perhaps the most important part in ensuring the good health and safety of its occupants. It is responsible for a number of very important functions related to the internal climate of the structure. While the mechanical system may play an important role in this function in a typical building, most refugees have limited or no access to electricity or driving power that allow most mechanical systems to function. This means that majority of the control of the internal climate will be done passively with the external envelope. The envelope of the structure must maintain a reasonable internal temperature throughout the entire day, and should resist fluctuations in external temperature from the summer to winter seasons or from day to night. The envelope should also prevent excessive moisture and water ingress. Condensation due to excess moisture is one of the leading problems of health issues in the refugee camps. Safety of the occupants and their belongings is also an essential FR. Crime is often a major problem in large camps. It is essential that refugees' security is maximized, and they can help protect the few belongings they have left. Protection from mosquitos is also important since malaria is a rampant problem in refugee camps.

Because a refugee house needs to be simple by nature, the decomposition of the FRs is also relatively simple. Systems that are more complex may require more iterations of the zigzag process. FR1s decomposition is shown below:

FR1.1= Allow Controllable Interaction with External Environment
FR1.2= Passively Control Indoor Climate
FR1.3= Prevent Entrance of Insects and Pest

Which are solved using the following DPs:
DP1.1= Fenestration (Door/ window)
DP1.2= Curtain Wall and Floor
DP1.3= Insect Resistant Features

Again this can be mapped into a Design Matrix to ensure the second axiom is not violated. The Design Matrix (7) below shows that the decisions regarding the Curtain Wall and Floor as well as the Fenestration both affect the ability of the structure to "Passively Control Indoor Climate." This intuitively makes sense since the Door and Window will be important in passively cooling the building in hot weather, and will be one of the main sources of heat leakage from the structure in cold weather. Likewise, choices of door and window will affect the buildings ability to prevent the entrance of insects (in addition to other insect resistant features).

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \end{Bmatrix} \quad (2)$$

Since the independence axiom is not violated, the third level of decomposition can be created by following the Zigzag process. First FR1.1 is decomposed into:

FR1.1.1= Allow Controllable Entrance to Structure
FR1.1.2= Allow Entrance of Natural Light into Structure
FR1.1.4= Remove smoke from cooking/heat fires

DP 1.1.1= Door
DP 1.1.2= Window
DP1.1.4= Closable Cooking Vent

$$\begin{Bmatrix} FR_{1.1.1} \\ FR_{1.1.2.} \\ FR_{1.1.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{1.1.1} \\ DP_{1.1.2} \\ DP_{1.1.3} \end{Bmatrix} \quad (3)$$

Next, FR1.2 is broken down into:

FR1.2.1= Regulate Air Flow/Quality
FR1.2.2= Regulate Moisture in Air and Prevent Accumulation of Free Standing Water within Unit
FR1.2.3= Maintain Internal Temperature of 23 ± 6 Degree C

DP1.2.1= Natural Ventilation
DP1.2.2= Water Resistant Barrier
DP1.2.3= Passive Cooling and Heating techniques

$$\begin{Bmatrix} FR_{1.2.1} \\ FR_{1.2.2.} \\ FR_{1.2.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.1} \\ DP_{1.2.2} \\ DP_{1.2,3} \end{Bmatrix} \quad (4)$$

In the last step of the level 2 zigzag decomposition, FR1.3 is broken into the following:

FR1.3.1= Prevent Entrance of Insects from Openings
FR1.3.2= Prevent Entrance of Bugs and Pest from Under Structure
DP1.3.1= Screen on All Openings with Mesh Size <1mm
DP1.3.2= Impenetrable Base

$$\begin{Bmatrix} FR_{1.3.1} \\ FR_{1.3.2} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.3.1} \\ DP_{1.3.2} \end{Bmatrix} \quad (5)$$

To demonstrate how this can be continued to be broken down into the leaf elements, FR1.1.3 (Regulate Internal Temperature) is brought down to the fourth level of decomposition.

FR1.2.3.1= Regulate Internal Temperature from Convection
FR1.2.3.2= Regulate Internal Temperature from Solar Radiation
FR1.2.3.3= Regulate Internal Temperature from Conduction

While convection, radiation and conduction are all highly correlated, in this case some assumptions were made to minimize correlation. The worst case scenario for regulating internal temperature occurs at night during the winter. During this time no energy is gained from Solar Radiation, so this correlation is negated (though this FR does matter in the middle of the day in the summer, and therefore should not be removed). It is further assumed that only a fraction of energy (~30%) is lost to convection through gaps between parts. The remainder of energy loss in winter is expected to occur by conduction through the ceiling and walls.

In another branch of the AD decomposition that is not shown in this paper, it was determined that a propone heater (that produces around 2.8 kW of energy per day) can be installed in the housing unit. The housing unit has been designed to have total area of 20 square meters with an average height of 2.5 meters. The heat produced by the heating unit and body radiation (0.1kW x 5 people) must be sufficient to counter the rate of heat loss through conduction through the walls and floor. Any additional heat energy gained by the house (from solar radiation, additional people, etc.) can be countered by reducing heat produced by propane heater. The average winter low for this case studies location is expected to be around 0 Degree C.

DP1.1.3.1= Adjustable Vent on Top of Ceiling
DP1.1.3.2= External Coating
DP1.1.3.3= Thermal Insulation Panel

$$\begin{Bmatrix} FR_{1.2.3.1} \\ FR_{1.2.3.2.} \\ FR_{1.2.3.3} \end{Bmatrix} = \begin{bmatrix} X & 0 & X \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1.2.3.1} \\ DP_{1.2.3.2} \\ DP_{1.2.3.3} \end{Bmatrix} \quad (6)$$

The use of a thermal mass is a popular passive heating/cooling method typically implemented to modulate daily temperature variations, however in the presented case this is a difficult proposition to implement given the importance of keeping the units light-weight for shipping. This means that an alternative effective passive heating and cooling techniques needs to be devised. This highlights the role of solar radiation, because home users might capture the heat of solar radiation when it is cold, but block it or reflect it when it is warm. Typically, this is done passively by orienting the house in a way that allows the solar heat to enter directly through windows during the winter (when the sun is lower in the sky) and be blocked by the roof in the summer, or through some form of thermal mass. Developing a method of regulating internal temperature will be a difficult task, and will be highly dependent on selecting an appropriate material.

8.3.4 Checking appropriateness of the solution

The information axiom of axiomatic design is used to select the best design parameter to meet the given functional requirement within the system constraints. In a complete design this should be done for every leaf-level component; however, for brevity a single sample has been selected to demonstrate the concept. In this particular case the best DP option to satisfy FR1.1.3.3, Regulate Internal Temperature from Conduction, is being selected from 3 different alternatives.

Table 3 provides the three options along with their material properties. The "Goal" line also provides the acceptable design range for each property for the given FR, data for both selection criteria and the design alternatives was assumed to be uniformly distributed.

Table 3 Material properties of three alternatives and the AD information content for each alternative

	Thickness	R-Value	Weight	Flame Spread Index	Vapor Transmission Rate	Recycled Content	Sum of Information Content
Unit	*m*	*M^2*/W*	*Kg/m^2*	-	*SI Perm*	%	
Goal	0 - 0.08	1.2 - 5	0 - 0.8	0 to 25	57 - 285	10 - 50	
Product 1	0.07 - 0.085	1.6 - 2	0.56 - 0.816	20 - 23	240 - 378	8 - 12	
Information	*0.585*	*0*	*0.093*	*0*	*1.616*	*1*	*3.29*
Product 2	0.065 - 0.07	1 - 1.4	0.488 - 0.60	24 - 25	265 - 400	30 - 50	
Information	*0*	*1*	*0*	*0*	*2.755*	*0*	*3.755*
Product 3	0.05 - 0.06	2 to 2.2	0.475 - 0.63	18 - 19	100 - 120	0 - 5	
Information	*0*	*0*	*0*	*0*	*0*	*Infinite*	*infinite*

The information axiom equation

$$I = \log_2(1/p) \quad (7)$$

is used to determine the I value for each property, where p is the probability that satisfying the goal. This value is then summed to determine the DP with the lowest information content. In this example, the information content of DP1.1.3.3[a], DP1.1.3.3[b], and DP1.1.3.3[c], was found to be 3.29, 3.75, and infinite respectively. This signifies of the three options, DP1.1.3.3[a], or Product 1, is the best possible option. This is interesting considering Product 3 is the best in every way except recycled content.

8.4 Conclusion and Future Work

The same tents have been utilized for most natural disaster and refugee camps for the past twenty years. While many design ideas for refugee shelters have been proposed, none have been able to completely replace the tent. This is because they are unable to adequately meet the stakeholder requirements, either from a design or cost point of view. Recently, many designers, including the IKEA foundation, have attempted to address this problem; however, only time will tell if their proposed designs will be successful.

This paper proposed a new method to systematically guide the process of creating a temporary house conceptual design based on stakeholder needs. The method is built on two proven design methodologies, QFD and AD. QFD has already proven its use to construction projects in literature, and AD has developed wide acceptance due to its ability to improve creativity, minimize the iterative process, and quickly optimize for the best solution [11, 21]. The new method integrated these two methods by using the strengths of both of approaches. After introducing the changes made to the QFD and AD process, a case study was provided to demonstrate the use of the process in the design of a temporary housing shelter. Although the case study does not present the complete design, it does demonstrate the methodology's ability to capture the VoC in a systematic design process.

The case study found that the combination of QFD-AD method streamlined the design process, and helped to ensure that the VoC directed the entire conceptual design creation. This new approach to combining the QFD-AD methodology may be applicable in other industries as well. Future work may include developing a more efficient way of combining the process to maximize the impact of the VoC on the design process, and perhaps expanding the QFD to include other design variables beyond nFRs, FRs and constraints. This includes Selection Criteria (SCs) and Optimization Criteria (OCs). Material selection using the AD information axiom also proved less efficient then desired.

There is complex coupling that occurs at the material level. This pairing makes material selection a complex process of managing a number of different tradeoffs. In the above example, the density, cost, thickness, and thermal conductivity all are highly coupled. An extremely dense and expensive material may have a much higher thermal conductivity, and ultimately be the most inexpensive option for the same thermal performance. While the information axiom presents a method of handling these tradeoffs, it creates a bias by weighing all factors effecting the decision equally. Suh [11] recommends applying weight factors to prevent this bias. Although this eliminates bias, it is difficult to correctly determine what value of weights to assign. The method also does nothing to directly differentiate between required material characteristics and preferred material characteristics, and it is poor at dealing with subjective criteria. Lastly, if a material option does not meet one of the FR's for the material, it will immediately be eliminated because it has infinite information content (as was the case with product three in the case study). Future work will investigate if material selection may be improved if carried through a decision making framework using methods such as AHP, which have proven to be efficient at handling subjective criteria and able to compare apples to oranges.

List of acronyms:

TH- Temporary House or Temporary Housing
QFD- Quality Function Deployment
AD- Axiomatic Design
VoC- Voice of Customer
CN- Customer Needs
CA- Customer Attributes
TR- Technical Requirements
FR- Functional Requirements
nFR- Non-Functional Requirement
C- Constraint
OC- Optimization Criteria
SC- Selection Criteria
DP- Design Parameter
PV- Process Variable
UNHCR -United Nations High Commissioner for Refugees

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