Proceedings of ICAD2014
The Eighth International Conference on Axiomatic Design
Campus de Caparica – September 24-26, 2014
ICAD-2014-11

AN INTEGRATED QFD AND AXIOMATIC DESIGN METHODOLOGY FOR THE SATISFACTION OF TEMPORARY HOUSING STAKEHOLDERS

Lindsey R. Gilbert III
lgilbert@masdar.ac.ae
Engineering Systems & Managemer
Masdar Institute
Abu Dhabi, UAE

Mohammed Omar
momar@masdar.ac.ae
Engineering Systems & Management
Masdar Institute
Abu Dhabi, UAE

Amro M. Farid
afarid@masdar.ac.ae
Engineering Systems & Management
Masdar Institute
Abu Dhabi, UAE
Massachusetts Institute of Technology
Cambridge, MA USA

ABSTRACT

Modern construction projects must meet the requirements of a diverse range of stakeholders, each of whom have their own unique needs and constraints. Ideally these needs would be identified early in the design process when the designers have the largest impact on cost and functionality of the project. Unfortunately, this stage is typically approached in an informal and non-homogenous manner. Designers often do not use formal and systematic tools until later in the design process. This study proposes a new systematic approach to the conceptual design of construction projects -specifically temporary housing- by combining Quality Function Deployment (QFD) and Axiomatic Design (AD). This combined methodology helps ensure that the design meets customer's needs, as well as satisfies the design objectives in a logical sequence. More precisely, the QFD-AD method proposed innovatively combines two prevalent design methodologies in a way that allows a seamless translation of diverse customer needs into a formal and methodical design approach. The design of a refugee housing unit is presented as an illustrative case study of temporary housing.

Keywords: Quality Function Deployment (QFD); Axiomatic Design (AD); QFD-AD; refugee housing; civil engineering design.

1 INTRODUCTION

The success or failure of a construction project is highly dependent on ensuring stakeholder satisfaction. In modern construction project, designers must to fulfill the requirements of a large and diverse range of stakeholders, as well as achieve an ever expanding list of life-cycle properties. Today, constructability, durability, life-cycle maintenance, energy efficiency, the cost of maintenance, environmental impact, and social-economic impact have been added to the more traditional concerns in building design like aesthetics, structural integrity and initial cost [Albano and Suh, 1992]. According to Marchesi et al. [2013], 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 their traditional domain for solutions, particularly during the early design phase [Albano and Suh, 1992, Armacost, et al., 1994, Delgado-Hernandez, et al., 2007, Dikmen, et al., 2005, Gargione, 1999, Pheng and Yeap, 2001, Yang, et al., 2003]

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"[Albano and Suh, 1992]. 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" [Dikmen, et al., 2005]. 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 [Formoso, et al., 2002]. Due to this similarity, methods used in NPD are easily adaptable to the construction industry. Two popular NPD methodologies 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 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 [Suh, 1995, Suh, 2001]. 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 [Gilbert III, et al., 2013, Gilbert III, et al., 2013].

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 [Delgado-Hernandez, et al., 2007]. 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 [Cohen, 1995]. 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. The idea of integrating QFD and AD has been explored in by Suh [2001], Taglia and Campatelli [2006] and El-Haik and Said [2005]. In his work, Suh states that he chose not to integrate the QFD process because it could impede the creative process of generating a new design by compromising the designer's ability to work in a "solution neutral environment." Taglia and Campatelli and El-Haik and Said both found the linked QFD-AD process could be potentially useful, but did not strongly demonstrate how to use the two methods simultaneously.

This paper seeks to address the conceptual design of TH using a QFD-AD methodology where the two have been seamlessly connected through a modification of the QFD process using the taxonomy of AD as proposed by Thompson [2013]. This combined method will work well with temporary housing because the design process of TH is more integrative than creative in application; therefor Suh's concern of QFD compromising the ability to create a solution neutral environment is of less concern. The fundamental needs are relatively well known; however, the relative importance of each need and how needs are integrated together is not known. QFD and AD will answer these questions in sequential order.

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 combined 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.

2 A QFD-AD METHODOLOGY

Quality 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.

2.1 EXISTING 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 [Chan and Wu, 2005]. 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 [Chan and Wu, 2002].

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 [Chan and Wu, 2002, Chan and Wu, 2005]. Kamera et al. [2005], and Griffin and Hauser [2002] 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 [Zakarian and Kusiak, 1999]. 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 [Armacost, et al., 1994, Delgado-Hernandez, et al., 2007, Dikmen, et al., 2005, Gargione, 1999, Pheng and Yeap, 2001, Yang, et al., 2003]. However, the trend is slowly changing.

In order to seamlessly integrate the QFD and AD design process, 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 4-12 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 [Thompson, 2013]. 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.

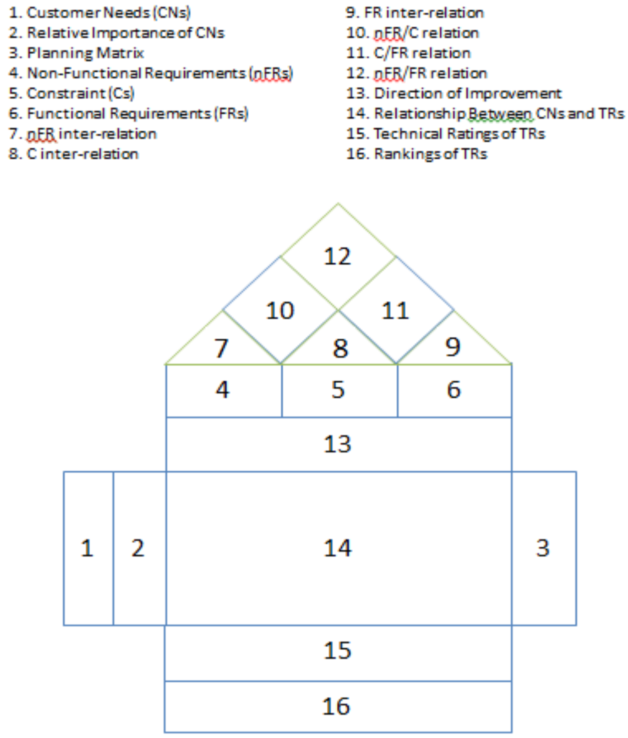

Figure 1 Modified QFD

2.2 Fundamental Concept of Axiomatic Design

Within this combined methodology, AD is used to translate/relate/link the Functional Requirements (FRs) to Design Parameters (DPs). While Axiomatic Design typically considers the customer needs; it does not yet have a methodical process of translating the customer needs into FRs.

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" [Suh, 2001]. These are formally stated by Suh [Suh, 2001]:

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 [Albano and Suh, 1992, Suh, 1995, Suh, 2001].

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" [Suh, 2001].

Axiomatic Design has been applied in architecture by Pastor and Benavidas [2011], structural engineering by Albano and Suh [Albano and Suh, 1992], and transportation engineering by Baca and Farid [2013]. 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 [Gilbert III, et al., 2013, Gilbert III, et al., 2013].

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 per Thompsons [2013] taxonomy. These FRs, nFRs and Cs can then be used in the AD zigzag process, where the Cs and nFRs from the QFD guide the decomposition of the FRs and DPs.

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 [Gilbert III, et al., 2013].

3.1 CASE STUDY BRIEF

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 [Brifcani, et al., 2012]. The camps are often overcrowded, and housing within the camps filled beyond capacity [De Felice and Petrillo, 2011]. 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 [Armacost, et al., 1994]. 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 [De Felice and Petrillo, 2011]. 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 results in 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 [Brifcani, et al., 2012, De Felice and Petrillo, 2011]. If dampness and mold is present, these problems may expand to include aches and pains, digestive disorders, and respiratory tract infections [Ho, et al., 1999]. 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.

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. [2013], Arnold [2009] and Ballerino [2002]. 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 the table gathers CNs from multiple stakeholders.

Table 1 Customer Needs and Level of Importance

Who it matters to	**Customer Needs (High-Level)**	**Importance High-level (1-9)**
End User	Be Climatically Comfortable	7
	Support Health and Safety	7.25
	Support User Activity	5.6
	Be Aesthetically Pleasing	4.67
End User/ Provider	Function and Performance	8.25
	Be Easy to Assemble	6.33
Provider	Be Easy to Manufacture	5.67
	Match Site	5.67
	Be Sustainable	6
	Minimize Cost	8
	Be Easy to Transport and Store	8.5

Similar to the CNs, the TRs are determined from the literature, designer experience, and an extensive review of the attributes highlighted by temporary housing like that proposed on habitat.com, morethanshelters.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. The high level TRs are shown in **Table 2** below.

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

Constraints
Environmental Impact
Volume During Transportation/storage
Number of Components
Number of Materials
Design/ Volume When Built
Complexity of Assembly
Complexity of manufacturing
Modularity
Material Physical Properties
Non-Functional Requirements
Durable
Inexpensive
Lightweight
Aesthetically pleasing
Functional Requirements
Protect and Maintain Internal Environment
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.

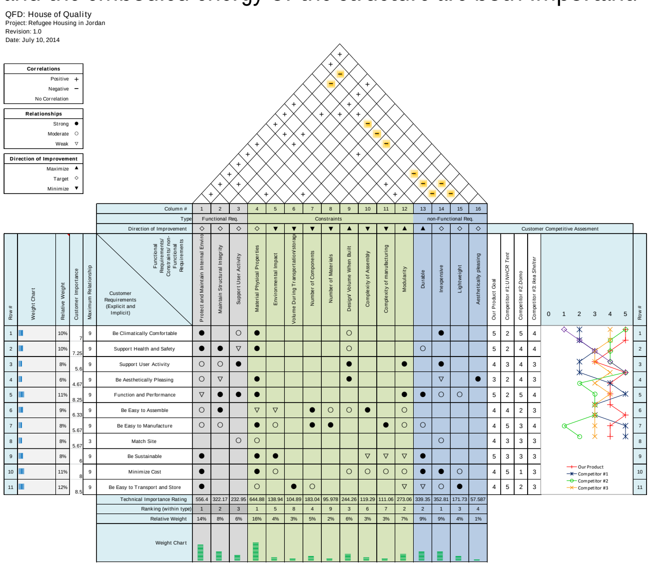

Figure 2 QFD for a temporary house

The displayed QFD in **Figure 2** 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 [Lolachi, 2010]. 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 [morethanshelters]. 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 [Zimmer]. 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.

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= Protect and Maintain Internal Environment
- FR2= Maintain Structural Integrity (against static and dynamic loading)
- FR3= 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= Passive Building Envelope System
- DP2= Active Mechanical System (i.e. fan ventilation)
- 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 (1) 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 structural system. For example, if the building envelope is designed to be load bearing, it will be part of the structural system. The DPs "Building Envelope" and the "Mechanical System" are created to form a redundant design which gives designer the option to add in an active cooling/heating element to improve buildings thermal performance.

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

Design Matrix (1) shows that the design is both designed to be redundant and is decoupled at the highest level (hence, the independence axiom is not violated). Next, each of 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 [Simons, et al., 1987]. The other three FRs all provide secondary, albeit important, functions for the users.

The building envelop 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.

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 first axiom is not violated. The Design Matrix (2) 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

DP1.1.1= Door
DP1.1.2= 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 Pests from Under Structure

DP1.3.1= Screen on All Openings with Mesh Size <1mm
DP1.3.2= Impenetrable Base

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

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 a successful design will emerge from their work. This paper proposes a method designers can use to improve the likelihood that better design is created.

To our knowledge, this paper is the first demonstration of a seamless and integrated application of QFD and AD for a particular application, and is used to systematically guide the process of creating a temporary house conceptual design based on stakeholder needs. 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 [Suh, 2001, Zakarian and Kusiak, 1999]. The seamless integration of the two methods uses the strengths of each approach. 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 combined methodology's ability to capture the VoC in a systematic design process.

The case study found that the combination 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 methodologies 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 than desired.

5 REFERENCES

[1] Albano L.D. and Suh N.P., "Axiomatic approach to structural design," *Research in Engineering Design*, vol. 4, pp. 171-183, 1992/09/01 1992.

[2] Armacost R.L., Componation P.J., Mullens M.A., and Swart W.W., "An ahp framework for prioritizing customer requirements in qfd: An industrialized housing application," *IIE transactions*, vol. 26, pp. 72-79, 1994.

[3] Arnold C. (2009, April 25). *Building envelope design guide - introduction*. Available: http://www.wbdg.org/design/env_introduction.php

[4] Baca E.E.S. and Farid A.M., "An axiomatic design approach to reconfigurable transportation systems planning and operations," presented at the

Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering, Worcester, MA, USA, 2013.

[5] Ballerino C.C., "Building materials & engineering design: Low-income housing projects, port elizabeth-south africa," Department of Infrastructure and Planning, Kungl Tekniska Hogskolan (Royal Institute of Technology), Stockholm, Sweden, 2002.

[6] Brifcani N., Day R., Walker D., Hughes S., Ball K., and Price D., "A review of cutting-edge techniques for material selection," 2012.

[7] Chan L.-K. and Wu M.-L., "Quality function deployment: A comprehensive review of its concepts and methods," *Quality Engineering,* vol. 15, pp. 23-35, 2002.

[8] Chan L.-K. and Wu M.-L., "Quality function deployment: A literature review," *European Journal of Operational Research,* vol. 143, pp. 463-497, 2002.

[9] Chan L.-K. and Wu M.-L., "A systematic approach to quality function deployment with a full illustrative example," *Omega,* vol. 33, pp. 119-139, 2005.

[10] Cohen L., *Quality function deployment: How to make qfd work for you*: Addison-Wesley Reading, MA, 1995.

[11] De Felice F. and Petrillo A., "A multiple choice decision analysis: An integrated qfd–ahp model for the assessment of customer needs," *International Journal of Engineering, Science and Technology,* vol. 2, 2011.

[12] Del Taglia A. and Campatelli G., "Axiomatic design & qfd: A case study of a reverse engineering system for cutting tools," in *Proceedings of ICAD2006, 4th International Conference on Axiomatic Design*, 2006.

[13] Delgado-Hernandez D.J., Bampton K.E., and Aspinwall E., "Quality function deployment in construction," *Construction Management and Economics,* vol. 25, pp. 597-609, 2007.

[14] Dikmen I., Talat Birgonul M., and Kiziltas S., "Strategic use of quality function deployment (qfd) in the construction industry," *Building and Environment,* vol. 40, pp. 245-255, 2005.

[15] El-Haik B., *Axiomatic quality: Integrating axiomatic design with six-sigma, reliability, and quality engineering*: Wiley. com, 2005.

[16] Formoso C.T., Tzortzopoulos P., and Liedtke R., "A model for managing the product development process in house building," *Engineering Construction and Architectural Management,* vol. 9, pp. 419-432, 2002.

[17] Gargione L.A., "Using quality function deployment (qfd) in the design phase of an apartment construction project," in *Proceedings IGLC*, 1999, p. 357.

[18] Gilbert Iii L.R., Farid A.M., and Omar M., "An axiomatic design based approach for the conceptual design of temporary modular housing," presented at the Proceedings of the 7th International Conference of Axiomatic Design, Worcester, MA, 2013.

[19] Gilbert Iii L.R., Farid A.M., and Omar M., "An axiomatic design based approach to civil engineering," presented at the Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering., Worchester, MA, 2013.

[20] Ho E.S.S.A., Lai Y.-J., and Chang S.I., "An integrated group decision-making approach to quality function deployment," *IIE transactions,* vol. 31, pp. 553-567, 1999.

[21] Lolachi M. (2010, 12/10/2013). *High tech solar tents, and how to design a refugee camp: An interview with manoucher lolachi, senior physical planner, unhcr*. Available: https://www.facebook.com/notes/unhcr/high-tech-solar-tents-and-how-to-design-a-refugee-camp-an-interview-with-manouch/462913067725

[22] Marchesi M., Kim S.-G., and Matt D.T., "Application of the axiomatic design approach to the design of architectural systems: A literature review," presented at the Proceedings of the 7th International Conference of Axiomatic Design, Worcester, MA, 2013.

[23] Morethanshelters. (11/16/2013). *More than shelters: Domo*. Available: http://www.morethanshelters.org

[24] Pastor J.B.R. and Benavides E.M., "Axiomatic design of an airport passenger terminal," in *The Sixth International Conference on Axiomatic Design*, 2011, pp. 30-31.

[25] Pheng L.S. and Yeap L., "Quality function deployment in design/build projects," *Journal of Architectural Engineering,* vol. 7, pp. 30-39, 2001.

[26] Simons J.A., Irwin D.B., and Drinnien B.A., "Maslow's hierarchy of needs," *Retrieved October,* vol. 9, p. 2009, 1987.

[27] Suh N.P., "Design and operation of large systems," *Journal of Manufacturing Systems,* vol. 14, pp. 203-213, 1995.

[28] Suh N.P., *Axiomatic design advances and applications*. New York, New York: Oxford University Press, 2001.

[29] Thompson M.K., "A classification of procedural errors in the definition of functional requirements in axiomatic design theory," presented at the Proceedings of the 7th International Conference of Axiomatic Design, Worcester, MA, 2013.

[30] Yang Y.Q., Wang S.Q., Dulaimi M., and Low S.P., "A fuzzy quality function deployment system for buildable design decision-makings," *Automation in Construction,* vol. 12, pp. 381-393, 2003.

[31] Zakarian A. and Kusiak A., "Forming teams: An analytical approach," *IIE transactions,* vol. 31, pp. 85-97, 1999.

[32] Zimmer L. (12/12/13). *Ikea unveils solar-powered flat pack shelters for easily deployable emergency housing*. Available: http://inhabitat.com/ikeas-solar-powered-flat-pack-refugee-shelters-offer-easily-deployable-emergency-housing/