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An Axiomatic Design Based Approach to Civil Engineering

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Abstract: Civil engineering projects are becoming increasingly intricate and interdisciplinary with a growing need to answer a number of complex socio-economic and environmental issues during the design process. Because each project is unique, civil engineers rarely develop formal techniques to ensure that customer requirements are properly captured and that the complex set of trade-offs affecting a building are fully understood. Understanding issues early in the design process is important, as this is when the designer is able to have the largest impact on the final product. In this paper Axiomatic Design and Product Platform Design are proposed as methods to address this issue. A case study of the design of a temporary housing shelter is presented to demonstrate how both methodologies can be applied to a complex civil engineering project that includes a number of socio-economic and environmental constraints.

Keywords: Temporary Housing, Civil Engineering, Axiomatic Design, Modularity, Large Flexible Systems

Introduction

There is a growing trend in the civil engineering community to embrace new design methodologies to handle mounting project complexity. Today, a civil engineer needs to consider life-cycle issues such as constructability, durability, life-cycle maintenance, energy efficiency, environmental impact and social-economic impact in addition to traditional concerns such as structural integrity and initial cost (Albano and Suh 1992). "The increasing complexity of architectural design entails the need for a more rational and systematic approach to the design process, especially in the conceptual design phase when decisions with fundamental and extensive effects on appearance, performance and cost are made" (Marchesi *et al.* 2013). In fact, there is a clear need to find a way to identify faulty design decisions as early in the design process as possible. Civil engineering work typically starts with a broad conceptual design performed by an experienced civil engineer. Generally the engineer uses his/her past experiences to develop the conceptual design that is then brought into a detailed design phase. However, "[r]igorous analytical methods and optimization schemes are used for decisions that impact project cost 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).

Although past experience plays an important role in design, the growing complexity of design problems makes it nearly impossible for all but the most gifted engineers to adequately capture all of the problems in the conceptual design phase. This problem is further compounded as customer demands become more diverse and segmented and more stakeholders have a role in the creation of the project.

Since traditional civil engineering design methodologies are not adapted to assist in the design of the conceptual phase of a project, engineers are beginning to look into other engineering fields for a solution. As is noted by Marchesi *et al.* (2013), "[t]he design of architectural systems has to be optimized with respect to a large number of different (sometimes conflicting) requirements and constraints, and the solution has to be selected from different available alternatives." It is the contention of this paper that Axiomatic Design (AD) and Product Platform Design will improve the conceptual design of complex civil engineering projects, ultimately resulting in a more appropriate and less expensive solution.

The remainder of the paper will proceed as follows. Section 2 introduces the concept of AD. Section 3 discusses another design methodology called Product Platform Design that works well in complement with AD. Section 4 presents a case study where AD and Product Platform Design are applied to the conceptual design of a temporary housing unit. Section 5 concludes the paper and introduces ideas for future work.

Axiomatic Approach to Design

Axiomatic Design (AD) is proposed as a methodology to develop a new approach for the conceptual design of complex civil engineering projects. AD is a well-established methodology from mechanical engineering design that is quickly moving into other design oriented engineering fields. Section 2.1 briefly introduces the fundamental axioms that govern Axiomatic Design, while section 2.2 delves into the Axiomatic Design approach for larger flexible systems. For more detailed information regarding Axiomatic Design, the reader should refer to Suh (2001) or Suh (1995). For examples of the application of AD to other Architecture, Civil or Transportation Engineering projects, see Marchesi *et al.* (2013), Albano and Suh (1992) or Baca and Farid (2013) respectively.

Fundamental Concept of Axiomatic Design

The heart of Axiomatic Design is the axioms upon which it is built. An axiom is a "truth that cannot be derived but for which there are no counterexamples or exceptions" (Suh 2001). There are two axioms that make up Axiomatic Design. They are known as the independence axiom and information axiom. These are formally stated by Suh (2001) in the following manner:

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

Axiom2: The Information Axiom. Minimize the information content of the design.

Both of these axioms will be discussed in further depth in the following section. However, in order to better understand these axioms, the reader should first understand the concepts of domains and the mathematics that support each axiom.

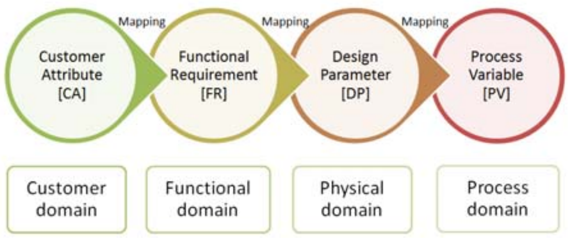

Figure 1. Domains of Axiomatic Design (Suh 2001)

According to Suh (2001), there are four domains that make up the world of design: the customer domain, the functional domain, the physical domain and the process domain. Domain relationships are shown in figure 1 above. As can be seen in the figure, each domain has a direct effect on the domain to its right. This is a graphical way of displaying the concept that the domain on the left is "what" the designer wants to achieve, and the domain on the right is "how" this will be achieved.

The customer domain is where the customer attributes (CAs), or needs, are defined. CAs are characterized by the attributes that the stakeholders are looking for in the product, process or system. For instance, the CAs for a building may include *keep space safe from intruders*, or *create an area large enough to provide living space for five people*.

The second domain is called the functional domain. This is where the customer needs are defined in terms of functional requirements (FRs), constraints (Cs) and non-functional requirements (nFRs). FRs are defined as the minimum number of independent requirements that entirely illustrate a design goal, and represent the objective and intent of the designer (Suh 2001, Thompson 2013). Cs set a hard limit on specific qualities, and nFRs describe characteristics of the final product or system, often in terms of aesthetics or durability. Thompson (2013) provides an in depth breakdown of the different elements of the functional domain. *Maintain shape*, *prevent erosion*, and *manage expectations* are possible FRs. Examples of constraints include *cost*, *weight*, and *density*. Lastly, nFRs include descriptions such as *durable*, *easy to use*, or *aesthetically pleasing*.

The third domain is called the physical domain and is the home of the design parameters (DPs) that were devised to fulfill the FRs within the specified Cs. Examples of DPs are *rebar reinforced concrete walls* or *double paned glass*.

The last and final domain is the process domain. It is in the process domain that the process variable (PV) used to achieve a specified DP is identified. This could include using *wooden forms to create concrete pillars* or *steel rollers to form a W section*.

One of the most important elements of Axiomatic Design is the mapping of properties from one domain to the next. Though mapping occurs from one domain to the next as in figure 1, another important process that occurs in Axiomatic Design is *the zigzag*. The zigzag process between the FRs and DPs is shown in figure 2**Error! Reference source not found.**. Though a similar zigzag process happens between the DPs and PVs, the primary focus is generally on the interaction between the FRs and DPs. The zigzag process works by first specifying a high-level FR. This is mapped onto the physical domain to create a high-level DP. The high-level DP is used to decompose the high-level FR into lower level FRs. The lower level design decision must remain consistent with the higher level design decisions. The FR should be defined without thinking about an already existing design solution. This is important because it allows the designer to be creative throughout the design process and possibly allows for the creation of innovative design solutions.

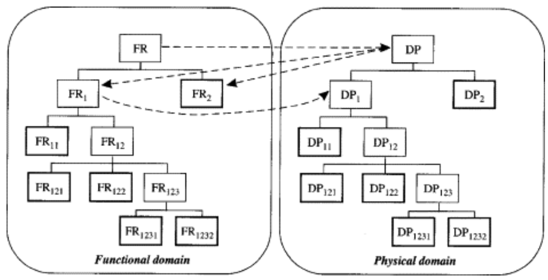

Figure 2. Zigzagging between FRs and DPs (Suh 2001)

Though figure 2 above shows the visual domain hierarchy, it can also be represented mathematically using matrices. If the generalized vector form of the functional requirements and the design parameters are represented by {FR} and {DP} respectively, then the matrix relationship can be expressed using the following equation (Suh 2001):

$$\{FR\} = [A]\{DP\} \tag{1}$$

In this equation, [A] is the design matrix that shows the relationship between the functional requirements and the design parameters, and it also determines whether or not the proposed design violates the independence axiom. The resulting design matrix can be either uncoupled (equation 2), decoupled (equation 3), or coupled (equation 4), where a zero in the design matrix represents low or no correlation between the FR and DP.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X_{11} & 0 \\ 0 & X_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X_{11} & 0 \\ X_{21} & X_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{4}$$

An ideal design will be an uncoupled design (equation 2). An uncoupled design means that FR1 is fulfilled by DP1, and FR2 by DP2. Changing DP1 will have no effect on FR2, and vice versa. This means the system is extremely flexible to changes made to the FR. This is in direct contrast to the coupled design (equation 4). As Albano and Suh (1992) explain, “the physical significance of a coupled design is the fact that the resultant solution is not flexible to change. The design has poor adaptability because it is difficult or impossible to adjust for any variations in the requirements due to loading change, interferences with other engineering disciplines, construction change orders, and varying environmental conditions.”

The remaining design notation or decoupled design (equation 3) is also an acceptable form of design that, like the uncoupled design, does not violate the independence axiom.

The second axiom, the information axiom, provides a numerical way to compare different designs and ultimately select the best design by minimizing the information content. The information content is a way of describing the probability of success of achieving the FRs with the selected DPs. It is defined by

$$I = \log_2(1/p) \tag{5}$$

where p is the probability of success. However, the information axiom plays a minor role in this paper. For additional information regarding the information axiom, the reader should refer to either the Axiomatic Approach to Structural Design (Albano and Suh 1992), or Axiomatic Design: Advances and Applications (Suh 2001).

Large Flexible Systems

Axiomatic Design has developed a way to design systems whose set of functional requirements evolve over the use phase of the system’s life cycle. Suh describes a system that needs to be able to “reconfigure itself to satisfy a different subset of FRs throughout its life” as a “large flexible system” (Suh 2001). The structure of a knowledge base for a large flexible system is modeled as in equation 6 below.

$$\begin{gathered} FR_1 \$ (DP_1^a, DP_1^b, ..., DP_1^r) \\ FR_2 \$ (DP_2^a, DP_2^b, ..., DP_2^r) \\ \vdots \\ FR_m \$ (DP_m^a, DP_m^b, ..., DP_m^r) \end{gathered} \tag{6}$$

Equation 6 states that any number of DPs can satisfy the specified FR. The addition of a DP to this equation is similar to expanding the database. As the database grows, the design can become more dynamic. For example, the DP of a “concrete column,” “steel column,” or “wooden column” can meet the FR of “support a vertical load”. As technology continues to evolve, should a new DP be created to “support a vertical load” this DP will be added to the database of DPs. The database will expand as new technologies are developed, and in doing so help ensure the best possible design can be achieved (Gilbert III *et al.* 2013, Suh 2001). The built database can be applied to a system that has FRs whose subsets vary as a function of time. Equation 7 below is an example of such a subset.

$$\begin{aligned} @t = 0 &\rightarrow \{FR\}_0 = \{FR_1, FR_4, FR_5\} \\ @t = T_1 &\rightarrow \{FR\}_1 = \{FR_2, FR_3, FR_5\} \\ @t = T_2 &\rightarrow \{FR\}_2 = \{FR_3, FR_4, FR_6\} \end{aligned} \tag{7}$$

In this example, the FRs at time zero are FR_1, FR_4, and FR_5. To satisfy each of these FRs, a corresponding DP from a knowledge base, like the one in equation 6, will need to be found for each FR. However, it is important to ensure that the independence axiom is not violated. In other words,

DP_1 must affect only FR_1 and have no effect on FR_4 and FR_5. The next part of equation 7 states that at time T_1 the FRs of the system change and a new set of DPs will need to be found (Suh 1995). Functions that remain constant, such as FR_5, should continue to work with the DPs selected for the new FRs. Using this method to model the design of a large system is useful when the system must be reconfigurable on demand. It is particularly helpful when the designers know at the start of the design process that customer needs are going to change over time. As will be demonstrated in the case study later in the paper, the reconfigurability of a large flexible system is an advantage when designing temporary housing.

Product Platform Approach to Design

In civil engineering nearly every problem is unique, encompassing a different set of requirements and stakeholders. Traditionally, it is uncommon for civil engineers to systematically seek economies of scale in a set of engineering projects.

Close analysis of many large-scale engineering projects, such as the temporary housing example provided in the case study, reveals that it is not uncommon to have a core set of functional requirements that are identical across multiple components of a project. When this occurs, civil engineering designers tend to use an informal system to take advantage of the commonalities. Though civil engineers do not often use a formal platform, there are methodologies from other disciplines that are applicable to this type of situation. Product Platform Design is a design concept that is well suited to helping to achieve a variable set of functional requirements, while at the same time capturing the economic advantages of economy of scale.

Product Platform Design is a recently developed approach to product architecture that shares a number of similarities to AD, and if used concurrently with AD theory, can help to significantly improve the design of modular systems (Gilbert III *et al.* 2013). A modular system is an approach to a problem that subdivides functionalities into smaller parts (modules) that are created separately but can then be used in conjunction to drive multiple functionalities.

The central idea of Product Platform Design is the concept of using a common platform to create a number of different products. "This approach allows manufacturing cost to be reduced by capturing economies of scale in the production process, and helps decrease the design cost as only a few aspects of each module need to be designed uniquely" (Gilbert III *et al.* 2013). The competitive advantage made possible by Product Platform Design is dubbed "mass customization" since it gives businesses the ability to meet a number of unique customers' needs at a low cost (Simpson 2004, Simpson*, et al.* 2005).

Critics of modular design often note the potential to "over-design" modules that have lower demands. Scale-based product families are a potential solution to overcome this constraint as well as an effective way to improve the flexibility of Product Platform Design. "Scale-based product families are developed by scaling one or more variables to "stretch" or "shrink" the platform and create products whose performance varies accordingly to satisfy a variety of market niches" (Simpson 2004).

A popular example of this concept in literature is the Honda automobile frame platform. The Honda platform can be "stretched" in length and width to satisfy the length and width requirements of any car frame design (Simpson 2004).

While this methodology is not often applied in civil engineering, the growing field of modular construction regularly utilizes methodologies similar to Product Platform Design in the design of structures (Lawson *et al.* 2012). Lawson claims that among the many advantages of modular construction is the ability to achieve:

- Economies of scale
- Faster speed of construction
- High level of quality control
- Minimum disruption to in situ area
- Adaptability for future extensions

Case Study: Axiomatic Design of a Dynamic Flexible Temporary Housing Unit

In this section, the use of Axiomatic Design and Product Platform Design is illustrated in the design of a generic temporary house. A brief introduction into temporary housing will first be provided in Section 4.1. Section 4.2 establishes the customer requirements that will be used in Section 4.3 to show the benefit of using a large flexible system in the design of temporary housing. Section 4.4 gives an example of an Axiomatic Design decomposition, and Section 4.5 concludes the case study by discussing how the Product Platform Design methodology can be applied.

Introduction

Every year, either because of some form of natural disaster or forced displacement, millions of people are left homeless. After these events, different organizations come together to work with the destroyed community to help restore a sense of normalcy and assist in community rebuilding. It is not uncommon for the slogan of these projects to be "build back better," though the literature shows that this is rarely the case. Temporary housing that is constructed to help the community's transition into a semblance of normality when permanent reconstruction is underway is often inadequate and is consistently unable to realize appropriately the stakeholder's needs and requirements (Johnson 2007a, 2007b).

Starting in the 1970's, a typical response to the need for temporary housing was prefabricated units. These units came in a variety of designs and styles, and were built to be shipped as turnkey units to locations affected by a natural disaster or conflict. However, these units suffered from a wide range of problems. "These shelters usually implied standardization and resulted in repetition of a "universal unit" that rarely responded to the specifics of climate, topography, local customs, and local forms of living" (Lizarralde *et al.* 2010). Johnson (2007b) elaborated on how these housing solutions also faced excessively high cost, late delivery, poor location, improper unit designs and other inherent issues.

Another problem that is gaining prominence is how providers of temporary housing "rarely anticipate and plan for a natural transition to permanent housing," nor do they have a plan for how to deal with the units when they are no longer needed (Lizarralde *et al.* 2010). Arslan wrote two papers centered on this problem, and a number of authors discuss it in their analysis (Arslan 2007, Arslan and Cosgun 2008). Units are used for years after their intended lifespan, either taking up space on valuable land, or morphing into a "shantytown."

In addition, temporary housing units can be extremely small and overcrowded. Typical unit sizes range from 15-35m^2, and occupant rates can be as high as ten people per unit (Johnson 2007a). What is notable is that "agencies tend to consider that a fair distribution of resources implies giving the same product to each beneficiary (instead of a more sensitive approach to fair distribution resulted from giving each beneficiary what he/she really needs)" (Lizarralde *et al.* 2010). This results in families of eight people being placed in the same size unit as a family of three. Families who previously ran a business out of their home (a common practice in developing countries) are left with no space for their business. Therefore, the "return to normalcy" the temporary housing unit was supposed to signify is a complete farce for them. The result is families' adding to their units ad hoc, often resulting in structures that will become a safety liability in the event of a subsequent disaster.

Unfortunately, the problems of the past are still present today, as temporary housing units are often culturally or climatically inappropriate, have large delays in their design and construction, and ultimately cause health and social problems within temporary housing camps (Johnson 2007a, 2007b). Some units are so inappropriate that the intended residents never use them and they remain empty, a useless financial drain on the entire rebuilding process.

Customer Requirements

The customer requirements for a temporary structure are not always clear or easy to define. However, in any project it is imperative to spend time to understand the customer requirements for the structure. In this paper, the customer requirements for the temporary house were determined based on typical requirements for a structure. These were determined from mistakes made in early temporary housing projects in literature and are shown in table 1 (Arnold 2009).

Though all of the requirements in table 1 are important in the design, many will become either constraints or nFRs and will not appear in the design decomposition.

Use of Large Flexible System

A large number of the problems experienced by existing temporary housing can be alleviated by approaching the problem as a large flexible system. There is a universal set of requirements that nearly every person wants in a house. These requirements remain the same if the house is for a single person or for a family of eight, if it is built in Southeast Asia or Northern Ireland, or even if it is for a fisherman or a home business owner. These core requirements remain the same even if the person living in the house situation changes. In addition, just like a permanent house, temporary housing should be able to change and adapt to the change in requirements. Therefore, the question becomes how to meet the core requirements of a temporary house while still allowing the structure to be highly customizable.

The proposed solution is a modular housing unit centered on a "core" module that can be combined with other modules to accommodate the user's fluctuating requirements. The FRs and DPs of the "core" and each module unit are designed with an AD knowledge base that includes the possible additions (though additional modules would be easy to add to the knowledge base as needed). The literature agrees with this approach arguing that the "need for the housing to be temporary motivates a flexible approach to the building's set of functional requirements" (Gilbert III *et al.* 2013, Simpson *et al.* 2005)

Figure 3 demonstrates a conceptual knowledge base that serves as a framework for the design of a modular temporary house. The modularity of the structure allows diverse user requirements to be achieved with separate module units, where the "studio module" is the "core" unit. As discussed in the introduction, the nature of temporary housing suggests the need for flexibility. One module may need to address multiple FRs. This can be seen by summing each column. The redundancy of how the functional requirements are realized is another important aspect as it allows for specialization. This is seen by summing the rows (Farid 2008).

Table 1. Customer Requirements for Temporary Structures (Arnold 2009)

Structural:	Support own weight and transfer lateral loads to building frame.
Water:	Resist water penetration.
Air:	Resist excessive air infiltration.
Condensation:	Resist condensation on interior surfaces under service conditions.
Movement:	Accommodate differential movement (caused by moisture, seasonal or diurnal temperature variations, and structural movement).
Sound:	Attenuate sound transmission.
Fire safety:	Provide rated resistance to heat and smoke.
Security:	Protect occupants from outside threats.
Maintainability:	Allow access to components for maintenance, restoration and replacement.
Constructability:	Provide adequate clearances, alignments and sequencing to allow integration of many components during construction using available components and attainable workmanship.
Durability:	Provide functional and aesthetic characteristics for a long time.
Extensibility:	Allow additions.
Reconfigurability:	Allow for adjustment based on occupants needs.
Reusability:	Provide an alternative use of whole structure of individual components when planned use is expired.
Aesthetics:	Do all of the above and look attractive.
Economy:	Do all of the above inexpensively.

The addition of modules not only allows additional functions to be achieved, it also allows for specialization, as mentioned above. An excellent example is a computer and a computer speaker. While most computers today have built in speakers, they are only able to provide basic sound quality. For higher performance computer audio, users need to purchase separate speakers (Gilbert III *et al.* 2013).

The advantages of an AD knowledge base approach to temporary housing can be made clear in an example. Following a natural disaster, a family of two are provided with a "core" temporary housing unit with hopes of moving into permanent housing within six months. However, the reconstruction takes longer than originally planned, and they have a child. The family is in need of additional space. However, instead of adding an informal and possible unstable addition to the house, the family simply adds an additional bedroom module.

Functional Requirement \ Design Parameter	Studio Module	Bathroom Module	Kitchen Module	Bedroom Module	Living Room Module	Dining Room Module	Study	Hall	Storage (Closet)	Stairs
Support Food Preparation	X		X							
Support Elimination of Human Waste		X								
Support Social Activity	X				X					
Support Relaxation	X			X						
Support Eating	X					X				
Support Personal Hygiene	X	X	X							
Support Sleeping	X			X	X					
Support Work	X					X	X			
Support Exercise	X						X			
Support Connectivity of Rooms	X							X		X
Support Storage	X								X	

Figure 3. Graphical Form of Axiomatic Design Knowledge Base (Gilbert III *et al.* 2013)

Decomposition of Studio Module

The Axiomatic Design method of mapping FRs to DPs by zigzagging provides an excellent method of designing the modules of the temporary house. "This analytical process complements the creative process of synthesizing a design solution and uses the design axioms as objective criteria for recognizing good design decisions" (Albano and Suh 1992). For space, only the studio module will be decomposed in this paper. However, the additional modules can be created by adopting the design of the studio module.

At the highest level, the structure is bound by a single functional requirement, FR0, "Provide 'Platform' Unit that Meets Basic Housing Needs" and can be achieved using the design parameter, DP0, Studio "Core" Module.

Based on the constraints and requirements of a temporary structure above, the second level functional requirements were selected as follows:

FR1= Passively protect and maintain internal climate
FR2= Actively maintain internal environment
FR3= Connect with environment
FR4= Remain structurally sound
FR5= Support user activities

The Design parameters selected to fulfill each of these FRs were:

DP1= Building Envelope
DP2= HVAC system
DP3= Connections
DP4= Structure
DP5= System configuration

Many of the DPs selected at high levels share similar names with the FRs they are fulfilling. This is common, and should be expected particularly at the first level of decomposition.

Table 2 shows the continued decomposition of the zigzag AD process to the second level. The DPs were selected to preserve the independence axiom, which figure 4 demonstrates was well done. Figure 4 is called the design matrix (DM) of Axiomatic Design, and is a visual way of presenting the decomposition of the FRs and DPs. It also can quickly show designers where DPs affect FRs, and clearly shows if the relationship between the FRs and DPs is uncoupled, decoupled or coupled.

As can be seen in table 2 and figure 4, FR1, which passively protects and maintains the internal climate, includes the ability to protect occupants from natural issues such as water, and other problems like intruders and fire. The DPs selected to fulfill these requirements were all related to the envelope of the building.

FR2 actively maintains the internal climate, and uses a number of mechanical functions to keep the internal climate at the appropriate temperature with adequate healthy air. The AD approach to the design allows these systems to change based on the requirements. Here, a fan is used for cooling, however, in a hotter climate this may be replaced with a solar powered AC unit.

FR3, connect with the environment, is decomposed to connect with other modules, allow controllable interaction with the external environment, and connect to infrastructure. These selections were made to allow a further decomposition of each FR without compromising the independence axiom, while also enabling an easier design of a standard platform. Figure 4 shows these were all further decomposed, but for brevity were excluded from the table. The interfaces between each module are key. Without them, the design of the entire concept falls apart. This makes it clear that the design must be simple to connect and include ways to allow the exchange of electricity, water, and people (Gilbert III *et al.* 2013). Design to connect with the external environment is often overlooked except for the most basic function of entering and exiting the building. However, in developing countries, internal and external areas don't have the same degree of separation of western houses. In fact, it is extremely important that the indoor and outdoor areas are closely tied together.

FR4, remain structurally sound, is decomposed to include remain stable, and maintain shape. The DPs chosen to meet these FRs were the foundation and frame. While these are important components of all buildings, they have a few distinctive features unique to temporary housing. For example, they "must be able to maintain their shape despite numerous dynamic loads, including normal loads such as seismic and wind loads, but also will need to withstand forces placed on the frame during transport" (Gilbert III *et al.* 2013). Likewise, since the structure is temporary, the foundation should be designed to be removable at the end of the structure's use to minimize site damage and the resultant loss of value to the property.

Table 2. Second Level Decomposition of Design

FR0*	Provide "Platform" Unit that Meets Basic Housing Needs	DP0*	"Studio Module"
FR0*	Provide "Bathroom" Unit that Provides for Hygiene Needs	DP0*	"Bathroom Module"
FR0*	Provide "Kitchen" Unit that Supports Food Preparation	DP0*	"Kitchen Module"
FR0*	Provide "Bedroom" Unit that Supports Privacy and Sleeping	DP0*	"Bedroom Module"
FR1	Passively Protect and Maintain Internal Climate	DP1	Building Envelope
FR1.1	Keep Out Moisture	DP1.1	Waterproof Shell
FR1.2	Resist Thermal Transfer Through Radiation, Convection and Conduction.	DP1.2	Insulation
FR1.3	Keep Internal Area Dry	DP1.3	Drainage
FR1.4	Protect from Insects	DP1.4	Screen
FR1.5	Protect Occupants from Outside Threats	DP1.5	Locks
FR1.6	Protect from Fire and Smoke	DP 1.6	Fire Board
FR2	Actively Maintain Internal Climate	DP2	HVAC System
FR2.1	Heat Interior Area	DP2.1	Electric Heating Unit
FR2.2	Cool Interior Area	DP2.2	Fans
FR2.3	Maintain Adequate Air Quality	DP2.3	Ventilation System
FR3	Connect with Environment	DP3	Connections
FR3.1	Connect with Other Modules	DP3.1	Standard Interface
FR3.2	Allow Controllable Interaction with External Environment	DP3.2	Controllable Inlet/Outlet
FR3.3	Connect to Infrastructure	DP3.3	Connection Modulus
FR4	Remain Structurally Sound	DP4	Structure
FR4.1	Remain Stable	DP4.1	Foundation
FR4.2	Maintain Shape	DP4.2	Frame
FR5	Support User Activities	DP5	System Configuration

Lastly, FR5, support user activities, is met by DP4, system configuration. This refers to the layout of the internal area of each module. It is in this area that the specific functionality of each unit will be

		DP0 "Studio Module"	DP1 Building Envelope	DP1.1 Waterproof Shell	DP1.2 Insulation	DP1.3 Drainage	DP1.4 Screen	DP1.5 Locks	DP 1.6 Fire Board	DP2 HVAC System	DP2.1 Electric Heating Unit	DP2.2 Fans	DP2.3 Ventilation System	DP3 Connections	DP3.1 Standard Interface	DP3.1.1 Large Portal	DP3.1.2 Inter-modular Electrical Connection	DP3.1.3 Fresh Water Piping Connection	DP3.1.4 Waste Water Piping Connection	DP3.2 Controllable Inlet/outlet	DP3.2.1 Door	DP3.2.2 Window	DP3.3 Connection Modulus	DP3.3.1 Connection to Power Source	DP3.3.2 Connection to Water Source	DP3.3.3 Connection to Waste Water Disposal	DP4 Structure	DP4.1 Foundation	DP4.1.1 Compacted Soil	DP4.1.2 Temporary Foundation Piles	DP4.2 Frame	DP4.2.1 Lateral Bracing	DP4.2.2 Semi-Rigid Frame	DP4.2.3 Columns	DP5 System Configuration
FR0	Provide "Platform" Unit that Meets Basic Housing Needs	O																																	
FR1	Passively Protect and Maintain Internal Climate		X																																
FR1.1	Keep Out Moisture			X																															
FR1.2	Resist Thermal Transfer			X	X																														
FR1.3	Keep Internal Area Dry					X																													
FR1.4	Protect From Insects			X			X																												
FR1.5	Protect Occupants from Outside Threats			X				X																											
FR1.6	Protect From Fire and Smoke			X					X																										
FR2	Actively Maintain Internal Climate									X											X	X													
FR2.1	Heat Interior Area										X																								
FR2.2	Cool Interior Area											X																							
FR2.3	Maintain Adequate Air Quality										X		X								X	X													
FR3	Connect With Environment		X			X								X																					
FR3.1	Connect with Other Modules														X																				
FR3.1.1	Provide Ingress for Users Between Modules															X																			
FR3.1.2	Provide Electrical Connection Between Modules																X																		
FR3.1.3	Provide Freshwater Connection Between Modules																	X																	
FR3.1.4	Provide Wastewater Connection Between Modules																		X																
FR3.2	Allow Controllable Interaction with External Environment		X																	X															
FR3.2.1	Allow Ingress Into and Out of Structure for People																				X														
FR3.2.2	Allow Entrance of Natural Light																				X	X													
FR3.3	Connect to Infrastructure		X			X																	X												
FR3.3.1	Provide Electricity																							X											
FR3.3.2	Provide Running Water																								X										
FR3.3.3	Dispose of Waste Water		X			X																				X									
FR4	Remain Structurally Sound																										X								
FR4.1	Remain Stable																											X							
FR4.1.1	Protect from Erosion																												X						
FR4.1.2	Protect from Differential Settlement																													X					
FR4.2	Maintain Shape																														X				
FR4.2.1	Protect from Lateral Loads																															X			
FR4.2.2	Protect from Dynamic Loads (Wind/ Seismic)																												X	X		X	X		
FR4.2.3	Protect from Vertical Loads																															X		X	
FR5	Support User Activities													X									X	X	X		X				X		X		X

Figure 4. Design Matrix of a Temporary House

achieved. For example, the studio module may include a counter area to help with the preparation of food, or a bathroom that will include a toilet and sink. This was not further decomposed in this paper, as the functionality will depend entirely on individual characteristics of the location for the structure.

Application of Product Platform Design

Product Platform Design is a powerful way to create highly customizable modules to form a house while simultaneously minimizing manufacturing and design costs. In the proposed example, the studio module needs to be a larger module to meet the diverse set of functional requirements with minimal coupling (Gilbert III *et al.* 2013). The kitchen and bedroom need to fulfill fewer functions, so the modules need not be as large. Likewise, the bathroom and hallway module can be smaller still. It is advantageous to conserve space when possible, as it will save the cost of material and land. Keeping the modules appropriately sized for the required functionality is highly advantageous. To achieve the diversity of size but still take advantage of Product Platform Design all modules can be designed and built on a scale-based product family. The scale-based approach "enables the units to continue to capture the benefits of Product Platform Design of having low design and manufacturing cost while achieving high customization" (Gilbert III *et al.* 2013).

Table 2 demonstrates the first two levels of decomposition of a module. The only difference between the conceptual model FRs for the studio module and the other modules is the size and the need to connect to the infrastructure (FR 3.3). When the decomposition is continued to the third and fourth levels, more differences become apparent, but these differences can be handled by not including them in the platform. Further specialization can be added at a later point.

Conclusion

In this paper, the fundamental concepts of Axiomatic Design and Product Platform Design were introduced as potential formal methods for the conceptual design of civil engineering projects. These two theories were applied to a case study of the design of a temporary house to demonstrate their application. The case study showed the advantages of treating the problem as a large-flexible system. It also demonstrated how to use Axiomatic Design in the design process to create improved designs. Applying Product Platform Design theory in addition to AD aided in creating better-defined product functional features. Most importantly, it enabled a new and a unique temporary house design that satisfies customer needs. One additional advantage of using Axiomatic Design is the flexibility it provides. For example, if electricity is not available, it is easy to see that neither a fan nor heating unit will work in the unit. This means the designers need to select another DP that does not require the use of electricity to meet the functional requirements *Heat Internal Area* and *Cool Internal Area*. However, more work still needs to be done to use AD and Product Platform Design in civil engineering.

One place of particular interest for future research is in using the information axiom to help select the best materials for structures like temporary housing. It would also be interesting to test the effects of the conceptual design by completing the design process and creating a physical temporary housing structure.

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