Performance House I
A CADCAM Modular House System

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Abstract

Millions of persons around the globe live in low quality indigenous, or Manufactured Housing (MH) systems that often result in low “performance” undesirable living environments and, at times, life threatening habitation. Our research has explored mass production principles in product design and architecture, currently at the single family housing scale, with a focus on the recent devastation along the US Gulf Coast as a result of hurricane impact, most notably hurricane Katrina.

“Modern architecture” theoreticians have conceived, written, prototyped and even launched business ventures in an attempt to bring their manufactured housing “ideas” to fruition. However, architects have generally had little “long-term” impact in the area of manufactured housing strategies and the current manufactured housing industry remains archaic and problematic. This paper includes our research of other architects attempts to leverage technology in the manufactured housing industry; additionally, we analyzed current problems in the US mass housing industry. We then derived a set of “design criterion” as a means of anchoring our design inquiry for a proposed factory-built modular house system.

Our research encompasses both process and product innovation; this paper reflects on our use of technology to leverage an Industrial Design (ID) process that is inclusive of many “design” partners and team members. We are using both virtual and physical output representation and physical prototyping for a factory-built house system; our Research and Development (R&D) is on-going with our collaborating design-manufacture engineering partners from the automotive, furniture and aerospace research labs here at Mississippi State University. Our goal is to use “industrial design” principles to produce mass housing components that provide durable-sustainable housing.

Introduction

Our research has included an overview of the efforts of modern architects to integrate industrial manufacturing in mass housing; section 2 includes a recap of our findings and correlative problems encountered by architects in their manufactured housing quests. In section 3, we review the current state of the US manufactured housing industry. In section 4, we briefly look at the theoretical underpinnings often used regarding CADCAM in contemporary architecture; and in Section 5 we briefly review technology in the Industrial Design process. In Section 6 we report on our progress to date for R&D of a “performance-driven” CADCAM modular house system.

Architecture and 20th Century Mass Housing

Architecture has historically been identified with the elite; however, with the advent of industrialization and the rise of a middle class in the 19th century, and
increasing civil rights and social justice for many in the 20th century, architecture has evolved into a “profession” with expanded responsibilities and pluralistic client typologies.

Industrialization of the building process, exemplified by the non-architect engineer Joseph Paxton's design for the Crystal Palace in 1851, which at the time was described as “the first miracle of prefabrication,” ultimately spurred architects’ efforts to use technology in the process of building. About 50 years later, the building industry, and housing in particular, were significantly impacted in theoretical exploration using mass production principles created by the US automobile industry. It was within that setting that early 20th century architects (Al Arayedh, 2006) initiated the feverish search for an approach to utilize the principals of mass-production in architecture.

Early modern architect theoreticians felt the basic human need for shelter was the perfect commodity through which mass-production principals could be put to test in architecture. The following is a summation of the architects, discovered in our literature review, who have proposed various concepts and tactics in an effort to bring their MH dreams to reality.

**Walter Gropius and the Copper and Packaged Houses**

Few architects were as devoted to the issue of mass housing and industrialization in building as Walter Gropius, Le Corbusier, and Buckminster Fuller. Their 20th century seminal contributions are well documented; therefore, we will only briefly review key points here of their, as well as other architects, work in the area of mass production and MH.

The following is a quote from Gropius regarding his view of the responsibility of the professional architect:

> *Architects have a responsibility towards society to help solve its acute housing problem; therefore, their involvement in this process is inevitable to assume the role of integrators of “the scientific, social, technical, and economic factors, inherent in the new architecture of the industrial age” (Sullivan, 1978).*

Gropius predicted, if architects dismissed their responsibility, industry would eventually assume that role on its own. Gropius made two attempts in the MH arena; both the Copper House and the Packaged House were confronted with political and financial problems (see Figure 1) (Al Arayedh, 2006).

Other modern architecture icons made attempts as well; like Gropius, Le Corbusier's work in the Quarters Moderns Fruges (QMF) in Pessac collided with regulations in addition to the lack of appeal for its aesthetic leading to marketing problems, and thus financial obstacles, which ultimately ended the venture (See Figure 2).
Buckminster Fuller viewed the work of Le Corbusier, and most of the architects of that period, as “trivial since it did not seek to fulfill the need for shelter from an engineering viewpoint, and without conforming to the demands of “style or tradition.” Fuller believed “homes should be thought of as service equipment, not as monuments” (Baldwin, 1996). Fuller also believed that in order to fully utilize the economies of mass production, identical housing units should be manufactured as a whole in the factory and flown to their final destination. Buckminster Fuller’s attempts; the 4D Dymaxion, the DDU and the Dymaxion Dwelling Machine faced some initial controversy regarding its aesthetic, which was gradually overcome, yet these attempts ended due to lack of supporting production technologies as well as restrictions of material utilized due to political circumstances (see Figure 3).

The Archigram Movement failed to realize any of its housing projects due to their shocking aesthetic at the time, and consequent lack of investor partners.

Architects continue to pursue new ideas relative to technology and new materials; most recently, Greg Lynn of GL Form has experimented with concept projects. According to Lynn, his approach is a departure from the Modernist mechanical Kit-of-Parts approach (Al Arayedh, 2006). However, most of Lynn’s projects remain un-built and at the conceptual rapid-prototype phase (see Figure 4).
A rare example of a residential project that employed digital technologies, in both the design, fabrication, and assembly phases, is the Turbulence House by architect Steven Holl (see Figure 5). However, this project was not conceived as a mass housing system, but rather for a specific site and client.

The contributions and efforts invested towards the industrialization of mass housing in the past century are by no means restricted to the architects mentioned above. Others such as Frank Lloyd Wright, Mies Van Der Rohe, Robert Venturi, Paul Rudolf, and Richard Neutra, among others, proposed “ideas” for MH. This being said, the point here is that architects have made significant efforts toward MH, and have generally been unsuccessful. The proceeding table provides a recap of generalized obstacles that have hindered architect’s efforts in MH (see Table 1 below) (Al Arayedh, 2006).

As a general summation, the research shows that architects, for various reasons, have had significant difficulties in making a sustainable contribution in the area of manufactured mass housing. As our next section will show; quality housing alternatives, for those with limited financial resources, remains a long-lived dilemma.

**Factory Built Housing**

Factory-built housing can be categorized in two (2) basic areas; “factory” or “site” assembled (Al Arayedh, 2006). In the “site” assembled area, an infusion of technology has occurred in the US housing industry. However, owners usually do not perceive this; “builders” have quite cleverly disguised the increased use of pre-fabricated housing components, to maintain marketability and positive perception, in the US homebuilding industry (Schuler, 2004). While technology is being increasingly leveraged in the “site-assembled” housing area, almost paradoxically, “factory-assembled” housing is suffering from many problems and has seen minimal change in manufacturing technology processes since the 1970’s (Barrow and Pan, 2004).

**Factory Built and Assembled “Manufactured” Housing**

The US manufactured housing (MH) industry is struggling with a drastic drop in sales that began in 1998. This is attributed to several factors, mainly lower interest rates for conventional site constructed homes. Additionally, the drop in sales is
contributed to a limited market share due to a focus on “cheap” initial cost resulting in a “low value” product. The perception of “low value” is increasingly paramount in the current context of intensifying storm damage, and associated injury and deaths, due to more frequent and higher wind events from hurricanes and tornadoes. Hence, in the current context of “global-warming,” and increasing awareness of MH structural instability (i.e. mobile homes) the marketing problems increase, while business profits for the MH industry decrease (see Figure 6) (Al Arayedh, 2006).

As noted in the introduction, we have chosen to focus our R&D on specific MH housing issues intrinsic to the Southeastern US, and particularly the recently ravaged Gulf Coast region (i.e. wind & water). Please note the prevalence of hurricanes and tornadoes in this area, often referred to as “tornado alley” (see Figure 7).

“Factory-assembled” manufactured housing, a known low-quality commodity product, is predominantly found in the Southeastern US (see Figure 8). Based on the prevalence of “extreme weather” in the Southeastern US, especially in coastal areas, this is “a recipe for disaster” (Al Arayedh, 2006).

Manufactured Housing Problems

This section reviews issues that plaque the “factory assembled” manufactured housing industry; these “problems” are well documented and widely acknowledged (Berk, 2004).

According to US insurance and federal housing agencies, billions of dollars and hundreds of lives are lost each year due to damage of both manufactured and conventional houses. The need to

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**Figure 6.** Site Assembled verses Factory Assembled Manufactured Housing Sales

**Figure 7.** Hurricane and Tornado Prone Areas.

**Figure 8.** Manufactured Housing in the US.
keep “factory-assembled” manufactured houses light-weight for transportation to the site, as well as the producer’s tendency to economize on cost by the use of cheaper materials, produces an excessively flammable structure that has the highest death rate per thousand fires among all other types of residential and non-residential buildings. The use of lighter materials, as well as the shape and structure (i.e. form) of the manufactured home unit, as well as poor site installation techniques, makes it extremely vulnerable to wind and flood damage. The result is an annual loss of $11.5 billion dollars and an average of 271 lives due to severe weather conditions (see Figures 9 & 10).

The current “factory-assembled” manufactured “mobile home” industry is, at best, dilemmatic if not catastrophic. As is often said, “a picture is worth a thousand words” (see Figures 11 and 12).

Problems associated with “factory-assembled” manufactured “mobile homes” are severe; however, these problems are not unique to “factory-assembled” housing. Hurricane Andrew in south Florida, where “site-assembled” housing was equally ravaged by high winds, vividly showed this point. Furthermore, flood and tidal wave action damage, are equally destructive to both “factory-assembled” or “site-assembled” housing when designed, constructed and sited in a conventional manner. Thus, in this section, we have established that many problems exist in the current US Manufactured “site-

Figure 9. Damage to Manufactured Housing Due to Extreme Weather.

Figure 10. Fatalities Due to Tornadoes.

Figure 11. Problems with Manufactured and Conventional Houses.

Figure 12. Distressed Homeowners-Hurricane Katrina Aftermath.
assembled” (i.e. conventional) and “factory-assembled” (mobile) Housing industry. The following is a ranking, from highest to least impact, of MH problems based on national research statistics for the US MH industry (see Table 2) (HUD, 2002 and Al Arayedh, 2006).

<table>
<thead>
<tr>
<th>PRIORITY</th>
<th>PROBLEM</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Flood Damage</td>
</tr>
<tr>
<td>2</td>
<td>Wind Damage</td>
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<tr>
<td>3</td>
<td>Fire Damage</td>
</tr>
<tr>
<td>4</td>
<td>Indoor Air Quality</td>
</tr>
<tr>
<td>5</td>
<td>Lack of Durability</td>
</tr>
<tr>
<td>6</td>
<td>Transportation Restrictions</td>
</tr>
<tr>
<td>7</td>
<td>Zoning and Regulation Restrictions</td>
</tr>
<tr>
<td>8</td>
<td>Insurance and Financing Complications</td>
</tr>
<tr>
<td>9</td>
<td>Aesthetics</td>
</tr>
</tbody>
</table>

In the following section we will take a brief look at the use of technology in contemporary architecture.

**Technology and Architecture; A Quest for Unique Form**

“Architects are encumbered by the need to be original.”
Dr. William McWhorden, Ph.D., Aerospace Engineer

Few question that technology has transformed architecture; fluid curvaceous forms stand as a testimony to both the potential of digital tools and the creativity of architects in engaging these tools in the design and construction process.

Generally, architects who do leverage technology, do so in their quest to bring to reality unique forms through the ability of CADCAM. However, as architects continue to stretch technology possibilities; extreme variation and complexity of one-off custom residences characterize the few housing projects that engage these digital capabilities, many of which remain un-built “ideas.” Generally, mass-housing has not benefited from the application of digital technology.

While some architects elect to give minimize CADCAM in their early conceptual design phases (i.e. Frank Gehry), others elect to give the conceptual form up to the computer (i.e. Greg Lynn) (see Figure 4). Some claim that variety and differentiation of building components is now ‘easy’ to design and build using technology (Willis and Woodward, 2005); however, our research of construction costs for most CADCAM projects in architecture, find them to be typically, very expensive and difficult to make (Barrow, 2000).

As architects continue their exploration of technology in architecture, a successful balance, from a mass-housing perspective, between mass production and mass customization waits to be achieved (Al Arayedh, 2006). As articulated by Dr. William McWhorden, Ph.D., an aerospace engineer at Mississippi State University, we as architects “are encumbered by the need be original” as we pursue aesthetics (Barrow and Pan, 2004).

**Technology and Industry**

In this section, we briefly look at technology and design strategy in related manufacturing fields (i.e. Industrial Design-Make), with the goal of extrapolating possible design principals for architecture in MH.

Table 2. Manufactured Housing Problems.
Driving Performance and Production

Industrial Design (ID) deals with the design and production of commodities using an integrative team approach and CAD/CAM. According to (Ettlie & Stoll, 1990, Kumar & Barrow, 2006) some ID design strategies are as follows:

- Axiomatic design Approach
- The Eliminate, Simplify, Standardize where possible approach
- Standardization and Rationalization Approach
- Process Driven Design approach
- Design for quality approach
- Design for change approach
- Design for flexible manufacture approach
- Design for analysis approach
- Design for assembly
- DFX approach

Further analysis of ID “approaches” is beyond the scope of this paper; the key-point here is the sophisticated means of ID systems thinking for design-make-operate. We as architects are typically not educated to think this systematically and inclusively relative to “ideas and making.”

The Role of Modularity in Industrial Design

The design of extensively complex products that are comprised of several complex systems, such as in the aerospace and automotive industry, comprises information necessary to manufacture massive numbers of related “parts.” An average sized car, for example, is composed of around 4,000 parts while a Boeing 777 is comprised of more than 1,000,000 parts and ships require millions of parts. In these cases, an ID approach is followed to control high levels of complexity; this requires breaking the product into several manageable ‘chunks.’ These chunks are further divided into smaller parts, better referred to as ‘modules.’ A module is “a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units.” Architecture is not typically thought of in this sophisticated manner.

Achieving variability through Mass Customization

The fabrication of modules is highly dependent on the repetitive mass production of identical parts; however, the independency of these parts allows for flexibility as they are easily interchangeable with other similar parts. This creates opportunities for the production of a diverse range of end products; end users have the ability to easily personalize products that were initially fabricated from an array of mass produced identical parts. This method for achieving variety, known as mass customization, depends greatly on decisions made by designers at the early stages of the conceptual design process (Kumar & Barrow, 2006. Al Arayedh, 2006). This requires breaking down products into smaller parts and defining the relationships between the parts. These strategies for mass customization as outlined by Joseph Pine are as follows:

- Component-sharing modularity
  Products of identical function are designed to have the capacity
to change some aspects of their aesthetical characteristics such as color pattern and texture while maintaining the fixed function (see Figure 13).

- **Component-swapping modularity**
  Products maintain the same appearance but have the capacity to interchange major parts within their assembly that provide different functions (see Figure 14).

- **Cut-to-fit modularity**
  Products of a two dimensional or extruded linear nature in at least one axis allow consumers to customize the product by cutting to the required length (see Figure 15).

- **Mix modularity**
  Two or more products are mixed to create a new one (see Figure 16).

- **Bus-modularity**
  A standard base is used as the frame that supports a combination of other parts. The characteristic of this frame determines the type of parts it can support (see Figure 17).

- **Sectional modularity**
  Different parts having different characteristics, whether in form or function, share a standard interface through which these different parts can be joined as they are assembled (see Figures 18 & 19).
The need for variation and diversity is intrinsic in the field of Industrial Design. Yet the design process in this field focuses mainly on enhancing the quality of the products performance while facilitating the manufacturability of the parts and products. This is accomplished by incorporating the input of engineers and manufacturing specialists at the very early stages of the process and following “Design for Manufacture” strategies (DFM). Thus, in Industrial Design, the act of “design” is seen inherent in the effort to “make” the artifact; thus a balance is sought between form, performance, costs, and time-to-market. Thus, unlike what we often find in architecture, the focus is on function, performance and manufacturing, out of which comes “beauty.”

**Performance House 1**

_A problem adequately stated is a problem well on its way to being solved._

*— R. Buckminster Fuller*

In this section, we will review our current CADCAM tactics regarding a proposed “Performance House” that has been conceived as a response to extreme weather conditions along the southeastern US Gulf Coast low-lying coastal zones. Our process and product(s) design is not complete, and part of our findings is the truly complex nature of trying to bring a mass-housing concept to market.

In section 3, we established the predominate problems in the MH industry; hence, we used them as our Design Criterion for Performance House 1 (see Table 3).

Note the top design factors are wind and water; hence, the driving force behind the current conceptual form is _fluid dynamics_. The fundamental premise is that the relationship of a house to wind...
or water, in a severe weather event, is not unlike that of a car, plane or boat in wind or water (i.e. a fluid). Physics tell us that Force = Mass x Velocity squared; therefore, as a car, plane or ship moves through air or water, the relationship of object A to B, that is artifact to fluid is relative. This is to say, during a severe weather event, a static house, is experiencing the same relative fluid dynamic forces as a car or plane traveling at 100 to 250 MPH. Deductively, the same premise can be said for the form of a house, exposed to moving water in the case of coastal or storm-water surges, is not unlike a ship hull in water. Hence, buildings (i.e. houses) are not static objects in space; rather, they are subject to the same relative fluid forces as cars, planes, and ships (i.e. Industrial Design artifacts). Therefore, we have coined the term “Performance House” (PH) as the system is seen as a long-term durable housing concept that is energy efficient and performs under extreme weather events.

The Problem and Conceptual Ideation

The worst case scenario of housing located in a waterfront tidal “V” (velocity) flood zone drove our initial conceptual schemes. Hence, we conceptualized the housing system to be erected on an elevated piling system. The fundamental premise to our design approach is borrowed from the aerospace and marine industries.

- First, we have chosen a spherical form which allows fluids (i.e. air and water) to flow over the form in an unobstructed manner, not unlike the inherent nature of form found in a car, plane, or ship.
- Second, to avoid the major problem of water intrusion caused by the peeling away of exterior skin during high wind events, we have chosen to work with a homogenous skin that is both structure and weatherproofing (see Figures 20).

Our initial reaction to rising tidal surge flood waters was to elevate the structure on pilings; however, after further analysis, we wished to design for the worst case scenario which requires consideration of velocity wave action and flood surges of 35’ to 40 above Mean Sea Level (MSL). Therefore, the house structure would need to be 20-25’ above the normal piling
platform height to avoid lateral loads and flooding due to rising flood water and velocity wave action. Essentially, this is impossible with normal residential piling construction. Consequently, the decision was made to push the concept of the house as a “boat house” that takes on the fluid dynamic form of an airplane wing and/or boat hull “shell” form.

We then conceived of the house piling system as a mooring/dry-dock structure from which the house “boat” would rise during hurricane or flood events. A tensioning system reacts to bring the house back to its mooring rack as flood waters recede (see Figures 21 and 22).

The next hierarchical design move was the decision to avoid the constraint of size limitation due to highway transportation; hence, as suggested by ID principals, we decomposed the building into modular building components. Further, again following Mass-Customization principals found in Industrial Design, we feel the decomposition of the “building” into “parts” offers more possibilities for variation in shape and form. We wish to maximize the advantages of factory build components by manufacturing all parts within the factory using CADCAM. Thus, the coastal building system is comprised of piling, floor, spline, wall, and roof panel components. Based on our literature review and patent research, this approach to factory-built panelized housing components is a unique strategy and this Intellectual Property is copyrighted © and patents are in-process and pending (see Figures 23, 24 and 25).

Iteratively, between 2D and 3D, digital “free-hand” sketches were produced using a PC tablet and Alias Sketchbook. Thereafter, 2D digital cross section profiles and 3D digital models were developed allowing a seamless “digital” interface of conceptual ideation and form development. Following development of the overall macro concept, 3D digital model prototype studies were undertaken of the panelized building component system (see Figure 26).

Using the innate power of 3D digital modeling, we modeled sub-components of the panel system to improve our understanding of the various elements of the building system. We are pursuing a means of flexibility for mass-customization of the exterior fenestration (see Figures 27 and 28).

Using the 3D objects as virtual library objects, we have done a “proof of concept” by “assembling” an array of possible house
forms using the modular “kit-of-parts” components (see Figures 29 – 36).

For further development, output was generated for the PH1 - “X House” 3D Rhino model, depicting the 2D building system components diagram, and a 3D physical prototype model (see Figure 37). The following is an assessment of

### Table: PH1 - Building System – Shape / Form Options

<table>
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<tr>
<th>Shape</th>
<th>Type</th>
<th>Size</th>
<th>Area</th>
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<th>Name</th>
<th>Size</th>
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<td>216 ft</td>
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Figure 23. PH1 - Concept Drawing – Optional Shapes – Linear to Square Plans.

Figure 24. PH1 - Building Panel System - Panel Types–Linear to Square Plans.

Figure 25. PH1 - Building System – Shape / Form Options.

Figure 26. PH1 - Prefabricated CADCAM Modular Building Panel System.

Figure 27. PH1 - Modular Wall Components System.

Figure 28. PH1 - Wall/Window Plug-in Panels for Mass-Customization.
our R&D process to date relative to our design criterion (see Table 4).

Further design development is underway and we are “partnered” with three high-technology engineering labs. Our collaborative design team includes architects, industrial designers, interior designers, industrial technologists, aerospace engineers, structural engineers, furniture and wood experts, as well as manufacturing systems engineers. The “design” team is highly diverse, quite large and we are attempting to amalgamate the broad range of “design-make” issues in the early design phase. As noted in sections 5, we feel this “integrated design” approach, as used in the development of products in industrial design, is the only design process that offers the “possibility” of a “successful” mass-housing project. That is to say, this in not intended to be a “concept” house, our goal is to bring the “concept” to market. A comparative analysis of our R&D progress to date, relative to the architects and MH discussed in section 2, is shown in Table 5.
Conclusion

We believe it is possible to improve mass housing by leveraging new material/methods and CADCAM. The following is a summation of what we feel we are doing “right” and “wrong” at this time in our Manufactured Housing R&D process.

RIGHT

- We understand ‘some’ of the problems in the US MH industry.
- Attempting to understand barriers for other architect’s efforts.
- Attempting to understand design-make-operate model in industrial design.
- Attempting to partner with investors for financial and marketing input.
- Attempting to partner with manufacturers for cost and making input.
- Using collaborative design-make design team at conceptual phase.
- Developing “virtual” test models for parts and assemblage tests and proof-of-concept.
- Long-term relation within a University setting for diverse knowledge network in a ‘Design Lab’.
- Publishing in academic venues (i.e. ACADIA) for criticism and feedback.

<table>
<thead>
<tr>
<th>Architect</th>
<th>Project</th>
<th>Technical</th>
<th>Collaborative</th>
<th>Regulatory</th>
<th>Financial</th>
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<td>6 Buckie Fuller</td>
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<td>9 Moshe Safdie</td>
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<td>11 Paul Rudolph</td>
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<td>13 Kisho Kurokawa</td>
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<td>14 Larry Barrow /</td>
<td>Performance House 1</td>
<td>X</td>
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<tr>
<td>DRIL Team</td>
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Table 5. Barriers to Manufactured Housing Concepts – PH1 Comparison.
WRONG

• Attempted to separate aesthetics from early conceptual design – impossible.
• Attempted to separate aesthetics from early process – cultural issues.
• No user or market assessment tests at this time.
• Not sure of materials or methods – which comes first?
• Need materials testing for analysis of flammability, off-gases, and manufacturability.
• Not sure of “repetition” in architecture relative to commodity housing, this needs more theoretical research.
• Not sure of “cultural” implications in architecture relative to “iconography” in commodity housing, this needs more theoretical research.

Emerging technology enables new forms to be conceived, visualized, analyzed, fabricated, and assembled. Some designers promote temporality and transformability, others pursue durability and performance; we believe, as have many of our past and contemporary architects, that technology can be better understood and applied to CADCAM factory-built housing componentized systems, for better quality mass-housing.

References


