Prefab the FabLab:

rethinking the habitability of a fabrication lab by including fixture-based components

by

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Abstract

This thesis is about defining a fixture-based system that can be adapted into a digital fabrication production system of friction fit assembly. It is inspired by the work and research conducted by the Digital Design Fabrication Group at MIT, specifically the work related to the Cabin House and the Instant House. The building industry in recent decades has experienced a fluctuation of different delivery methods; within that variation has been prefabricated construction. Numerous examples, academic and professional, have demonstrated the benefits of prefabrication construction and as result this delivery method has gradually become more attractive to those considering alternative building types. I am interested in proposing a fixture-based system that would assist in electrical components, storage, and lightings and openings in order to improve the usability and flexibility of FabLab that is deployed as friction fit build. Modular systems of architecture have to a large extent remained in the combination of mono-material assemblies; therefore, this thesis asks the question, can mono-material assemblies be flexible enough to include other kinds of fixtures that support the addition of such amenities as electrical appliances, lighting, storage, and expandability?

Thesis Supervisor: Lawrence Sass
Associate Professor of Computation and Design

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[1.0] Introduction

1.1 Personal Background

As a student completing my undergraduate in architecture I had the good fortunate of studying during the transitional period of design methodology and technology. Within the timeframe of my completed Bachelors degree I experienced architectural design initially through hand drawn representations and later finished my undergraduate education with an appreciation for the various rapid manufacturing technologies available to students. The transition in design methodology and technology was aided by the integration of powerful 3D modeling applications in combination with digital fabrication tools.

Figure 1. Milling artifact and 3D printed object

With the available technologies such as a CNC machine and 3D printer I was able to design with a different mentality, capable of going beyond the 'usual' design process. This was possible because I understood that the fabrication of these otherwise 'idealistic' designs could now be fabricated with the aid of digital fabrication tools. Figure 1 shows those fabricated artifacts. The first was a block of laminated plywood modeled as a canyon surface. Its fabrication resulted in it be easily, rapidly, and accurately milled with the use of a 5-axis milling machine. The second artifact, explored through the use of a 3D printer, was intentionally designed with tiny features so as to experiment with the tolerances of 3D printing. Again, this technology also showed that the fabricated product could also be easily and accurately produced.

This initial exploration of the capabilities of digitally designed and fabricated objects would later propel me to study and research these technologies within the context of my graduate education. As interesting as these new tools were they were still only available at a professional or intuitional level. What I was becoming interested in was understanding what would happen if these tools were to be available to anyone. I found the answer to this through the work of MIT's Center for Bits and Atom in the form of what Neil Gershenfeld was calling fabrication labs or FabLabs.

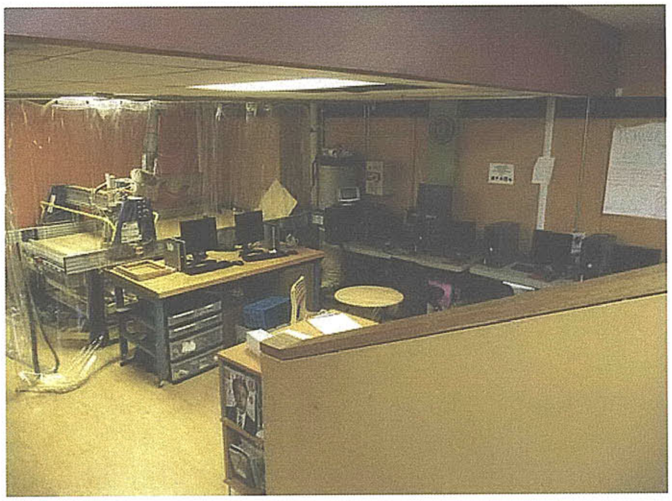


Figure 2. FabLab Space [courtesy of Fab Lab Boston]

1.2 The Direction

Buildings are complex artifacts, composed of numerous parts and integrated components. This same description of complexity is also distributed among the professionals (architect, engineers, contractors, etc.) who realize these artifacts. As building systems become more and more complex, demanding the intensive innovational use of new technologies, these same professionals will need to adopt new practice models in order to simultaneously address emerging challenges in design and building. In addition to the growing complexity of delivery models there have been growing interests for prefabricated construction and an increasing interest of introducing personal fabrication to ordinary people. That is, more and more individuals are discovering and using fabrication tools to build "stuff". This suggests that in the coming decades the ideas of prefabrication construction and fabrication of structures could extend from the designer to the common user as a do-it-yourself project because of the availability of these fabrication tools.

Examples of this have already surfaced in Massachusetts and New York as micro-factory businesses and home garages inventing and manufacturing sophisticated components for use with other products (Chris Anderson, Wired Magazine). Figure 3 shows this startup idea of potential micro-factories. Another example of this trend are the FabLabs spread throughout the world, offering ordinary people the tools to build "almost anything" and empowering individuals to solve local technological problems with their products.

Figure 2a. Micro-factories available custom manufacturing

[source: www.wired.com; photo credit: Dan Winters and Leon Chew]

This thesis is a research into the component design of a personal fabrication lab –FabLab. The research focuses on fixture-based components because in the coming years as delivery methods of digital fabricated mono-material assemblies become more available the question of how to make these structures more habitable or livable will challenge the system. The research documents the process of both designing and producing; exploring this process through: workshop participation and observations, case studies, design modeling and small-scale prototyping.

The progress of society should be a reflection of the progression in our industries and technology. While other sectors of the economy have adapted to our changing society by adopting new models and technologies, the AEC (architecture/engineering/construction) industry continues to face 20th and 21st century problems with 19th century attitudes. The relevance of this thesis is such that the research will support the transformational use of new delivery methods that promise to improve productivity and collaboration. The thesis is distinct because it also recognizes the coming digital revolution in fabrication and will explore the relationship between intelligent design and manufacturing.

1.3 Thesis Question

The work of this thesis will consider design options for making a FabLab, designed by a friction fit method, more habitable by considering the integration of user-supported fixture objects. The thesis question attempts to test the flexibility of mono-material assemblies by inserting systems of space planning, services, and skin into its construction to enhance the usability of the space by optimizing storage needs, electrical management, and expandability/adaptability. Therefore, the question pursued is: *Can mono-material assemblies be flexible enough to include other kinds of fixtures that support the addition of such amenities as electrical appliances, lighting, storage, and expandability in order to make friction fit construction more useable?*

[2.0] Background

2.1 The Instant House Project

The instant house project, developed within the Digital Design and Fabrication Group (DDFG) at MIT, is a model of fabrication that employs digital design methods with onsite construction and assembly in order to provide fast, low cost design systems. The systems "aims to present a novel design and prefabrication process for mass customized emergency, transitional and developing contexts."(Botha, Sass)

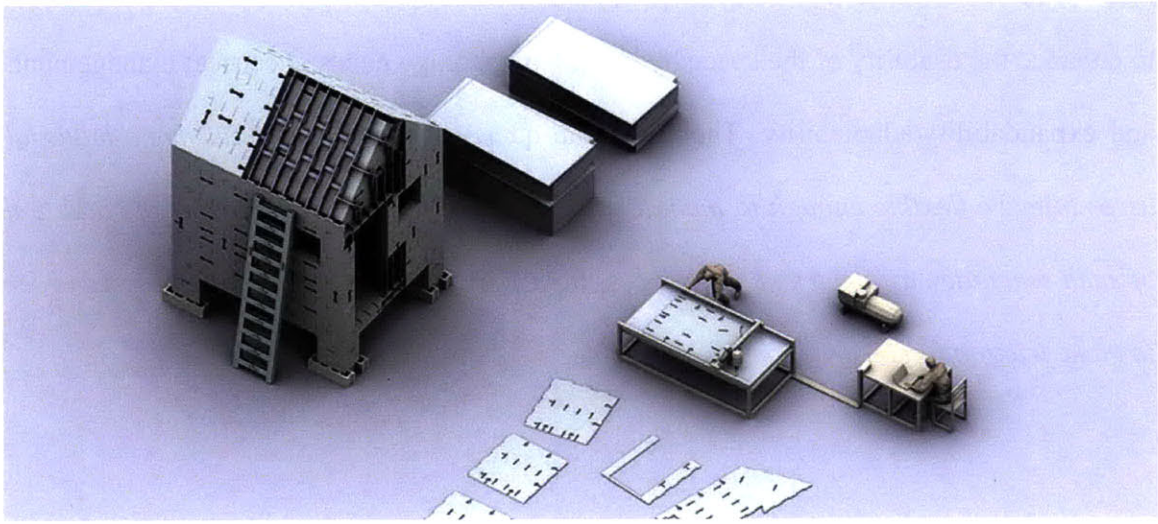


Figure 3. The Digital Design and Fabrication workflow of the Instant House Project [source: http://momahomedelivery.org/]

Novel solutions addressed by the instant house include the ideas that the units would be rapidly deployable, scalable, and "foster a large degree of individuality within the newly rebuilt community." (Kolarevic, 2003) The guiding logic that makes the instant house *instant* is the fact that the system experiments with a mono-material system. The use of a mono-material system means that the assembly method would be embedded within the elements of the design and material. The embedded assembly method is attained by fabricating friction fit connection notches and slots, similarly to the embedded elements found within LEGOS, Knex, or 3D Puzzles.

Other important effects of this embedment is the ability to encode a relatively comprehensive description of both design and construction information in a single digital file readable by a single machine, rather than having to create separate descriptions for different fabricators and contractors (Sass and Oxman, 2006).

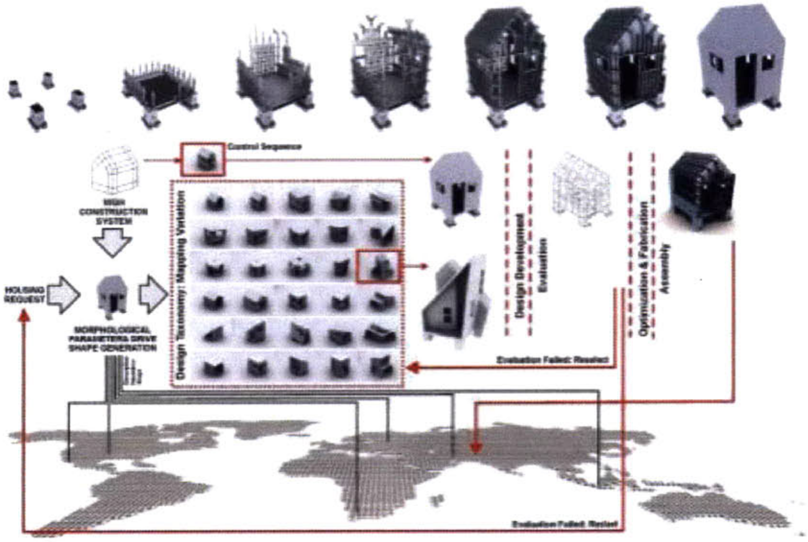


Figure 4. The Instant House: generative procedure and fabrication process. [Botha and Sass, 2006]

2.2 Customized Digital Manufacturing

Customized Digital Manufacturing (Botha 2005) is a research project which explored opportunities in creating customized assemblies that could be paired and recombined to create unique spatial enclosures. Additionally, the project illustrated that by understanding how assembly design works, the design could benefit from the deletion of materials and that the creativity of customized manufacturing could be attained through tools of design media. Botha proposes a tool that allows the designer to focus "on proportion, aesthetics and personalization, while the more complex processes work seamlessly in the background."

Botha depicts this tool with the objective of allowing people without technical skills to "design". By separating the constraint that the tool would need a technically skilled designer, the designer would be freed enough to "incorporate human emotion and vernacular expectation" into the building and to "alleviate community apprehension by allowing them to take ownership of the process." Through this process of non-skilled "design" the inherent flexible decision made offer a suitable complete and creative product that then becomes "digitized features of a marketing model often described as mass-customization" (Cardoso, 2007).

2.3 GIK

The GIK system stands for "Great Invention Kit" and was first developed by Neil, Eli, and Grace Gershenfeld as a system of interlocking 2D pixels that form 3D volumetric pixels. The system is similar to the Lego that it requires the press-fit of single elemental types, also called GIK, and that can also be broken down and re-assembled into other objects. The system is unique because the elements can be produced at different scales, given appropriate cutting machine and material, allowing for the manufacturing of objects from a nano-size to a macro-size. It is suggested that through the scaling of the base pixel sizes, large scale GIK assemblies could be used to assemble entire buildings. Its materiality advantage also suggests that this system could become a building block for other manufactured products such as electronics and optics by merely applying the appropriate tools and varying the material type. The GIK set also has the feature of reversibility allowing it to be assembled and deconstructed for recycling, reuse, and a reduction in waste.

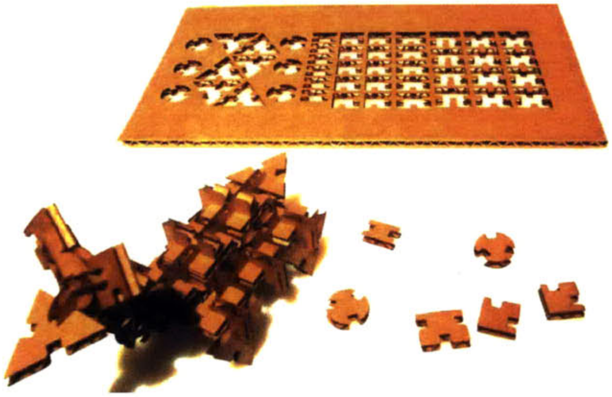


Figure 5. Classical cardboard GIK assembly [source: www.fab.media.mit.edu]

The GIK assemblies certainly demonstrate the potential for the beginnings of interlocking systems to play an important role in manufacturing and construction due to its flexibility in composing artifacts with limited design vocabularies. This limitation in design vocabulary unfortunately also presents the challenge for this type of assembly to create enclosed habitable spaces.

2.4 The Lego

Lego bricks can be assembled and connected in many ways to create a variety of different objects, from buildings to vehicles. Anything constructed can be disassembled again and the pieces can be used to make other objects. Legos were originally derived with the potential that brick shaped objects could be a system for creative play and the simplicity of the bricks could make the toy available to all. Figure 6 shows the units and an example of a derived build with additional components. The initial development and the simplicity of the brick unit meant that the units could be assembled and disassembled very easily. This also suggested that that the built artifacts, or builds, would to some degree remain as abstracted objects because of the limited configurations available with press-fit orthogonal assembly

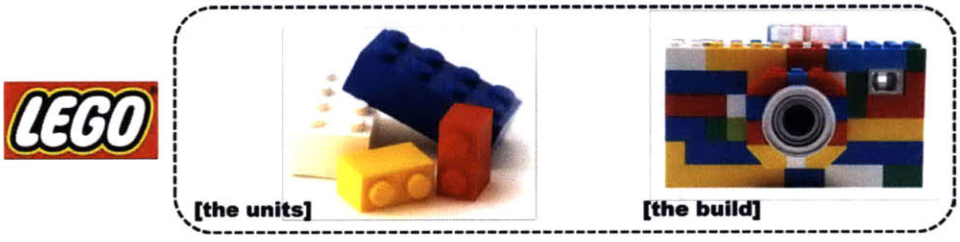


Figure 6a. Traditonal Lego units and introduction of functional build

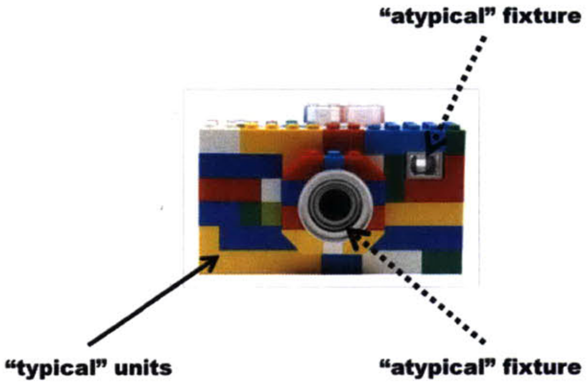


Figure 6b. Build with "atypical" fixtures adding more meaning to build

Since the patent of the first Lego brick in 1958, new families of elements have been introduced that add functionality and introduces additional configurations of objects. The additional interlocking pieces are meant to encourage creativity and arts and crafts. This range of expanded Lego accessories adds functionality to a build by introducing what I define as "atypical" features to an already tested "typical" feature. The typical features are the traditional building block units that have limited configurations and suggest abstract built objects. The addition and of the "atypical" features extends the type of configurations now possible and also introduces flexibility. This observation is important and related to the fixture-based system that I am interested in because it too suggests that by allowing for the addition of “atypical” fixtures into a friction fit construction, additional functionality of the space can be gained. Applied to the context and design of a FabLab the added functionality would respond to what is needed within that working environment and could be thought of as: storage, electrical layout, lighting, and expandability fixtures.

[3.0] Case Study

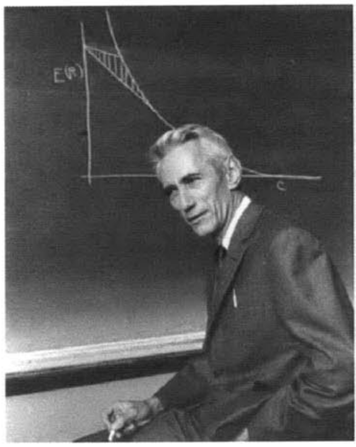
3.1 FabLab: The Beginnings

"My hope is that Fab will inspire more people to start creating their own technological futures. We've had a digital revolution, but we don't need to keep having it. Personal fabrication will bring the programmability of the digital worlds we've intended to the physical world we inhabit. While armies of entrepreneurs, engineers, and pundits search for the next killer computer application, the biggest thing of all coming in computing lies quite literally out of the box, in making the box."

–Neil Gershenfeld in *Fab*

Tracing the course of history of revolutions we'll find that technological revolutions have been historically closely linked to social evolutions. That is to say, that as society progresses and invents new tools, systems, and standards for survival and growth these same inventions inherently impact society economically, culturally, and in many other ways. When historians look back at this period they should note that our societal progress was the product and reflection of the technological progression explored and executed during our own digital age.

Within the last century our society as experienced a flux of digital revolutions in communications and computation. Beginning with the advancement in telecommunications during the 1940s, Claude Elwood Shannon demonstrated, while at M.I.T., that a Boolean logic could be worked with electrical switching circuits. This was particularly important to the telephone industry as it meant that the industry could move from a human operator to complex switching circuits. Shannon's contributions and pioneering efforts in information theory laid the ground work for the digital communication fundamentally important for the development in our own information age.



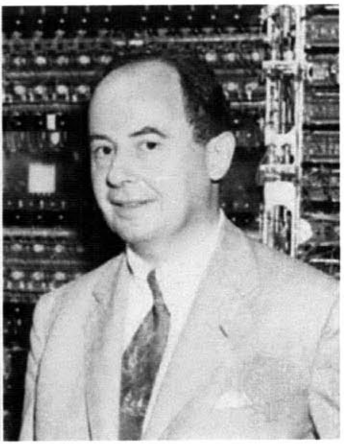


Figure 7 (Left). Claude Elwood Shannon [source: www.nyu.edu]

Figure 8 (Right). John Von Neumann [credit Alan W. Richards]

This era of digital advancement continued into the 1950s with the computing revolutions and theories of John Von Neumann. Von Neumann contributed a new understanding of computer structure and organization, often referred to as the stored-program technique. As a result, this configuration of structure meant that data and program could be stored in the same space; therefore, allowing the machine the capability to alter its program or its internal data. This configuration became fundamental for future generations of high-speed digital computers and ultimately gave rise to the use of random access memory (RAM) used in first-generation commercially available computers.

In both these examples evolution occurred in the transformation of how these systems were to be thought of and explored in. This particular advancement was a transformation from an analog methodology to a digital methodology. As stated, we've had digital revolutions in communication and computations with transformation from analog to digital, yet the ideas that propelled these fields have yet to come out to the physical world. This is changing because what is emerging is the digitization of fabrication. Just as Programmed Data Processors (essentially *minicomputer*) during the mid-1960s became the essential step between behemoth mainframes and personal computer, the research and deployment of model FabLabs are becoming the essential steps between traditional methods of manufacturing and personal fabricators.

3.2 FabLab: The Class

The early concepts of the FabLab grew out of course introduced in 1998 by Professor Neil Gershenfeld, director of M.I.T.'s Center for Bits and Atoms, "How To Make (almost) Anything". In his book titled *Fab*, Gershenfeld describes the initial impression of the class and the surprising attitudes emitted by the students, "...they were motivated by the desire to make things they'd always wanted, but that didn't exist....Their inspiration wasn't professional; it was personal."

By 2002, with support from the National Science Foundation and curious about what would be learned from launching a proto-personal fabricator prior to a completed research, Gershenfeld and the Center for Bits and Atoms deployed the first fab lab into inner-city Boston. The strong Ghanaian connection with Boston ultimately influenced the city of Sekondi-Takoradi, Ghana to also adopt an early proto-lab. This city-to-city connection trend continued with a city in Ghana and to a city in South Africa (Soshanguve). Eventually, these connections led to the spread and deployment of early proto-labs in rural India, Costa Rica, and northern Norway.

Quite simply, FabLabs (personal fabrication laboratories) are small workshops with an aim to make just about anything. The labs foster an environment for inventing, building, and testing through the use of commercially available machines. FabLabs serve the purpose of accomplishing three goals: to empower, to educate, and to create "almost anything". Furthermore, these goals attempt to demonstrate the intersections between the digital world and the physical world, between design and manufacturing.

3.3 FabLab: The Purpose

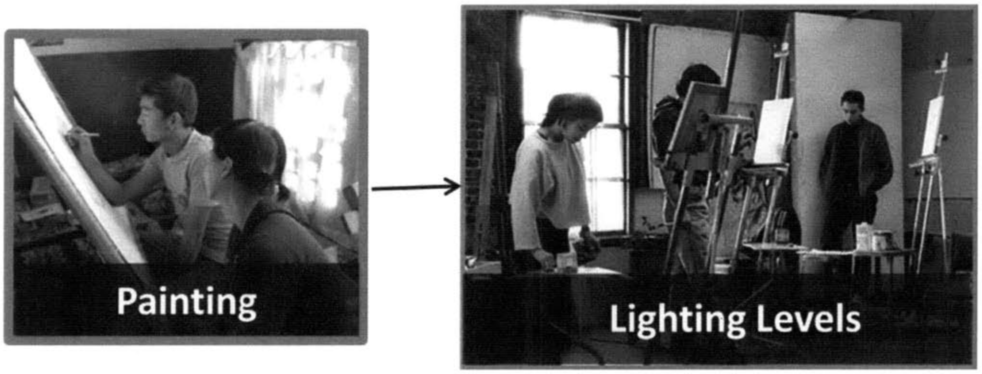
The FabLab experience suggests that instead spending vast amounts of computers and energy to deliver final products around the world a FabLab can deliver the means to create the product. This inherently suggests that ordinary individuals can empower themselves with the ability to realize their ideas, but more importantly also suggest the ability to think, develop, and produce local technological solutions to local problems. The educational natural of the FabLab also suggests that those interested in learning about design and fabrication would have the opportunity to gain new knowledge and apply it to future development and evolution of what a FabLab is or how it is defined.

[4.0] Reflections

4.1 Reflections and Responses

As a point of reflection, I am fascinated by the potential in personal fabrication and even more fascinated with the possibility of empowering a user to design and fabricate a structure based off of a DIY method. Research projects such as those conducted by MIT and specifically the Instant House demonstrate the potential in deploying prefabricated cut sheets with the ability to assemble the build very quickly and easily. My response to this, while considering the extent of the conducted background research, is how can a system like this begin to evolve into a habitable space? This inquiry attempts to fuse the ideas and methodologies of architectural design and manufacturing into a single interest.

On one side there is concern for designing a space that conforms to the user's necessities. The decisions made during the design phase ultimately affect the level of comfort and level of habitability of the space. This search for habitability can begin to be examined by thinking about the tasks to be performed within a particular space. For instance, the program of *painting* would require ample lighting and depending on the artist's medium ample storage.



Considering traditional approaches to architectural design, this example relates to the designer's understanding of the program and to the program's function. Therefore, what makes a space habitable? An architectural approach would be to think about lighting, ventilation, circulation, public and private zones and maybe even consider the flexibility of the space.

[5.0] Hypothesis

5.1 Thesis Question

Can mono-material assemblies be flexible enough to include other kinds of fixtures that support the addition of such amenities as electrical appliances, lighting, storage, and expandability in order to make friction fit construction more useable?

5.2 Addressing the Question

The question is heavily interested in examining the usability of a space and determining the specifics for performing end user related tasks. Therefore, and while there exist other means for demonstrating the extent of the question, I would like to address the proposed question by first defining the association of space habitability with performance-based designing. This definition sets the ground for understanding the direction for the methods and procedure and is elaborated on by looking at two relevant works of performative design and constructionist kits as presented in [12],[15].

5.2.1 Performative Design

Oxman presents a framework for thinking about design and performance beyond the traditional 'generate and test' model. She examines the conventional steps to design and building performance, synthesis-analysis-evaluation, and presents the basis of performative design and performative architecture. In this basis of performative design, Oxman distinguishes it from its counterpart by explaining that in this model performance is considered to be a shaping force rather than the evaluative criteria. She elaborates this by providing an example in architectural practice: "In the case of this building [referring to the Greater London Authority Headquarters Building – Foster and Partners] the complex geometry was the result of the performative requirements, rather than the predetermined formal preferences. From was "found" (modified) on the basis of performative requirements, rather than complex form being a specific objective and starting point of the design [Oxman, 2009]." Oxman's research into this issue of integrating systems of design with systems of building performance inspires my position for interpreting performance context into kit-of-part designs in order to measure levels of habitability required by a program.

5.2.2 Parametric Constructionist Kits

The second paper examines the design process through constructionist learning principles in combination with digital and physical prototyping. The relevance of this article to my problem statement is in the process for manifesting an object library as "objects-to-think-with when designing new elements [Sass]." Specific procedures in the development of this design methodology (constructionist kit with rapid prototyping devices) were explored in the generation of a library of objects. These objects began as nodes in space, translated into connection pieces for different conditions (e.g. corner, side, top, base), and finally, derived its form from the function of each connector piece. Further developments of this library of objects were designed to satisfy three criteria: retain structural integrity, be assembly compliant, and to consider the constraints related to manufacturing. What is important about the procedures underlying this research that can influence the executed method of my problem statement is the creation of a library of objects. The library of objects governs, in this example, the creation of form to some degree, but that also allows for precise fitting of connections. Similarly, and as I start to speculative about results, I can assume that by initially establishing a similar 'library of objects' the building shape and quality of space would be the result of the performance vocabulary rather than the preferences for integrating predetermined construction or formal preferences.

5.2.3 Optimization Through 'interfacing' and 'vocabulary'

A reflection of these works would suggest that the proposed problem statement can be addressed by developing a vocabulary that becomes specific for designing performative features within a space. This vocabulary could begin to take the form of being interfaces embedded within the vocabulary units in order to accommodate features for optimization. I will clarify this by making reference to the relationship of a light source and its fixture. The array of light sources available includes incandescent light bulbs, fluorescent lamps, high-intensity discharge lamps, and light-emitting diodes (LEDs). They share the characteristic of producing electric light but differ in the installation or replacement due to the varying caps which require users to screw, snap, plug, or twist-lock bulbs into fixtures. The installation or replacement "interface" of these light sources only allows them to be installed into socket-matching bases. This embedded quality informs the user that only certain light sources can be used. The characteristic of these objects which require them to be screwed-into, snapped-into, or plugged-into demonstrates their "interface", while the collection of these fitting mechanisms demonstrates their vocabulary.

Similarly, a space with interfaced defined vocabulary units can begin to accommodate particular units of installation which would respond to strategies for optimizing specific aspects to a task, site, or function. This observation also suggests that to optimize a space for specific tasks the design of the FabLab could start by considering the systems of the building.

5.3 Expected Results

The level of production and delivery as related to the sample work of the Instant House can and usually is associated at the level of an established manufacturing business or research environment of an institution. Could the same level of production be available to an average person and if so, what are the impacts or changes to habitability that these mono-material production systems could start to be defined as?

In the context of the building industry, as the building industry moves closer and closer to delivering products similar to automotive and aerospace industry, [i.e. through processes of automation] and as periods of economic and societal flux influence consumer decisions, people will seek alternative options for reasons of cost, time, quality, and as they become more environmentally conscious. Time and time again we see that alternative delivery methods (e.g. kit-of-parts and modular construction) have delivered projects faster, cheaper, and sturdier. I hypothesize that as these productions systems, tools, and methods become readily available to non-expert users the potential benefits include:

1. The ability to customized components and the benefits of designs being generated by the user(s) who inhabit the space(s).
2. The design of more livable or usable and adaptable structures.

The FabLab is unique instance for this research to be tested on because FabLabs are already equipped with the fundamental tools to begin experimenting with the idea of creating more habitable mono-material assembly systems.

[6.0] Method

6.1 Equipping the FabLab

To first understand what the capabilities of the FabLab are one must first understand how they are equipped. As described earlier, personal digital fabrication laboratories, or FabLabs, are places where people with minimal training can design and make just about anything they can imagine. This is possible by using computers that are linked to advanced manufacturing machines. Since having originated at the Massachusetts Institute of Technology, t he idea of FabLabs have spread around the world. The labs cost between $50,000 and $100,000 to setup and typically include the following machinery:

Figure 9. Desktop Computer

Figure 10. Vinyl Cutter

Figure 11. Roland Modela

Figure 12. Epilog Laser Cutter

Figure 13. ShopBot CNC Router

Figure 14. 3-D Printer

Design and creation start by designing the product using a desktop computer (Figure 9). FabLabs are meant to be user-friendly and that begins with the design software available on these computers. The range of software available on these computers varies from software developed at MIT to commercial applications such as Rhino or Google Sketchup. All are intended to get the FabLab user started and learning.

Vinyl cutters are used to cut very thin sheets of vinyl, paper, acetate and foil by using a precisely controlled blade (Figure 10). The ability to be able to cut a range of thin materials makes the vinyl cutter ideal when having to cut copper sheets that can be used to make electrical circuits. The roland modela is a tabletop-sized milling machine used for drilling holes and milling small parts and prototypes (Figure 11). The roland modela advantage is that it can also scan a part and then replicate it.

Laser cutters come in a variety of sizes, ranging from desktop to shop-sized machines (Figure 12). The laser cutter is one of the most intensively used tools because of its quick output of 2D cuts. Laser cutters typically cut thin sheet materials such as wood, paper, chipboard, museum board, cardboard, foamboard, and plastics. These tools also have the added feature of being able to engrave on the same diversity of materials.

ShopBots are computer-guided routers capable of making complicated cuts on a range of materials (Figure 13). Similar to other digital fabrication computed-numerically-controlled (CNC) processes, ShopBots are meant to cut large, flat, sheet materials. Many architecture schools have CNC routers setup in woodshop and typical uses for the router range from creating large site models to creating individual press-fit components that later are assembled into a friction-fit object.

Not every FabLab is equipped with the expensive machine of the 3-D printer; this might be because even though most FabLab types (business, education, communal, or research) experiment with design and fabrication some types are gauged towards providing specific environments such as educational exposure whiles others gauged toward prototyping small parts for research. Nevertheless, 3-D printers are powerful machines capable of printing 3-D objects by layering either plastic or powdered material to build the designed shaped (Figure 14). The finishing process for each type of layered material varies. For plastics extruded models two types of materials are used, one remains as the final model, typically made of ABS plastics, and the second material is used for support. The finishing process for plastic 3-D printed objects involves dissolving this supporting plastic in a solution that only dissolves the support. For powder layered models the finishing process includes separating the glued powdered build from the non-printed powder. The non-printed powder in the bed acts as the support material, but does not require dissolving since it is dry and not attached to the glued model. Finishing requires blowing excess powder from the surface of the model, baking the model in an oven, and then binding its pores with fluids such as a wood hardener or hot wax.

6.2 System and User-Supported Fixtures

Outlining the tools equipped within a FabLab provides an initial start for a designer or FabLab user by which they can begin to understand what can and cannot be fabricated. The bases of any FabLab are its tools, but what happens when the design of a component goes beyond the capabilities of those same tools? How then does this impact how a FabLab is used or defined? Outlining the typical machinery of a FabLab allows me to consider how the design of a building system or user-supported fixture could evolve in this mono-material assembly method if additional tools are introduced. This suggests then, that the definition of a FabLab could also begin to evolve.

6.2.1 The System

In order to understand how specific fixture-based designed components can start to be integrated into a mono-material production method one must consider the systems already implemented into this method. Figure 15 shows what variable the current mono-material assembly satisfies. Currently, projects like those examined by the DDF such as the Instant House satisfy the design variable for providing a structural layer. This layer can be delivered and assembled very quickly because of the single-material and because of the accuracy for the parts to fit upon arrival. Figure 16 shows the added variables of skins, mechanical, interior finishes, and thermal components that would potentially add to the usability of the space.

Figure 15. Mono-material structure as a given

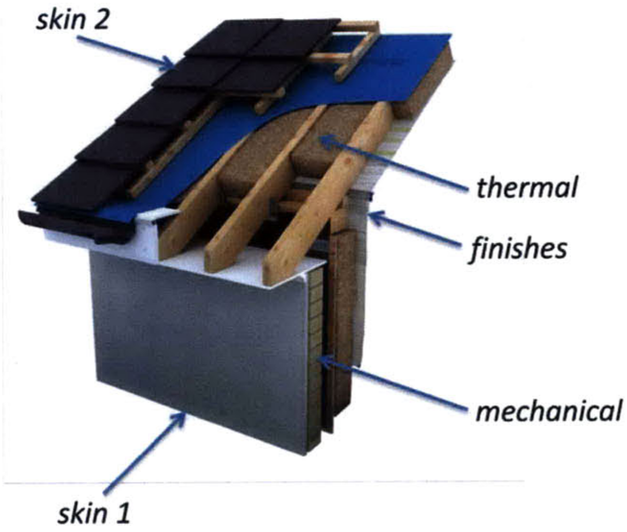


Figure 16. Mono-material structure and additional layers for habitability

Buildings are not only associated with the fundamental need of shelter, but are also synonymous with being a system of layers. Stewart Brand author of *How Buildings Learn* writes exactly about this topic of buildings being a large system of related layers able to respond to instances of time and place. "*How Buildings Learn* is a masterful new synthesis that proposes that buildings adapt best when constantly refined and reshaped by their occupants…"(Brand, 1994) In his book Brand raises the questions of how buildings can begin to evolve over time by manipulating these layers. Brand identifies six layers: 1) Stuff 2) Space plan 3) Services 4) Structure and 5) Skin (Figure 17). The notion that buildings may be adaptable, refined, and reshaped objects of architecture rather than a permanent snapshot of certain eras inherently evokes the idea that buildings can be flexible in design as the building changes to meet the needs of new tasks, users, or programs.

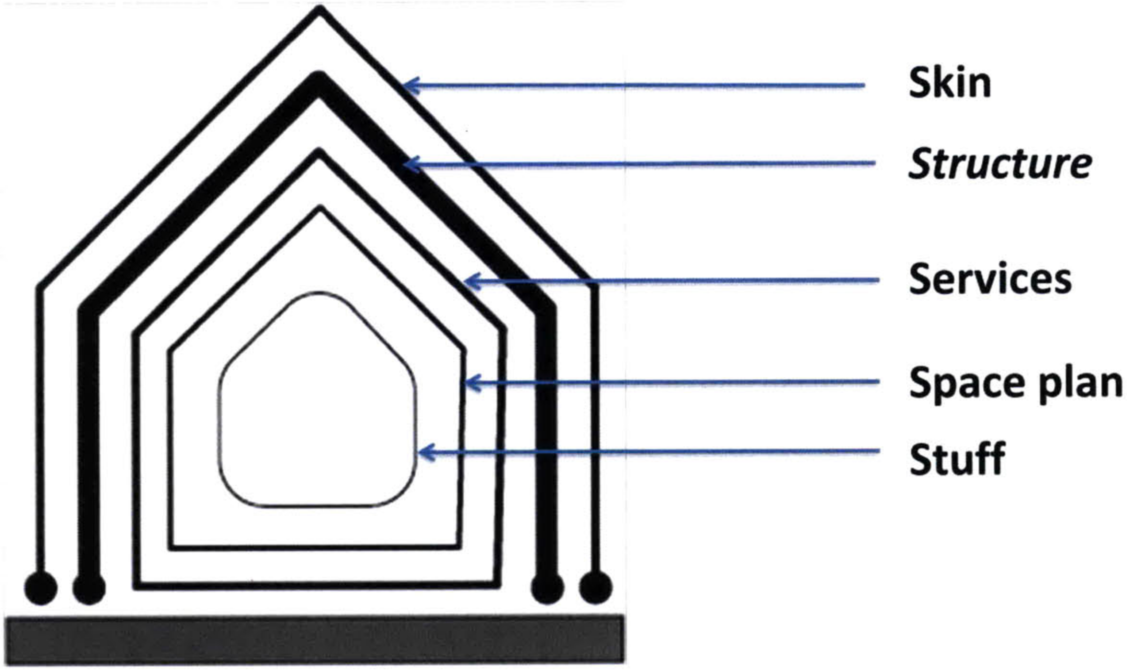


Figure 17. Buildings as layers [diagram inspired by Stewart Brand, How Buildings Learn]

Brand further defines these layers to embody the following:

1. Stuff: Chairs, desks, phones, pictures; kitchen appliances, lamps, hairbrushes; all the things that change as fashions come and go
2. Space plan: how we arrange the stuff around us to be fun, comfortable, or efficient part of our lives; also the interior layout of space composition
3. Services: the working guts of a building: communications wiring, electrical wiring, plumbing, sprinkler system, HVAC
4. Structure: The foundation and load-bearing elements. The given.
5. Skin: Exterior surface reflecting changes in trends, technology, region. This layer defines the appearance of building.

6.2.2 The Design

The design of these FabLab user-supported fixtures and systems were derived and influenced from combination of various sources. My participation in a FabLab workshop early in the research provided an outline of current issues needed to be addressed when considering the start up of a lab. Conversations with FabLab experts Amy Sun and Sherry Lassiter, from the MIT's Center for Bits and Atoms, provided the essential background information and experience necessary to understand what components and amenities were still unresolved within the FabLab. Within this discussion a series of topics arose including the need to investigate the design of flexible storage. The following example illustrates the design proposal for a modular shelving and storage unit.

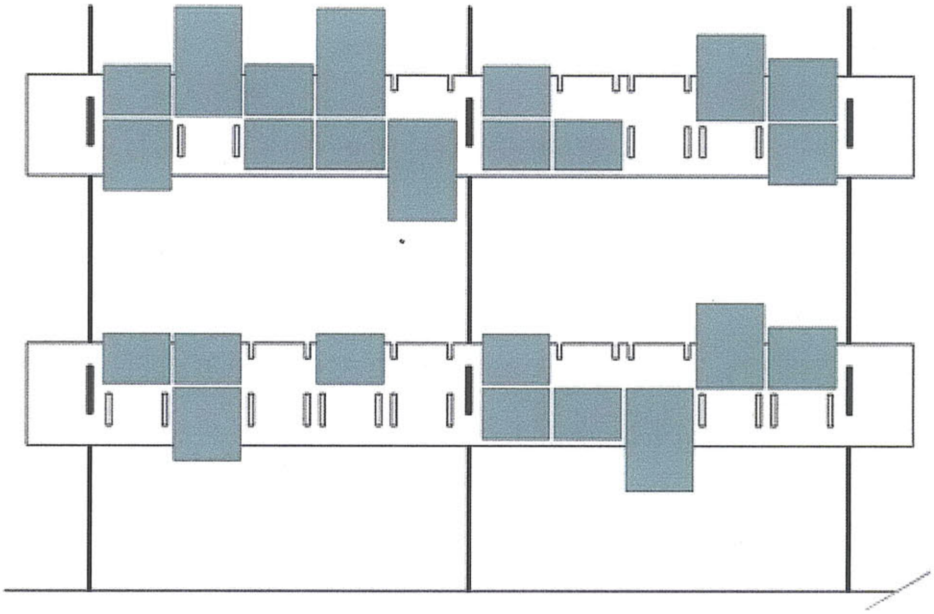


Figure 18. Modular adjustable wall storage units and shelving

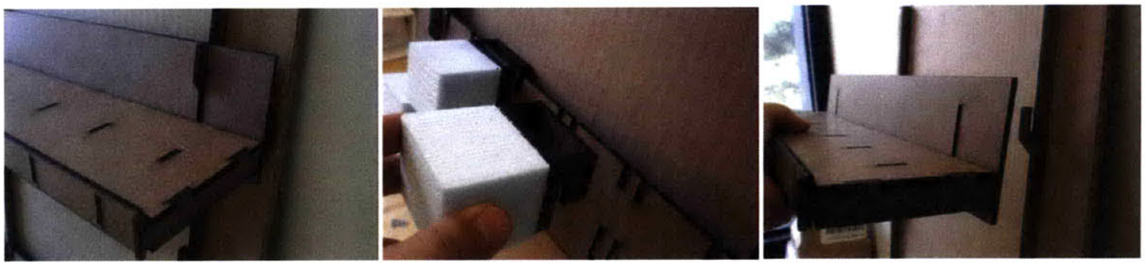


Figure 19. Unit prototype and assembly

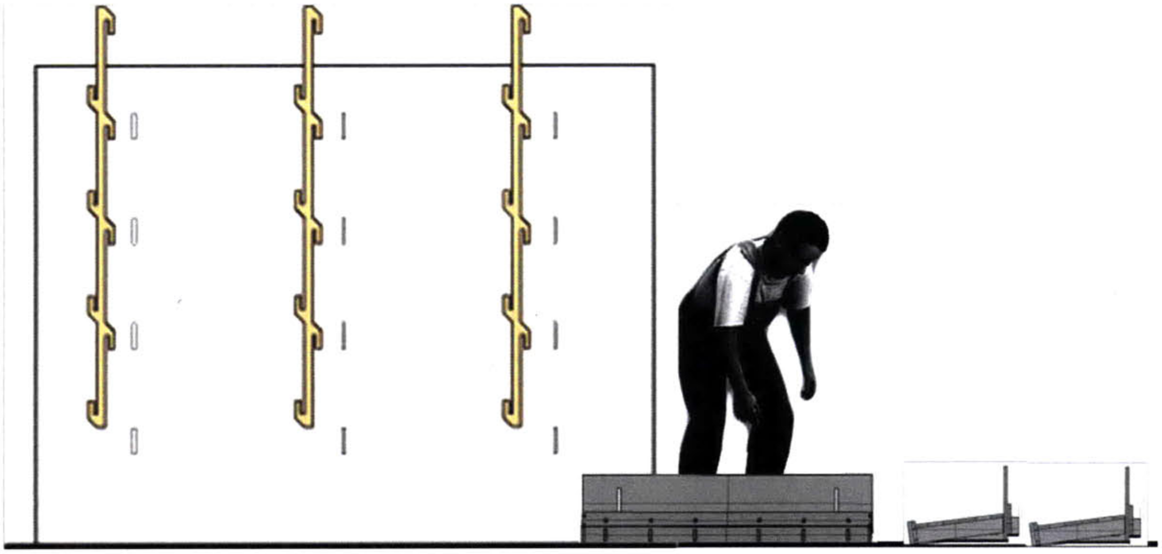


Figure 20. One person installation. Rail system with shelving units

This initial attempt to satisfy the issue for storage provided an instance of specific fixture design. While this design could be integrated into most wall assemblies what was becoming important was to understand how specific user-supported fixtures such as these would begin to relate to larger systems of the buildings. Systems such as those discussed earlier.

The next step into the design was to consider the relationship of the "given" system, which was previously defined as the mono-material construction as used by the Instant House Project, with the layers of Services and Skin.

The Services layer was particularly important to focus on because intelligent design within this layer would assist in the organization and management of the building's "guts": communications wiring, electrical wiring, plumbing, HVAC. The following proposal illustrates the design of interchangeable wall panels governed by a system of hierarchy. The hierarchy responds to the tools, machinery, or mechanical components nearby.

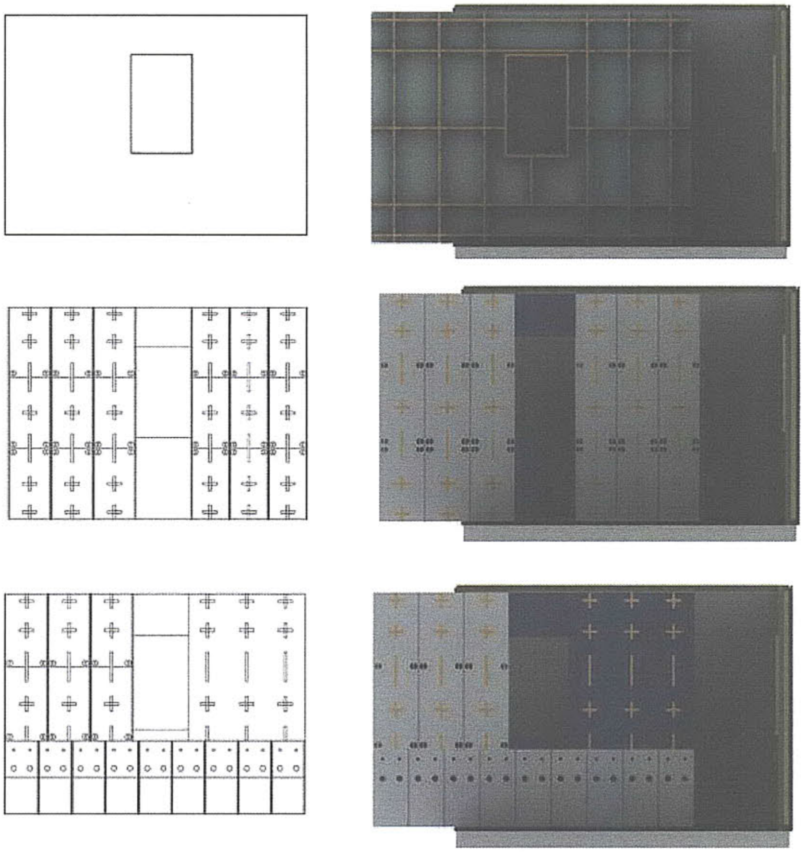


Figure 21. Interchangeable wall panel units-permanent panel and interchangeable panels

Figure 21 provides an illustration of this system of interchangeability. The top most illustration depicts the existing mono-material friction-fit assembly. As discussed earlier this layer provides the structure and bases for attaching additional systems. The middle and bottom illustrations provide two instances of the modularity and interchangeability of the panels. In these examples the light colored panels represent operable or non-fixed panels while the darker colored panels represent fixed panels. The importance behind this differentiation of panels relates to how easily accessible and adjustable the wall could become as the FabLab evolves. Identification of accessible panels is important because the lighter colored panels or non-fixed panels would inform the user or designer to consider these regions for placement of mechanical and electrical fixtures (Figure 22).

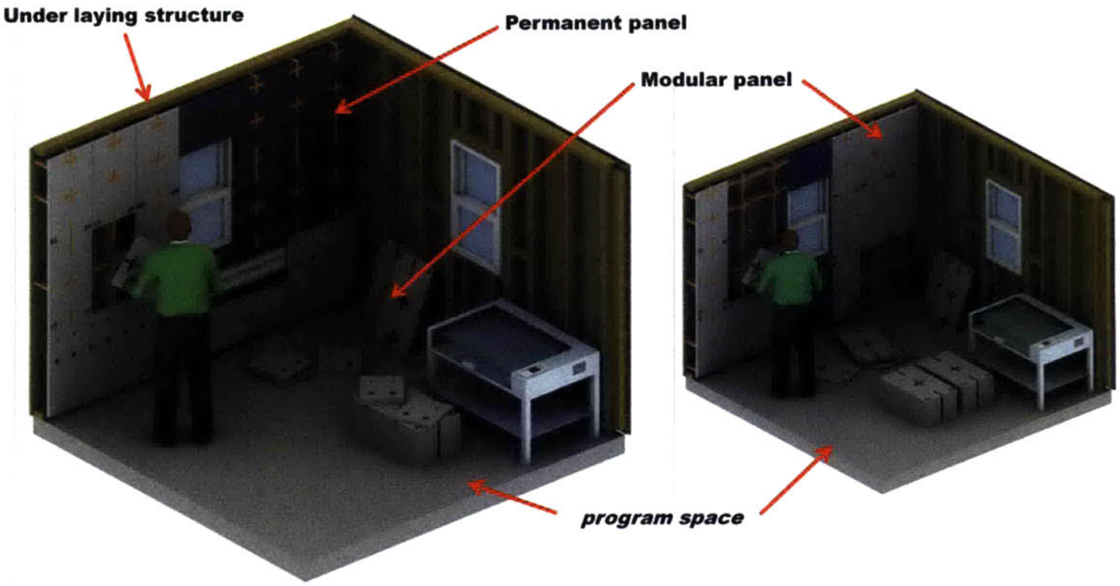


Figure 22. Hierarchy Space Planning; Interchangeable modular panels could govern layout of electrical cabling, storage, and fixtures.

The same hierarchy system of operable, flexible, and fixed panels would later benefit how the flooring system could begin to function. Often when a FabLab is started up the building is provided and the machinery and layout of those tools are filled into the space. When considering the FabLab deployed as a friction-fit building there is an opportunity to apply a hierarchy panelized system not only to the wall but also to the floor (Figure 23a). By doing this there is thoughtful process of how to manage the mechanical and electrical components and a consideration of how these components can be routed throughout the floor. (Figure 24)

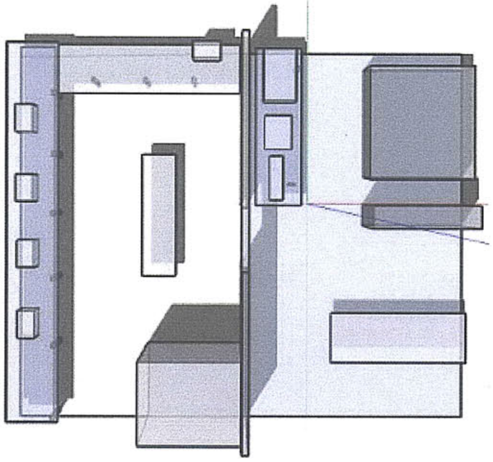


Figure 23a. Existing Providence FabLab Layout [source :www.as220.org]

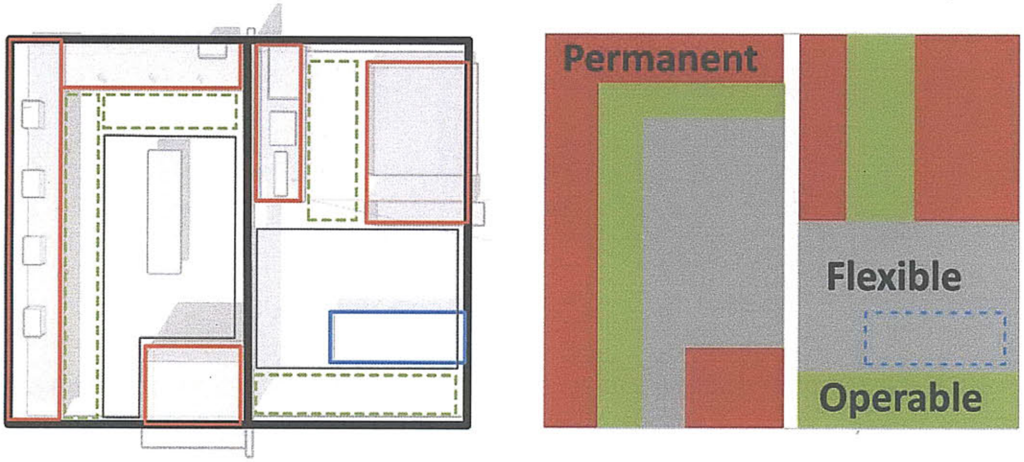


Figure 23b. FabLab Layout and Overlaid Zones

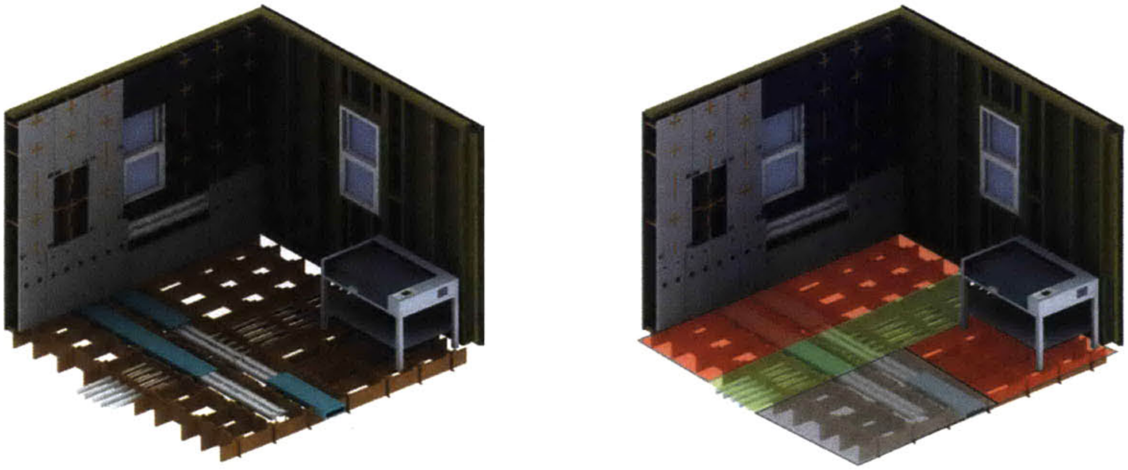


Figure 24. Hierarchy Space Planning adapted to flooring

6.2.3 Rain Screen System – Skin Layer

The design and consideration of the rain screen systems were derived by considering that if a FabLab were to be constructed and assembled from a friction-fit assembly method then the exterior protection of the building should also be influenced and manufactured with the same digital fabrication tools. This also begins to evoke the idea of introducing additional machinery to fabricate specialized design components. In the first iteration of a rain screen system a focus was placed on the design of hardware components onto a mesh like rain screen system capable of being operated so to introduce the added function of being able to control the amount of light intensity, create air circulation, and to regulate temperature to create warm or cool environment (Figure 25) (Figure26).

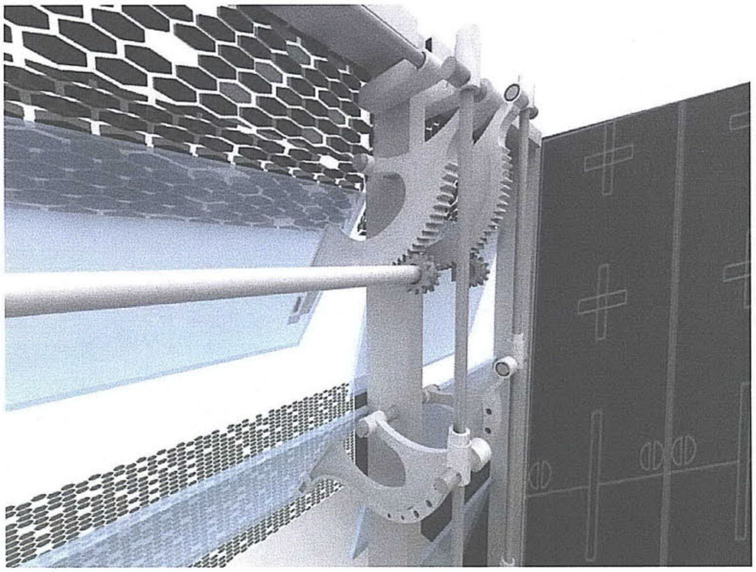


Figure 25. Rain Screen Louver Hardware and Mechanics

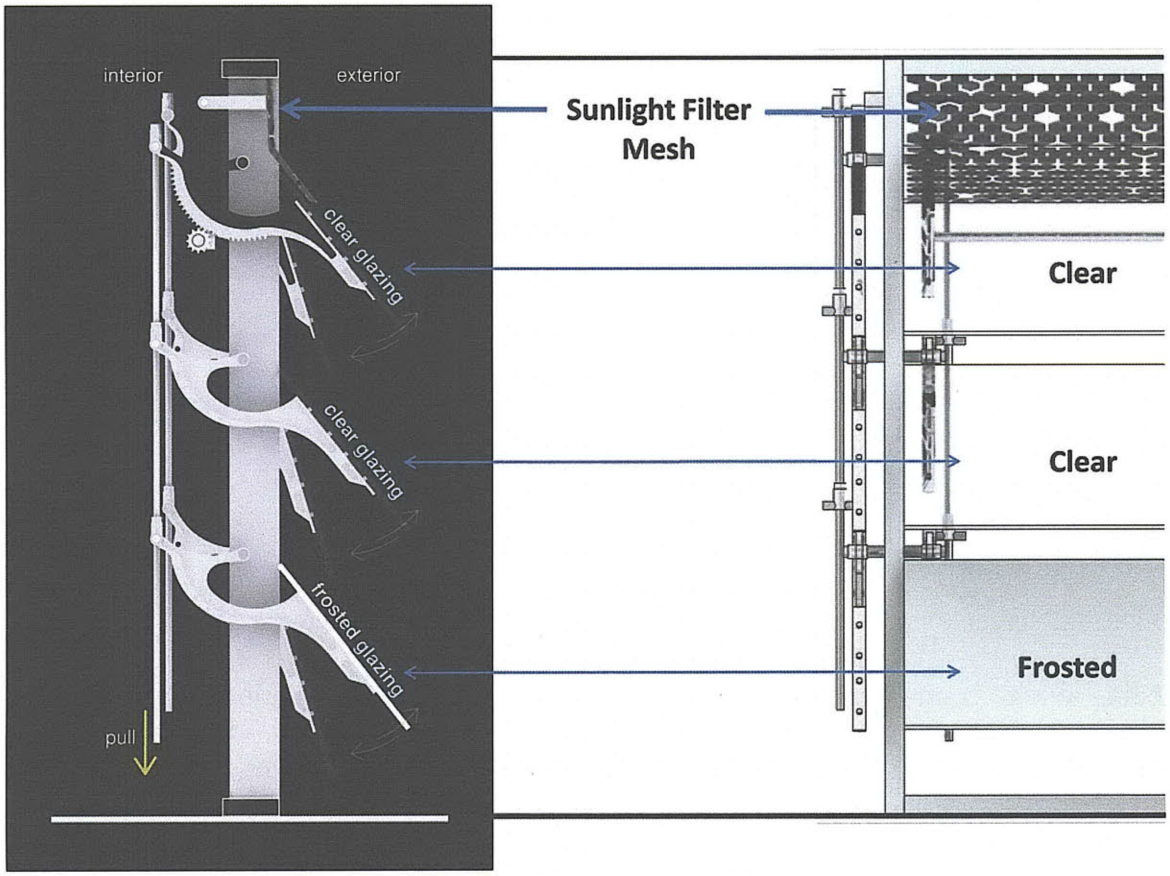
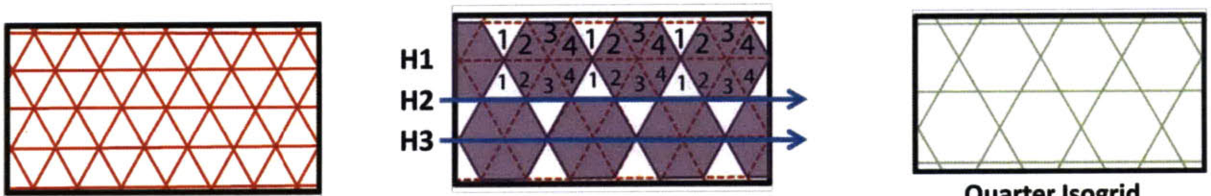


Figure 26. Rain Screen Louver; Section to Elevation

The designed hardware for this first iteration went beyond the fabrication capabilities of the current tools available to the labs. Therefore, a conclusion was made that for a design of this complexity to be experimented with in combination with friction-fit assembly additional machinery such as a CNC milling machines capable of milling metals components would be needed. The addition of machinery such as a CNC waterjet cutter would also provided the extended capabilities to cut large sheets of materials. The wide spectrum of materials a waterjet cutter is able to cut gives the users an added advantage in fabrication over the use of the table router.

The second iteration of the design of a rain screen system involved the consideration of using the exiting tools available to a lab, but this time integrating the use of additional processes of design, material, and fabrication. The component design of a FabLab was evolving into a system of interchangeable and modular parts. So to complement the systems already explored and to utilize the machinery that a FabLab user would have available the decision to consider rain screen panels was introduced.

The design process began by considering how to make a panel that was lightweight and that could be easily replicated. The panel would need to be lightweight so that a user could easily mount the panel onto the surface of the structure. This quality would also benefit the user in the event that a panel would need to be replaced, adjusted, or removed. I began exploring the framing process for these panels by considering how conventional press-fit objects are assembled. Conventional fittings for 2D cut pieces such as those explored by the DDF included press-fit assembly into ninety degree notches. This led me to explore the possibility of including diagonals into the assembly. Introducing diagonals into the assembly meant that some material could be reduced since the diagonals would create a series of triangles making the construct stronger. The pattern I explored was an isogrid. The triangular pattern of the isogrid receives its strength from the stiffening of the diagonal ribs, which also creates a very efficient structure. The self-stiffened structure of the isogrid has applications in aircraft and space vehicles because the stiffened structure is capable of producing structures that are lightweight, rigid, and very strong. Seeing the potential to reproduce these same qualities into individual rain screen panels I continued with the pattern by reducing the amount of triangles. I manipulated the conventional isogrid by taking each horizontal line of triangles, grouping the triangles into sets of four and eliminating three of the four triangles. The manipulation resulted in keeping one triangular structure for every three removed. This process continued for the additional rows of triangles; the result was a quarter isogrid (Figure 27).



Conventional Isogrid **Isogrid Manipulation** **Quarter Isogrid**

Figure 27. Design Pattern, Manipulation, and Resulting Structure

The resulting quarter isogrid reduced the amount of stiffening ribs, but its strength testing could only be confirmed once the pattern was transferred into a model and then later fabricated. The next step was to take the resulting pattern and transfer it into a modeling software to create a digital rendering and representation of what the rain screen panel would start to look like (Figure 29). This would be the same process a FabLab user would engage into in order to begin the fabrication and testing of a part. Consideration of the material to be used in the fabrication influenced the design of the individual pieces. The panels were intended to have the quality of begin lightweight, strong, and durable. The quarter isogrid satisfied the quality for constructing an object that needed to be strong. Material selection for this panel would influence how heavy the final object would be; therefore, since cardboard can both be lightweight and readily available throughout the world, modeling and tolerances were designed with cardboard as the final material.

Figure 28. Modeled panel showing 3- layers of interlocking segments and its frame

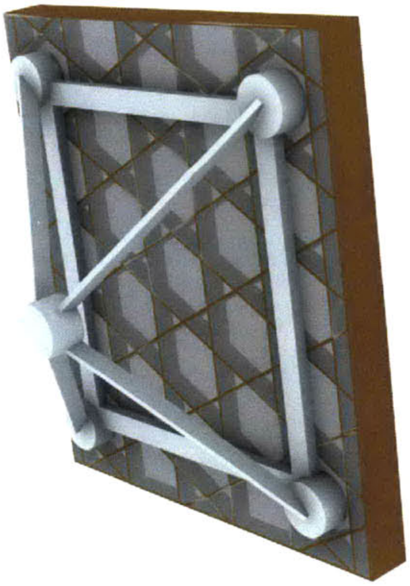


Figure 29. Quarter isogrid rain screen panel representation

Fabrication of the panel included the use of an epilog laser cutter and one-eighth inch corrugated cardboard as the material. The speed and accuracy of the laser cutter resulted in a quick fabrication and exact cuts with little to no loss in material dimensions, since the thickness of the laser is nearly negligible (Figure 30). Assembly of the first few pieces proved to be extremely accurate. An observation of this mockup showed that the pieces remained quite loose and flexible until all three layers (layers depicted in Figure 28) were locked into place. Once these layers were interlocked the panel proved to be very stiff and strong.

Figure 30. Cut sheets of cardboard strips waiting for assembly

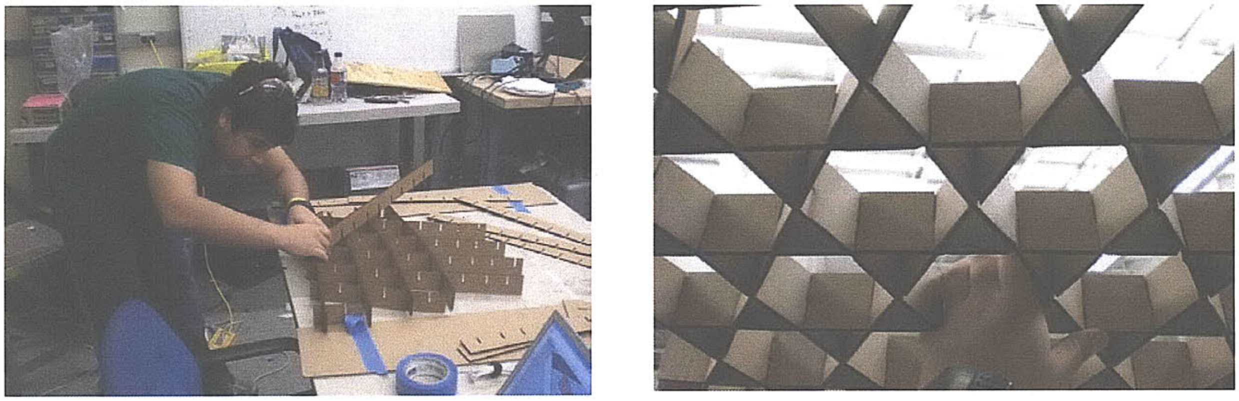


Figure 31. Assembly

The final step to this design was to coat the structure with materials that would protect the structure from water exposure. A coating of epoxy and resin were included in order to do two things. The first was related to the extraction process of finished 3-D printed powder model. By dipping a 3-D printed powder model into a binding fluid such as hot wax the pores within the powder are filled and create a stronger bond. The same process of coating the corrugated material with thin layers of epoxy and resin helped to strengthen the panel and to fill in the gaps characteristic of corrugated cardboard. The second benefit of coating the panel with these layers was for adhesion. The waterproof, durable, and lightweight monokote film membrane added to the panels received more adhesion from the resin than it would from just being applied directly onto the cardboard. The system was then represented in model form with the earlier proposed systems. (Figure 32).

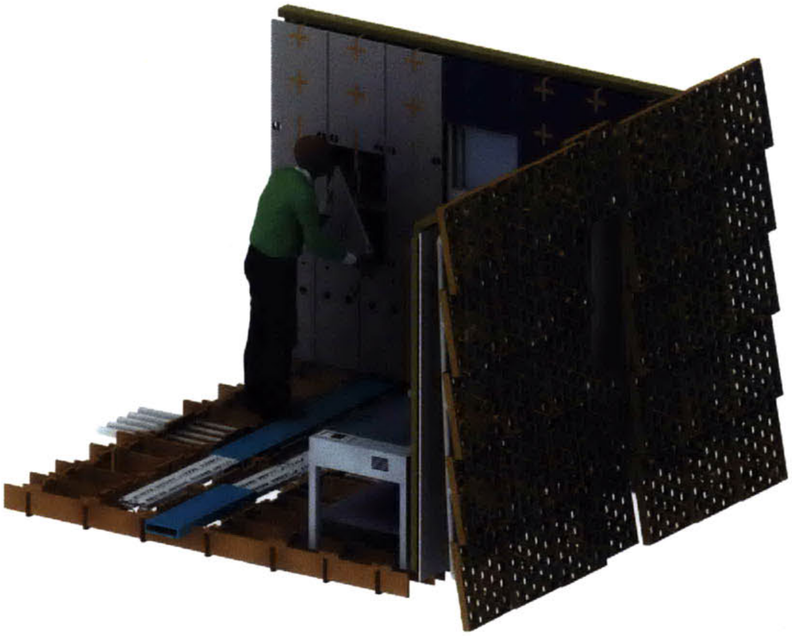


Figure 32. Interacting systems of wall and floor modularity and rain screen system

One component not fully explored or investigated were the rack systems in which these panels would rest on. A continuation of this research would investigate the connection between grouped-panels and the existing structure of a friction-fit assembled FabLab. Earlier proposals illustrated the design of metal hardware components, but to fabricate these types of components the tools and machinery currently available to a lab would need to be revisited to include equipment capable of working with metals and capable of cutting on multiple axes. By repackaging a lab with particular tools for specific production types and materials, future research on this topic can begin to consider the extent of what can and cannot be fabricated. The rack systems for this panelized, lightweight, rain screen system would certainly benefit from the continued investigation into FabLab tool and material exploration.

[7.0] Conclusion and Future Direction

7.1 Overview

The conclusion of this thesis is such that for mono-material productions assemblies to be applied at the level of existing construction methods additional building layers would need to be considered as fundamental elements that would make the designed spaces more usable. A FabLab deployed using the existing mono-material assembly has particular advantage of exploring and resolving the issue of habitability because of the tools already associated with a FabLab. These laboratories are already equipped with the technology used to help solve local technological problems and can apply the same resolutions to a building scale by designing custom components that meet the needs of a task, user, or program.

FabLabs have the potential to have significant impacts on three levels:

1. Personal Fabrication: If a FabLab user needs a tool or an object, they design it to fit their needs then fabricate it
2. Grassroots Community Development: The FabLab provides tools for communities to develop at their own rate and within their own cultures.
3. Customize Building Manufacturing: Evolving FabLabs will have the ability to interchange systems to satisfy changes in the needs of the lab. The modularity in storage needs and rain screens, the hierarchy of operable panels for better integration of mechanical, electrical, and plumbing and the flexibility to expand

laboratory space all contribute to the redefinition of how a FabLab is design, used, and how it adapts.

Further conclusion for this thesis shows that for specific designed components to be realized the introduction of additional tools will need to be considered as part of a FabLab package. The design of a panelized rain screen system attempts to make use of material that can be easily found through any region, but would still require a certain amount of working space to handle the different epoxies and resin used in its fabrication. The louvered rain screen fixture design included hardware components that would not typically be able to be fabricated within the existing tools of a lab and therefore would also require that additional tools be integrated as part of a FabLab package.

Finally, the novelty of the thesis is such that it attempts to propose methods for making a mono-material build more habitable by introducing design strategies for creating interchangeable features in combination with existing material such as plywood, but also considering additional materials such as cardboard and metals. The flexibility to interchange one system of storage to another system allows the FabLab space to become more adaptable, useable, and expandable as the needs of the space and user change.

7.1.1 Importance

The importance of this research is that it combines an existing tested production system of friction-fit assembly with the possibility of customized manufacturing of user-supported components that may be tested and manufactured within the space of FabLab.

The importance of this work also shows that by empowering users to test and manufacture specific fixture components the method (friction-fit, digitally fabrication, kit-of-parts, etc) in which these type of structures are delivered may become more flexible. That is, a design for a friction-fit assembly may be completed and delivered to a certain level with the intention that the remaining features and finishes could be designed, fabricated, and added to the "base" structure of the building by the end user. The research suggests that by enabling the user to take part in the manufacturing of specific parts the processes of delivery, integration, and interchangeability of building systems can become much more simplified. The FabLabs provide this simplification because they are already equipped with the tools used by the professional industry. As building processes and conventions evolve to this production system of friction-fit assembly so can the function of a FabLab. The importance of this research illustrates that FabLabs are certainly laboratories for testing customized manufacturing for individual production such as toys and gadgets, but the research attempts to show there is also the potential that these same experimental laboratories could be transformed as labs that mix personal fabrication with industrial manufacturing in order to reduce and rethink the complexities in realizing friction-fit assembly building systems.

7.1.2 Opinion of the Work – About the Research and the Field

My opinion of the work is that there still remains plenty of research to be investigated on this topic, but like most new ideas, the acceptance of something different lies in the ability of the idea to further benefit the end user. Similarly to the misconceptions of modular housing in the 1980s, that homes built in a factory were poorly constructed and did not measure up to stick-built homes, friction-fit delivery systems will encounter some of the same resistance, but only because the system is only one system. My opinion and what this research attempted to demonstrate was that by combining a combination of other systems into the equation of this tested single system (friction-fit-prefabricated-delivery), buildings can begin to be outfitted with additional details that would then bring this type of building method one step closer to delivering complete products. The complete products would be products that are delivered as whole packages and would include systems of structure, skin, mechanics, finishes, and a system of assembly that assumes to be flexible. The system of flexibility is critical because this part enables the embedding of customized components. Additional opinions of this work and about the research in this field are that no single system of design can provide the habitable spaces that people need in order to function and use meaningfully.

Integration of multiple layers and material are critical in order for friction-fit assembly systems to compete and be adopted by consumers. The research being conducted in this topic has a particular advantage due to the cutting-edge technology becoming more and more available throughout institutions and neighborhoods around the world. Expanding these tools and methods to both experts and non-experts in my opinion stimulate exploration and problem solving into the issues of integrated systems within friction-fit assembly. I support the research into alternate building methods and in recent decades these same methods have proved to deliver products more efficiently with respect to time, cost, and quality. The research in this thesis and as part of a broader research into digitally-fabricating-buildings has the same potential of providing complete buildings or building components that are delivered or fabricated faster, cheaper, and with better quality, but only with the integration of multi-materials, addition of multi-systems, and influences by both experts and non-experts. The integration of these requirements into this production method could then begin to evolve and compete with other production methods.

7.1.3 Discovery in the Work

Discovery in the work came when I realized that some of the same principals used within the automotive and aerospace industry could be applied to this research of customized components. These principles include parts capable of being replicated numerous times all while having the exact same accuracy and precision in fabrication. The difference in the methods implemented by those industries is that products are manufactured by the many, the parts then delivered to an assembly line, and pieced together by both hand and an automated assembly (Kieran, 2004). The end product leaves little room for customization or addition. While the method is a century long tested method proving efficiency in delivery and cost of automobiles, the same system cannot apply directly to the building industry because of the diversity in function and program required in a building.

Therefore, the discovery of this research comes when productions methods of multiple industries can be combined to create a hybrid production method that utilizes specific methods from each system. In the case of this presented research, friction-fit assembly provides the link between accurate manufacturing of parts, which can be delivered quickly and assembled precisely, with the link of customized design expected in buildings. The discovery of this link also suggests that as research into this topic of building construction progresses buildings can begin to be outfitted and designed with not only basic building systems (e.g. structure, skin, finishes, etc) but with systems that are able to generate and control sources of energy for the building. An example of outfitting a production method with energy systems and building systems has been begun to be explored within the research at the Institute for Advanced Architecture of Catalonia (IaaC) in a project identified as the FabLabHouse (Figure 33).

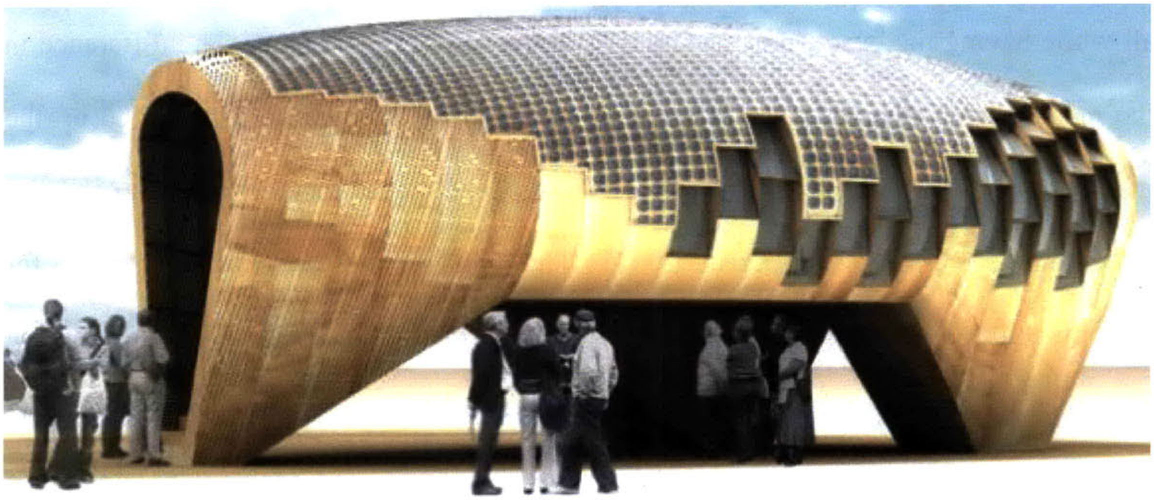


Figure 33. IaaC FabLabHouse Renderin. Research into multiple system construction: building system with energy system [source: http://www.fablabhouse.com/]

7.1.4 Shortcomings

While the work presented in this research attempts to support and test the integration of multi-systems and materials, the shortcomings of this work show the limitation in scalability both structurally; that is the size of the building being design and constructed, and the availability of the technology. The work of this research recognizes the potential for personal fabrication to be combined with architectural customization strategies, but the shortcomings of this work assume that even in developing countries the tools and materials would be available to produce the components needed. While some machinery could be obtained easier than others, the limitation in tools ultimately limits the production of design, which inversely limits the output of a part. Future research of this work will ultimately demonstrate that a system of labs are capable of not only producing personal products, but also capable of expanding its production into producing building components with new developing and easily accessible technologies.

Specific shortcoming observed during the conducted work was the ability to redesign and evaluate multiple design features. Changes in the design ultimately consumed a lot of effort and time. The same scenario applied to a FabLab user or non-expert could potentially affect the user's ability to continue the design and fabrication of specific designs; essentially discouraging the user. Inversely, advanced software could be introduced into the design process to simplify revision and output of a design, but then the issue of educating non-experts with such complicated software comes up.

Future research could show that processes of digitally-fabricated-buildings/parts might not need sophisticated modeling platforms, but instead need only to revisit strategies for simplifying the production methods of construction and systems integration. This suggests that components are not only designed for user, task, or program functions, but designed to consider the context or region of the component's application. A FabLab user designing a building component for use in a dry desert climate would have different criteria and needs from the component than would a FabLab user designing a similar component in a wet tropical climate.

7.2 Direction of the Work

7.2.1 To Explore and How to Proceed

Based off of both the observations and trials during the fabricated pieces during this thesis and the proposed designs, the next steps into the research would be to:

1. Survey the effects of additional machinery into these labs
2. Explore the possibilities of fabricating components from alternate materials such as recycled or "found" materials.

Similarly, to the controversial environmental and learning issues of the project *One Laptop Per Child*, surveying the impacts of introducing additional technology and tools into these lab would provide data supporting whether the manufacturing of personal or buildings components are actually more efficiently fabricated and the impacts of these customize components when combined with separate production systems such as the a friction-fit method. Furthermore, I would be interested in exploring the fabrication of components fabricated from recycled or "found" materials. This would have the application for serving labs with limited resources. The use of found materials for fabrication process means that communities of different cultures and economics could still take advantage of the available fabrication tools, but would create components which have less of an environmental impact because of the reusability in the selected material. This also means that future research going into this direction of using material with varying properties, would need to explore and proceed by considering design of algorithms capable of recognizing useable material from already cut materials and explore scanning technologies that could scan materials with indeterminate properties that could then be used to influence design decisions while the design is still conceptual.

[8.0] References

[1] Bjork, B.C. 1989. “Basic Structure of a Proposed Building Product Model.” *Computer-Aided Design*, Vol. 21, No. 2 (March 1989): 71-78.

[2] Boothroyd, Geoffrey, Peter Dewhurst, and Winston Knight. 2002. *Product Design for Manufacture and Assembly*. New York: CRC.

[3] Brand, Stewart. 1994. “How buildings learn: what happens after they're built.” New York, NY: Viking\

[3] Botha, Marcel and Lawrence Sass. 2006. *The instant House: Design and digital fabrication of housing for developing environments*. [Online] Available at: http://ddf.mit.edu/papers/09_botha_sass_caadria_2006.pdf [Accessed 19 February 2010]

[4] Botha, Marcel. 2006. “Customized Digital Manufacturing : Concept to Construction Methods Across Varying Product Scales” (SMArchS Thesis, Massachusetts Institute of Technology)

[5] Cardoso Llach, Daniel. 2006. “A Generative Grammar for 2D Manufacturing of 3D Objects” (SMArchS Thesis, Massachusetts Institute of Technology)

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[6] Clayton, Mark J., Paul Teicholz, Martin Fischer, and John Kunz. 1999. “Virtual Components Consisting of Form, Function, and Behavior.” *Automation in Construction*, Vol. 8, Issue 3 (February 1999): 351-367.

[7] Eastman, Chuck M., Paul Teicholz, Rafael Sacks, and Kathleen Liston. 2008. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*. New Jersey: John Wiley and Sons.

[8] Gershenfeld, Neil A. 2005. *Fab: the coming revolution on your desktop--from personal computers to personal fabrication*. New York: Basic Books.

[9] Kamath Vasant, Ayodh. 2009. "Integrating Digital Design and Fabrication and Craft Production" (SMArchS Thesis, Massachusetts Institute of Technology)

[10] Kieran, Stephen and James Timberlake. 2004. *Refabricating Architecture: How Manufacturing Methodologies Are Poised To Transform Building Construction*. NY: McGraw Hill.

[11] Kolarevic, Branko. 2003. *Architecture in the Digital Age: Design and Manufacturing*. New York: Spon Press.

[12] Oxman, Rivka. 2009. "Performative Design: A Performance-Based Model of Digital Architectural Design". *Environment and Planning B: Planning and Design.* 36, no. 6: 1026-1037.

[13] Sacks, Rafael, Charles M. Eastman, and Ghang Lee. "Parametric 3D Modeling in Building Construction with Examples from Precast Concrete." *Automation in Construction*, Vol. 13, Issue 3 (May 2004): 291-312.

[14] Sass, Lawrence. 2005. *Wood Frame Grammar: CAD Scripting a Wood Frame House.* [Online] Available at: http://ddf.mit.edu/papers/06_lsass_caad_future_2005.pdf [Accessed 19 February 2010]

[15] Sass, Lawrence. *Parametric Constructionist Kits: Physical Design and Delivery System for Rapid Prototyping Devices.*

[16] Smith Dana K. and Michael Tardif. 2009. *Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers.* New Jersey: John Wiley and Sons.