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AN AXIOMATIC DESIGN BASED APPROACH FOR THE CONCEPTUAL DESIGN OF TEMPORARY MODULAR HOUSING

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ABSTRACT

Temporary housing has emerged as a practical solution to a plethora of contemporary circumstances, including, though not limited to, emergency housing, worker housing, and large-scale events housing. Interim housing is also a possible solution to future housing on lunar and Martian expeditions. Unfortunately, achieving the short-term nature of temporary housing is less than straightforward. One design pitfall leads to scanty housing that does not meet occupants' functional requirements, while another leads to overdesigned, permanent homes that may evolve into unsightly unstructured settlements. Thus, current design practices may not fully meet the diverse range of stakeholder requirements adequately. This paper addresses the central issue of temporary housing as a non-functional requirement on the housing system's lifecycle properties of modularity, reconfigurability, extensibility, and reusability. The large flexible system proposed in Axiomatic Design and the modularity found in product platforms impact the proposed conceptual design from the beginning of the design process. Design interdependence is systematically addressed to avoid needless coupling and maximize cohesion within the modules. The large flexible system knowledge base framework and the Independence Axiom serve to achieve the central goal of temporary housing. The first illuminates the high-level functional requirements (FRs) of a temporary house as well as the common module unit that serves as a product platform with standard interfaces. Next, to ensure the functional requirements for each unit are met, a design matrix (DM) is made for each module highlighting the respective FRs and design parameters (DPs).

Keywords: temporary housing, knowledge-based design, Axiomatic Design, modularity, large flexible systems.

1 INTRODUCTION

The use of temporary housing (TH) stretches back into the depths of human history. For thousands of years, the only "housing" used by humankind was temporary, and although today most people live in permanent housing, there remains a strong demand for TH in a number of unique settings. Despite the long history of the use of temporary shelters, literature shows that TH consistently is unable to realize appropriately the stakeholder's needs and requirements [Johnson, 2007a; 2007b]. This is in part due to the approach that designers of TH take in the design process. No formal methodology of the design of temporary housing is readily available in the literature. This lack of structure forces designers to rely on their intuition or previous experience, making the design more of an art form than a science.

For these reasons, producing a temporary housing unit that optimally meets the stakeholder's requirements has proven to be difficult, particularly because the stakeholder's requirements and constraints change rapidly with time and fluctuate drastically from location to location. While it may be difficult to find a "one-size-fits-all" house design, a one-size fits all approach to the design process may be possible. In recent years, approaches such as Axiomatic Design have been developed to make design less of an art and more of a science [Suh, 2001]. Axiomatic Design is a useful tool that systematically allows designers to map user requirements onto function, and the function onto form.

The use of Axiomatic Design's knowledge base can ensure that the high-level requirements of a large flexible system, such as temporary housing, are accomplished. The modularity afforded by proper large flexible system design is further benefitted by the use of product platform philosophy [Simpson, 2004]. A design matrix ensures the functional requirements (FRs) and design parameters (DPs) are achieved by satisfying the Independence Axiom.

The goal of this paper is to prove that the design of modular, reusable temporary housing will be improved through the application of a product platform and Axiomatic Design from the beginning of the design process. The rest of the paper proceeds as follows. Section 2 introduces Axiomatic Design, and provides a background into existing literature on Product platform design and Axiomatic Design. Section 3 contains the knowledge base and the design matrix for the proposed modular house, and discusses how the use of Axiomatic Design can ensure functional requirements are met during the design process.

2 BACKROUND

This section provides the background necessary for the development of a conceptual design of temporary housing based upon Axiomatic Design principles in Section 3. First, Section 2.1 describes the existing literature on temporary housing design, and Sections 3.2 and 2.3 discuss how the product platforms and Axiomatic Design are well equipped to meet these needs.

2.1 Existing Literature on the Design of Temporary Housing

Temporary housing is a shelter that is meant to be used for a short period, and in the context of this paper refers to a man-made, short-term, modular, and reusable structure [Johnson, 2007b]. Whereas in the past, temporary shelters were predominantly the domain of migratory groups, today the applications are far more diverse and facilitate all of the following and more:

- Refugee and Internally Displaced Person (IDP) housing [Mooney, 2009]
- Natural Disaster Relief housing [Johnson, 2007a]
- Recreation
- Military housing [Ferguson, 2010]
- Entertainment venues overflow housing [Bundhun, 2010]
- Housing on Martian or lunar expeditions [Carlson and Criswell, 2004]

Different functional requirements are needed to meet the diverse uses and varying locations of temporary housing.

Emergency temporary housing is used whenever a person or group of people is forcibly evicted from their home, such as a natural disaster or military conflict. To satisfy this need, temporary shelters are often provided by governments and non-government organizations (NGO's) while permanent houses are built [Johnson, 2007b]. People may pass through four sheltering and housing stages after an emergency:

- Emergency shelter: One night to a couple of days during the emergency while normal routines are suspended. Often takes the form of mass shelter or tarp.
- Temporary shelter: A few weeks following the disaster, normal routines continue to be suspended. May take the form of a tent or public mass shelter.
- Temporary housing: A few weeks to several years while waiting for a permanent solution. People should be able to return to normal daily activities. Temporary housing can take the form of a rented apartment, a prefabricated home or a small shack, depending on the context
- Permanent housing: Return to the reconstructed former home, or resettlement in a new home [Johnson, 2007b; Nigg *et al.*, 2006]

Because it can take years to rebuild an adequate supply of permanent housing, temporary housing becomes very important. Temporary housing units provide secure accommodations that allow people to return to normal life.

Though the focus of this paper is on the design of the physical structure of the TH, it is important to remember that the house is only part of the larger "housing program." According to one paper, a "program for temporary housing must not only include a roof, but also offer aspects that make it possible to return to normal life, such as housing in a location that has reasonably convenient access to services and jobs or an affordable transport system, schools, shopping… etc." [Johnson, 2007b]. They also need to be situated in a location that will not be affected by post-natural disaster problems [El-Anwar *et al.*, 2010; Nigg et al., 2006]. While these considerations may not always directly influence the design of a TH, it is important that the larger context be kept in mind both while specifying the user requirements and throughout the remainder of the design process.

Pre-planned temporary housing is used when there is existing knowledge of the need for a short-term housing. One example is when a temporary military camp is needed to serve as a base of operation. Another is for mobile recreational needs including campers, RV's and tents. A third situation for pre-planned TH is to deal with a large-scale influx of people coming into an area for a particular event. The needs for temporary housing solutions arise in this case because the current housing solutions are insufficient for the size of the group. An excellent example of this would be the influx of people to a World Expo, the Olympics or even the World Cup. Qatar, the host of the World Cup in 2022, is currently experimenting with different ideas on how to fulfill the housing demand of football fans that will be entering the country for a span of a few months while the World Cup is being held. Building hotels is a very tricky solution, as they are a massive expense, and will only be needed for a few months during the World Cup. Qatar does not have a particularly large tourism industry, and there is low expectation for significant growth after the World Cup. "Analysts said to avoid 'white elephant' properties, Qatar would have to find as many short-term solutions, such as temporary pre-fabricated accommodation" [Bundhun, 2010]. However, for this to be a practical solution, these units will need to make economic sense to build in the first place, and must be reusable in the future.

The current practices used in the design of temporary housing often do not meet the all of the user requirements. Johnson [2007b] concisely states a number of problems facing temporary housing: "Temporary housing programs suffer from excessively high cost, late delivery, poor location, improper unit designs and other inherent issues". Other problems in unit design included: leaky units, units built with faulty electrical systems, units with poor foundations, and units unable to meet the standards for a cold climate [Davidson *et al.*, 2007; Johnson, 2007b]. In addition, TH can be extremely small and overcrowded, with units sizes ranging from 15-35m^2, and occupant rates often as high as 10 people in a single unit [Johnson, 2007a].

The 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 the temporary housing camps [Johnson, 2007b].

A number of conflicting constraints may inhibit temporary housing. For example, TH may be used for a significantly longer period than was originally planned during the design process [Arslan and Cosgun, 2008; Johnson, 2007a; Nigg *et al.*, 2006]. However, because policy makers and landowners around the location where the temporary housing has been built do not want the area to turn into a "slum," it cannot be built to be too permanent. This suggests it should be "targeted to last long enough for people to resume daily activities, but not comfortable enough to become permanent" [Johnson *et al.*, 2006]. This issue is further compounded by the fact that in many developing countries, home based businesses serve as one of the primary sources of income. As such, it is important that the house be able to continue to serve this FR [Lizarralde, 2011; Rubio *et al.*, 2004]. There is also often no plan as to how to remove, reuse or recycle the units when their original planned use is over [Arslan, 2007; Arslan and Cosgun, 2008].

Unlike traditional housing where the home is sold directly to the customer and the customer can influence the design and market, temporary housing is generally driven by a third party, often a government or NGO. This means that the link between the functional requirements and the stakeholders is not as clear with temporary housing as it would be in the case of traditional housing.

2.2 Product Platform Literature

The discussion on temporary housing above shows that a core set of functional requirements are required for as long as the housing is in service, while a number of occupants' functional requirements evolve over the usage phase of the building's life cycle. Furthermore, the need for the housing to be temporary also motivates a flexible approach to the building's set of functional requirements [Simpson *et al.*, 2005]. Product platform design is one design concept well-suited to achieving a variable set of functional requirements.

Product platforms, or product families, is another recently developed approach to product architecture that shares a number of similarities to AD, but also provides approaches that, if used concurrently with AD theory, can help to significantly improve the design of modular systems. Product platform design is built on the concept of using a common platform upon which a number of different products are built. 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. This creates the competitive advantage that has been dubbed "mass customization" since it affords businesses the ability to meet a number of unique customers' needs at a low cost [Simpson, 2004; Simpson *et al.*, 2005].

One of the handicaps of the product platform approach to design is that it often results in "over-design" of the 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]

Take, for example, the design of the Honda automobile platform. The Honda platform is capable of being "stretched" in length and width to satisfy the length and width requirements of any car frame design [Simpson, 2004].

2.3 Axiomatic Design Literature

In addition to product platforms, Axiomatic Design has also accounted for 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 FR's throughout its life" as a "large flexible system" [Suh, 2001]. The structure of a knowledge base for a large flexible system is modeled like Equation 1 below.

$$\begin{aligned} &FR_1 \$(DP_1^a, DP_1^b, ..., DP_1^r) \\ &FR_2 \$(DP_2^a, DP_2^b, ..., DP_2^r) \\ &\quad\vdots \\ &FR_m \$(DP_m^a, DP_m^b, ..., DP_m^r) \end{aligned} \qquad (1)$$

Equation (1) states that the FR can be satisfied by any of the following DP's. The addition of a DP to this equation is similar to expanding the database, and as the database grows, the more dynamic the design can be. The database will grow and change as new technologies are developed. This is important since "available knowledge and technology determine the best design we can develop at a given point in time" [Suh, 2001]. Once the database is built, it can be applied to a system that has subsets that vary as a function of time. Equation (2) below is an example of such a subset.

$$\begin{aligned} &@t = 0 \rightarrow \{FR\}_0 = \{FR_1, FR_4, FR_5\} \\ &@t = T_1 \rightarrow \{FR\}_1 = \{FR_2, FR_3, FR_5\} \\ &@t = T_2 \rightarrow \{FR\}_2 = \{FR_3, FR_4, FR_6\} \end{aligned} \qquad (2)$$

In this example, the FR's at time 0 are FR_1, FR_4, and FR_5. This means that to satisfy each of these FRs a corresponding DP from the database like the one in Equation 2 will need to be found. However, to maintain the Independence Axiom, DP_1 must affect only FR_1 and have no effect on FR_4, and FR_5. However, at time T_1 the FR's change and a new set of DP's will need to be determined [Suh, 1995]. Using this process to model the design process of a large system is very useful when the system must be reconfigurable on demand, such as when there is a change in customer requirements. As will be demonstrated in the model later in this paper, the reconfigurability of a large flexible system is an advantage when designing temporary housing.

The Axiomatic Design large flexible system provides an excellent framework for the high-level architectural design of a system. In complement, a traditional AD design matrix can be used for the more detailed levels of the design hierarchy.

A Design Matrix (DM) is created by mapping the functional requirements (FRs) to the Design Parameters (DPs) of the system. First, the highest level FR is determined, and used to find the high level DPs. Next, lower levels of FRs are created by "mapping" the DP back to the FR. This process is continued until the system is sufficiently decomposed to be used by the designer. A set of axioms, theorems, and corollaries govern the entire process.

3 MODELING AND DISCUSSION

The previous section proposed product platforms and Axiomatic Design as useful design concepts for temporary housing. The modular house proposed is built in individual "units" where each unit fulfills specific high-level functional requirements. For example, the kitchen module fulfills the high-level requirement of supporting the preparation of food, and personal hygiene. The knowledge base model presents all of the high-level requirements of temporary housing, and the modules that are able to fulfill the specified FR. The "studio module" is a base module that is able to satisfy limited amounts of all the FRs. That is to say, while it may have a small area to prepare food, it does not provide all the functionality found in the kitchen module. The creation of a DM model is also provided to give an example of how the FRs and DPs can be created using the Independence Axiom.

3.1 AXIOMATIC DESIGN KNOWLEDGE BASE

An Axiomatic Design knowledge base can be applied to a large flexible system, such as TH, to map the various DPs that can achieve a specified FR. Since the FRs of TH varies with time, the DPs have to be flexible to meet the new FR without violating any of the axioms. This means the TH needs to be extremely customizable.

A modular housing unit refers to a structure that has a "core" centre, but expands to accommodate the user's fluctuating requirements. The use of Axiomatic Design ensures that the core is built with the ability to add additional sections to the house based on the user's needs. The FRs and DPs of the "core" and each module unit are designed with an AD knowledge base that includes the possible additions.

		Design Parameter									
		Studio Module	Bathroom Module	Kitchen Module	Bedroom Module	Living Room Module	Dining Room Module	Study	Hall	Storage (Closet)	Stairs
Functional Requirement	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 1. Graphical form of Axiomatic Design knowledge base.

The model presented in Figure (1) demonstrates a conceptual knowledge base that serves as a framework for the design of a modular TH. The modularity of the structure allows the diverse user requirements to be achieved with separate module units, where the "studio module" is the "core" unit. The driver of temporary housing suggests the need for flexibility of the modules. One module needs to address more than one FR. As well as redundancy of the functional requirements as to how the functional requirements are realized. The first is the sum of a column, the second is the sum of the row [Farid, 2008].

An example can be used to explain the advantage of approaching the problem using an AD knowledge base. In the first example, imagine a TH for a single male after a natural disaster. This man does not often host social engagements, rarely brings work home, and often eats out. He is expecting to live in the unit for a very brief period. In this case, a studio module with an attached bathroom module will be able to meet the high-level needs of the stakeholder. However, if the time to rebuild the man's permanent house should be extended, and the man marries and decides to cook more at home, the addition of a kitchen and possibly bedroom module will better serve the user's changing requirements.

This is similar to a computer and a computer speaker. While most computers today have built in speakers, they are only able to provide basic sound quality. Users that wish to have higher performance from their speakers will need to purchase separate speakers to obtain this higher functionality.

3.2 COMMON INTERFACES

The use of a common interface ensures the versatility of the modular units. Though the "Studio" module has the potential to act as a bus to which the other modules can connect, the design of the common interface should be such that the individual modules can connect even should the "studio" module not be present. This allows for a more adaptable layout of the structure, and an ability to customize each total "unit" to the individual user's needs. The opportunity to customize the unit also has the added benefit of improving the users experience with the house.

The common interface includes an electrical connection between the modules, and two water connections, one for wastewater, the other for freshwater. This helps to improve the functionality of the design by not limiting functions that require electricity or water to a single unit. Lastly, the units will be able to be connected for physical passage by removable curtain walls between them.

3.3 AXIOMATIC DESIGN DESIGN MATRIX

Understanding the stakeholder requirements is paramount in achieving a good design for a temporary housing unit. However, as noted above, this becomes difficult to define as the requirements change from location to location and with every temporary housing type. On the other hand, when designing a pre-planned TH, the time constraint is less important, and the comfort and cost of the structure is more important. Irrespective of which group the house is being designed for, it is important that the designer understands the local, social, economic and climatic conditions.

The list below shows a consolidated high-level list of requirements of all TH, regardless of location or type:

1. Safety from elements
2. Minimum level of sanitation
3. Comfort level to match local standards
4. Located in close proximity to centers that provide for needs/wants (jobs, schools, medical centers, shopping centers, etc.) or adequate public transport to reach such centers

How each of these requirements is broken apart, and what other high-level requirements are needed changes from location to location. For example, military housing, tents and RV's all may have the added requirement of being mobile or easy to transport. The requirements shown were taken primarily from the work Arnold [2009] which highlights the requirements for the design for permanent structures, adjustments were made based on TH literature.

What is meant by "safety from elements" will vary drastically from location to location and will depend a great deal on the reasoning for the TH. There are often codes and regulations that ensure these safety needs are met. However, often for temporary structures this code is incomplete or non-existent and, in nearly all cases, the regulations for TH are less strict then that of permanent housing. However, no matter the regulations, TH is required to fulfill some, or all of the following:

1. Resistance to water
2. Insulation for cold weather
3. Insulation for hot weather
4. Structurally sound for transportation and seismic loads
5. Resistant to earthquakes
6. Ability to keep out intruders
7. Sturdy foundation
8. Resistance to high winds
9. Fire resistant

An acceptable level of sanitation also depends heavily on the location and type of TH used. To achieve this minimum level of sanitation any combination of the following may be needed:

1. Sufficient ventilation
2. Natural Lighting
3. Access to running water
4. Area that supports personal hygiene
5. Elimination of human waste

As with safety from elements and sanitation, there is a great deal of variation in what is considered an appropriate level of comfort. Comfort also takes into account a number of cultural specific requirements, and may have overlaps from any of the above two sections. A list of what features may be needed to be included in a TH are:

1. Access to running water
2. Access to hot and cold water
3. Electricity
4. Ability to maintain an ideal temperature
5. Lighting (Natural and artificial)
6. Area that supports personal hygiene and elimination of human waste
7. Area that supports privacy
8. Area that supports sleep and relaxation
9. Area that supports social activities
10. Area that supports food preparation
11. Area that supports work
12. Area that supports storage
13. Regional specific requirements
14. Access to materials to expand house (and ability of house to be expanded)

The last section, access to centers that provide basic needs and wants, may not be important in the design of the individual housing unit, but it is important for the designer to know. The following list shows a number of services that may be important for residents in temporary housing:

1. Access to jobs
2. Access to schools
3. Access to shopping center
4. Access to public transit
5. Access to religious center

A DM of the studio module was created by using the Design Matrix theory of mapping the FR's to the DP's, and is shown in a Figure 2. Table 1 below shows a list of the first two levels of decomposition. The decisions used to make the selected FRs and DPs is also discussed below. In an attempt to preserve the Independence Axiom, when possible, interactions were designed to be either uncoupled or decoupled.

The Design matrix started with recognition that the improved design of temporary housing implies customizable, flexible, and changing needs. Knowing this, a central "core" module that allowed the addition of "extra" modules was determined to be the best possible solution, with modularity, reconfigurability, extensibility, and reusability being the most important life cycle properties to focus the design. As shown in Table 1, the FR0 was selected to be "Provide 'Platform Unit that Meets Basic Housing Needs," and this was achieved by a studio "core" module DP.

Based on the constraints and requirements of a temporary structure above, the second level functional requirements were selected: Protect internal climate (FR1), Connect with environment (FR2), Remain structurally sound (FR3), Support user activities (FR4). An exterior barrier, connections, structure, and system configuration DP were selected to meet each FR respectively. These DP's become significantly more clear in the next decomposition. FR1, Protect internal climate, was met by DP1, an exterior barrier, and was further decomposed to the following: Keep out moisture, insulate from hot/cold fluctuations in external environment, heat interior area, cool interior area, keep interior area dry, protect from insects, and protect from intruders. DP's were selected to preserve the Independence Axiom. If the DPs properly meet the FR, then problems like leaking roofs and improperly insulated units will not be a problem. It will be important to specify the acceptable parameters for all FRs and DPs and optimize using the Information Axiom.

As shown in Table 1, FR2, connect with the environment, is met by DP2, connections, and is further decomposed to the following: connect with other modules, allow controllable interaction with external environment, and connect to infrastructure. The DPs selected were standard interface, controllable inlet/outlet, and connection module. 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. Table 1 also shows that FR2.3 will only be required in the studio and bathroom modules. Also, as can be seen in Figure 2, these were all further decomposed, but were excluded from the table for brevity. Proper design of the standard interface is important to allowing the unit to meet the life cycle properties of modularity, reconfigurability, extensibility. The design must include ways to allow the passage of key elements such as electricity, water, and people, while also being simple to connect. Design of the other two connections is important as they provide access to key requirements for any structure, temporary or otherwise.

FR3, remain structurally sound, is met by DP3, structure, and is further decomposed to the following: remain stable, and maintain shape. The DP's selected to meet these FRs were the foundation and frame. While these are both common elements in all structures, they have unique characteristics when implemented with a temporary, re-usable structure. 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. Likewise, the foundation should be designed to be removable at the end of the structures use so as to minimize site damage, and the resultant loss of value to the property. These requirements are both important to ensuring the safety and reusability of the structure.

Last, FR4, support user activities, is met by DP4, system configuration. It is decomposed into the following: provide artificial lighting, support storage, support food preparation, support eating, support social activity, support relaxation, support sleeping, support work/study, support exercise, and support elimination of human waste. As can be seen in Table 1, not all of these FRs and DPs will occur in every unit. This is important because it is in satisfying these diverse FRs that the modularity of the house becomes important. Also, as the discussion about the knowledge base explained, this variation allows the entire house to be customizable to each user's needs.

As previously mentioned, TH is often constrained by the total permissible square area. This becomes even more of a problem when the units are re-usable and need to be easy to transport. While the modularity of the structure helps to eliminate the space constraints, it remains a problem for the design of the "studio" module. The studio module is constrained by space but still must be able to meet a number of functional requirements each of which require a minimum amount of space. The spatial constraints affect the functional requirements specified in FR4 in particular. All of these FR's require a certain amount of space, which, when all are added together, is greater than the area of the unit. This produces unintentional coupling. As AD Theorem 20 states, this coupling is an unavoidable side effect of tightening the spatial constraint [Suh, 2001]. While this coupling is not ideal and should be avoided where possible, it is an unfortunate consequence of attempting to maximize functionality in a limited space. This coupling can be seen in Figure 2. It is important that designers keep this in mind throughout the design process.

It is also important to recall that because the housing is temporary it has to be easy to disassemble. Functional requirements will ramp down to zero when the structure has finished fulfilling the high-level functional requirements.

Table 1. Level one and level two FRs and DPs.

FR #	Functional Requirement	DP #	Design Parameter	
FR0*	Provide "Platform" Unit that Meets Basic Housing Needs	DP0*	"Studio Module"	S
FR0*	Provide "Bathroom" Unit that Provides for Hygiene Needs	DP0*	"Bathroom Module"	Br
FR0*	Provide "Kitchen" Unit that Supports Food Preparation	DP0*	"Kitchen Module"	K
FR0*	Provide "Bedroom" Unit that Supports Privacy and Sleeping	DP0*	"Bedroom Module"	B
FR1	Protect Internal Climate	DP1	External Barrier	S, Br, K, B
FR1.1	Keep out Moisture	DP1.1	Waterproof Shell	S, Br, K, B
FR1.2	Insulate from Hot/cold Fluctuations in External Environment	DP1.2	Insulation	S, Br, K, B
FR1.3	Heat Interior Area	DP1.3	Electric Heating Unit	S, Br, K, B
FR1.4	Cool Interior Area	DP1.4	Fans	S, Br, K, B
FR1.5	Keep Internal Area Dry	DP1.5	Drainage	S, Br, K, B
FR1.6	Protect from Insects	DP1.6	Screen	S, Br, K, B
FR1.7	Protect from Intruders	DP1.7	Locks	S, Br, K, B
FR2	Connect With Environment	DP2	Connections	S, Br, K, B
FR2.1	Connect with Other Modules	DP2.1	Standard Interface	S, Br, K, B
FR2.2	Allow Controllable Interaction with External Environment	DP2.2	Controllable Inlet/outlet	S, Br, K, B
FR2.3	Connect to Infrastructure	DP2.3	Connection Module	S, Br
FR3	Remain Structurally Sound	DP3	Structure	S, Br, K, B
FR3.1	Remain Stable	DP3.1	Foundation	S, Br, K, B
FR3.2	Maintain Shape	DP3.2	Frame	S, Br, K, B
FR4	Support User Activities	DP4	System Configuration	S, Br, K, B
FR4.1	Provide Artificial Lighting	DP4.1	Lights	S, Br, K, B
FR4.2	Support Exercise	DP4.2	Floor Space	S, B
FR4.3	Support Storage	DP4.3	Shelves	S, K, B
FR4.4	Support Food Preparation	DP4.4	Kitchenette	S, K
FR4.5	Support Eating	DP4.5	Table	S, K
FR4.6	Support Work	DP4.6	Desk	S, B
FR4.7	Support Social Activity	DP4.7	Gathering Area	S, K
FR4.8	Support Relaxation	DP4.8	Sofa	S, B
FR4.9	Support Sleeping	DP4.9	Pullout Bed	S, B
FR4.10	Support Elimination of Human Waste	FR4.10	Wash Room	Br

* indicates FRs and DPs that cannot occur concurrently
S=studio, Br= Bathroom, K= kitchen, B=Bedroom

		DP0 "Studio Module"	DP1 External Barrier	DP1.1 Waterproof Shell	DP1.2 Insulation	DP1.3 Electric Heating Unit	DP1.4 Fans	DP1.5 Drainage	DP1.6 Screen	DP1.7 Locks	DP2 Connections	DP2.1 Standard Interface	DP2.1.1 Large Portal	DP2.1.2 Inter-modular Electrical Connection	DP2.1.3 Fresh Water Piping Connection	DP2.1.4 Waste Water Piping Connection	DP2.2 Controllable Inlet/outlet	DP2.2.1 Door	DP2.2.2 Window	DP2.2.3 Ventilation System	DP2.3 Connection Modulus	DP2.3.1 Connection to Power Source	DP2.3.2 Connection to Water Source	DP2.3.3 Connection to Waste Water Disposal	DP3 Structure	DP3.1 Foundation	DP3.1.1 Compacted Soil	DP3.1.2 Temporary Foundation Piles	DP3.2 Frame	DP3.2.1 Lateral Bracing	DP3.2.2 Semi-Rigid Frame	DP3.2.3 Columns	DP4 System Configuration	DP4.1 Lights	DP4.2 Floor Space	DP4.3 Shelves	DP4.4 Kitchenette	DP4.4.1 Sink	DP4.4.2 Countertop	DP4.4.3 Stove	DP4.4.4 Cabinet	DP4.5 Table	DP4.6 Desk	DP4.7 Gathering Area	DP4.8 Sofa	DP4.9 Pullout Bed
FR0	Provide "Platform" Unit that Meets Basic Housing Needs	O																																												
FR1	Protect Internal Climate		X																																											
FR1.1	Keep out Moisture			X																																										
FR1.2	Insulate from Hot/cold Fluctuations in External Environment			X	X																																									
FR1.3	Heat Interior Area					X																																								
FR1.4	Cool Interior Area						X																																							
FR1.5	Keep Internal Area Dry					X		X																																						
FR1.6	Protect from Insects			X					X																																					
FR1.7	Protect from Intruders			X						X																																				
FR2	Connect With Environment		X				X	X			X																																			
FR2.1	Connect with Other Modules											X																																		
FR2.1.1	Provide Ingress for Users Between Modules												X																																	
FR2.1.2	Provide Electrical Connection Between Modules													X																																
FR2.1.3	Provide Freshwater Connection Between Modules														X																															
FR2.1.4	Provide Wastewater Connection Between Modules															X																														
FR2.2	Allow Controllable Interaction with External Environment		X				X										X																													
FR2.2.1	Allow Ingress Into and Out of Structure for People																	X																												
FR2.2.2	Allow Entrance of Natural Light																	X	X																											
FR2.2.3	Maintain Adequate Air Quality		X				X						X					X	X	X																										
FR2.3	Connect to Infrastructure		X					X													X																									
FR2.3.1	Provide Electricity																					X																								
FR2.3.2	Provide Running Water																						X																							
FR2.3.3	Dispose of Waste Water		X					X																X																						
FR3	Remain Structurally Sound																								X																					
FR3.1	Remain Stable																									X																				
FR3.1.1	Protect from Erosion																										X																			
FR3.1.2	Protect from Differential Settlement																											X																		
FR3.2	Maintain Shape																												X																	
FR3.2.1	Protect from Lateral Loads																													X																
FR3.2.2	Protect from Dynamic Loads (Wind/ Seismic)																										X	X		X	X															
FR3.2.3	Protect from Vertical Loads																													X		X														
FR4	Support User Activities										X										X	X	X		X				X		X		X													
FR4.1	Provide Artificial Lighting																																	X												
FR4.2	Support Exercise																								X				X		X				X											
FR4.3	Support Storage																								X				X		X				X	X										
FR4.4	Support Food Preparation										X										X	X	X		X				X		X			X			X									
FR4.4.1	Provide Easy Access To Running Water																						X															X								
FR4.4.2	Provide Prep Area																												X		X			X					X							
FR4.4.3	Provide Heat Source										X										X	X																		X						
FR4.4.4	Store Food																																								X					
FR4.5	Support Eating																								X				X		X											X	X			
FR4.6	Support Work/study																								X				X		X			X								X	X			
FR4.7	Support Social Activity																								X				X		X			X	X	X						X		X		
FR4.8	Support Relaxation																								X				X		X														X	X
FR4.9	Support Sleeping																								X				X		X														X	X

Figure 2. Design Matrix of the "studio" module for a temporary house.

3.4 PRODUCT PLATFORM

The DM presented in Figure 2 has a large number of functional requirements and is not decomposed to the lowest level FRs and DPs.

As Table 1 shows, the modules share a number of similarities, particularly in FR1, FR2, and FR3. The largest difference between the studio module and the additional modules occurs in FR4: support user activities.

The concept of a product platform based module design is a useful way to encourage a large variety of modules and highly customizable housing while minimizing manufacturing and design cost. The studio module needs to be larger to be able to meet its diverse set of functional requirements with minimal coupling. Likewise, the bathroom and hallway module need not be as large as the either the studio or other modules. This diversity in module size can still be achieved through the use product family design. The design of the architectural units can be approached as a scale-based product family. This 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.

In the proposed model, the functional requirements that are shared across all four modules, shown in Table 1, are met by the product platform. The remaining functional requirements, such as those in FR4, use customized DPs for each individual module.

4 CONCLUSION AND FUTURE WORK

This paper shows how Axiomatic Design is applied to the early design stages of a TH in order to ensure stakeholder's needs are met without inhibiting the creative process. Treating the TH as a large flexible system and applying the knowledge base concept to the high-level requirements and design parameters allows the designer to assign specific functionalities to individual units. This modularity has an added benefit of minimizing accidental coupling in the design process. When applying the AD to the design process, the addition of the product platform theory aided in better defining independent product functional features.

Future work will investigate the robustness of the design through the use of the AD Information Axiom. The model will also be tested by the actual design and creation of a working TH model. The process variables, such as manufacturability, will also be investigated.

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