

**Chassis + Infill:
A Consumer-Driven, Open Source Building Approach
for Adaptable, Mass Customized Housing**

by

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**B.S. Mechanical Engineering
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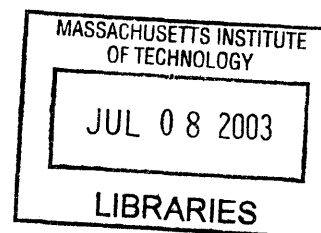
**Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of**

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at the
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ABSTRACT

The housing industry is not taking advantage of advances in manufacturing practices. Almost all new homes are generic, disruptive to change and upgrade, low quality, low tech, and expensive. A system architecture, which takes advantage of new technology and allows efficient coordination between industry players, could change the entire industry. To this end the chassis + infill system has been developed. It allows factory manufactured components to be easily assembled on-site to create a mass customized, adaptable, high quality, high tech, and high value home. This is made possible by dividing the house into two notional elements: the chassis, the standardized, mass produced part of the system, provides the structure and services for the building, and the infill, which consists of interchangeable wall and floor components, provides for customization and adaptability.

Keywords: modular, component based, panelized, home of the future, construction, residential, fabrication, development, engineering, engineered, network, infrastructure, embedded, integrated, distributed, ubiquitous, plastic, pultrusion, remodel, dynamic

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Chapter 1: Introduction

1.1 Motivation

Industry is reaching a new stage, one that offers exciting new possibilities for consumers and manufacturers alike. Moving from craft to mass production allowed quality goods to be brought to the masses, but personalization was lost. With the advent of new manufacturing technology personalization is again possible, through a new production method: mass customization. Mass customization represents a return to the basic truth that consumers want their possessions to accurately meet their individual needs, something that was easily accommodated in the days of craft production, but is impossible to address with mass production.

One hundred years ago cars were custom made for each owner by highly skilled laborers with simple tools. This craft process allowed the car to be personalized to the unique specifications of each buyer. Unfortunately the process also resulted in a product that could only be purchased by the very wealthy, and an industry that only produced a thousand vehicles a year. Henry Ford saw this inefficient process as a business opportunity. He met this opportunity with interchangeable parts, a uniform product, and the assembly line; mass production was born. Mass production reduced the need for skilled labor and allowed much higher production rates. Henry Ford had achieved high quality at low cost, but there was no longer any significant customization. This lack of customization is immortalized in his quote, "You can have any color you want as long as it's black." It is only now, in the 21st century, that car manufacturers are beginning to seriously consider the issue of providing individual customization. For years, insignificant choices like power windows and upholstery color have been possible, but the major aspects of the car have been fixed. Consumers are only able to choose which of a few models is closest to what they want, without the opportunity for a personalized solution. GM has suggested a new model for car production that may change all that. The Hy-wire or AUTOmomy fuel cell concept relies on a generic mass produced chassis, but allows the body of the car to be customized. The easily replaceable body could be exchanged for different occasions or as new styles became popular.

Computers followed a similar path from custom one off solutions to mass production. The first computers were hand made by highly skilled craftsmen, one at a time. In 1965, with the creation of the IBM 360, computers entered the world of mass production. As with the car interchangeable parts and assembly lines allowed the computer to become attainable to a much larger portion of the population. However, unlike cars, which for the most part have yet to offer any real mass customization, computers now offer the consumer a wide variety of personalization. By creating modular systems computer manufacturers like Dell are able to customize computers for each consumer without significantly increasing costs. The buyer may choose the speed of the computer; the amount of RAM; the size of the hard drive; what sort of storage media, such as CD-ROMs or ZIP disks they would like to use; as well as monitor type and size and other peripherals. An integrated system might still be able to offer some small level of choice, but it would be insignificant compared to the level of customization possible with the modern PC. In addition to customization, the modularity of computers also makes it possible to

adapt and upgrade the computer as situations and technologies change. Consumers are enamored with these ideas of customization and upgradability. They demand choice, personalized solutions, and the ability to change the product over time, even with a product as short lived as a computer.

Mass customization is cropping up in other industries as well. From jeans to electronics to software, companies are seizing the opportunity to gain competitive advantage by combining the efficiency of mass customization with the differentiation possibilities of customization.

The advances in other industries are leading consumers to expect more from the construction industry as well. Consumer products have changed drastically over the past hundred years while housing has remained virtually stagnant. Places of living should also reflect the individual's needs and values. In addition to providing users with choice and adaptability, new products in other industries address issues such as energy and resource conservation, health, and style. By taking advantage of new methods of manufacturing and advanced computer driven technologies, many industries are able to meet these needs while maintaining high quality and competitive prices.

Meanwhile, the home is increasingly becoming a center for work, commerce, entertainment, learning, and health care. Parents work at home over the Internet and the phone, so they can be with their young children or simply avoid the congested commute. Amazon.com, ebay.com, and other websites do millions of dollars of business a day with people in their homes. DVD players, advanced video game systems, and digital high definition television make going to the movies or the arcade unnecessary. Children and adults alike are able to find volumes of information on virtually any subject that interests them merely by surfing the web. Diabetics are starting to more actively monitor their own blood sugar keeping themselves out of the hospital and extending their lives. These changes are driven by advances in technology and the difficulties of transportation. Furthermore, there is every reason to suspect that things will continue in this direction as technology becomes even cheaper and more potent, and the growing population makes unnecessary travel less desirable. To properly accommodate these new complex activities, the home must allow for plan customization, privacy, acoustic personalization, multigenerational living, and the integration of technology. Furthermore, the home should allow for change over time as needs and resources change, such as when children are born, parents move in, residents age, or new technology and styles become available.

The housing industry must change to meet these new needs. It must catch up with other industries that have already embraced mass customization. The homeowner of tomorrow should be able to expect a personalized solution that allows for changes and upgrades over time. They should be able to take advantage of new technology to help manage energy and resource conservation, health, communication, and learning within their home. This should be possible at high quality and reasonable cost.

1.2 Market Situation

Unfortunately, housing has continued to be built in a craft manner much the same way it was hundreds of years ago. This lack of improvement in the manufacturing process has severely

limited the industry's ability to improve its product. The cost of housing has continually risen, as quality has fallen. Resources and labor have become more expensive, and the inefficient craft system is not well equipped to deal with these problems. The shortage of skilled labor is identified by more than 80 percent of US contractors as the most significant challenge facing the housing industry over the next five years [1]. Compounding the labor shortage problem is the industry's heavy dependence on labor. According to experts in the industry, on-site labor can account for up to 80% of the cost of a stick built home while only 20% is spent on materials produced off-site. Part of the reason so much labor expense is necessary is that craft based on-site labor is inefficient and expensive. In addition, the labor is divided into guilds: the framers, the painters, the electricians, the plumbers, etc., who all work in something less than harmony, often causing each other to perform rework and in general spend more time than should be necessary.

Developers have responded to this crisis by adopting prefabrication and by building a more uniform product. Prefabrication techniques transfer some of the construction to a controlled factory environment, and a more uniform product decreases the amount of learning required to put up a house. The combination of these solutions leads to repetitive "cookie-cutter" houses. Most consumers cannot afford an architect to custom design their house for them, so they are forced to accept the "cookie-cutter" house. The result is no one really gets what he or she wants. Furthermore, developers are still unable to provide a high level of quality or make reliable cost and time predictions. Another factor preventing personalization in homes is scheduling. Even if the high cost of customization could be overcome, the current approach would still not allow personalization, because homes are designed long before the customer is present. A typical housing development project can take many years to design. Governmental permitting and construction bidding require that key decisions be made about unit layouts, fire alarm locations, electrical outlets, wheel chair access, etc., long before an occupant is present. With no individuals to design for, developers simply strive to hit the center of their market.

As for remodeling, conventional construction systems (including current prefabrication methods) simply cannot allow for any significant change without becoming even more expensive and more labor intensive. In order to modify an existing structure it must be demolished and replaced. This system is clearly inefficient from both a materials and labor point of view, but is unavoidable within the current method of building. Despite these difficulties over \$450 billion was spent on remodeling in 2002 alone, demonstrating that change is so important that it is undertaken extensively despite difficulty and cost [2].

To complicate matters the current housing industry is non-centralized and resistant to change. The total market is very large, new construction for 2003 is at a seasonally adjusted annual rate of \$328.5 billion as of March, but most construction firms are small regional operations, and even the few large firms tend to operate in a regional manner competing with numerous firms in each region [3]. This limits the efficiency of pre-fabrication by keeping quantities low. Furthermore, unions and small companies see change as a threat to their livelihood and will do whatever they can to keep things the way they are. Any significant increase in efficiency will most likely lead to a decrease in jobs, causing an outcry from unions. From the developers point of view construction already has a huge monetary risk factor, and change causes even more uncertainty.

In summary, the consumer is facing an industry that provides an expensive, low quality product, with no opportunity for choice, and upgrade and change only at great expense. Furthermore, there is very little technology used during construction or installed in the typical house. This lack of technology and the difficulty of installing technology after construction leads to a missed opportunity to meet needs such as energy and resource conservation, health maintenance, communication, and education. Worse, is that after construction the average consumer has nowhere to turn when something goes wrong. Should they complain to the real estate agent, the developer, the builder, the manufacturer? Despite the plethora of options, in the end no one cares about their problems and they are forced to hire someone else to come and fix mistakes the others made.

Fortunately there are some opportunities for the market. Computer aided design and manufacturing offer as yet untapped efficiency gains. Computers and the Internet can also help improve communication channels. Players who formerly had no contact could now offer information to each other. For example, the consumer could communicate their needs directly to a component manufacturer, rather than having the information be modified and confused as it travels through the real estate agent, to the developer, to the builder, to the architect, to the manufacturer. New materials are also available that have been largely ignored by the construction industry due to fear of change. One of the most significant types of new materials available may be low cost electronics, allowing for cheap sensing and computation, which could offer benefits both during and after construction.

1.3 Project Goals

The consumer needs and market situation outlined above clearly demonstrate the necessity for a new approach to residential construction. This approach must allow for mass customization and adaptability to tailor the home to the needs and values of each individual. It must allow new technologies to be easily incorporated into the house to meet needs such as energy and resource conservation, health maintenance, communication, and education. It must be efficient and compel the production of a high quality product. Furthermore this new approach should provide for the branding of components to give the consumer a quality and style reference.

The customization of the house should efficiently provide a level of choice that would be equivalent to a made to order solution for the vast majority of the population. In order for the system to be efficiently manufactured it cannot allow for all designs, but it should allow for a large enough variety to meet the needs of almost all consumers. This variety and choice should allow for independent change of the following aspects: size, layout, exterior aesthetics, interior aesthetics, technology, and energy efficiency.

Adaptability is strongly related to customization. A system that can be customized must also allow for change to provide for resale, and a system that can easily be adapted can be customized using the same method. The system developed must be able to reconfigure to meet changes on a daily, monthly, yearly, or lifetime basis, and allow easy upgrade to new technologies as they become available. The homeowner may get married or have children, they

may come into money, or they may simple have a change in stylistic preference, and of course when a space is sold it should allow for the new owner to re-customize it to their preference.

There are millions of dollars and hours being spent developing new technology to help solve problems like energy and resource conservation, health maintenance, communication, and education. Unfortunately even old technologies are not being taken advantage of in the average household. This lack of technology penetration has a number of aspects, but one of the main issues is that incorporating technology into homes is costly and disruptive, often resulting in obtrusive fixtures and damage to existing structures and finishes. Furthermore, because traditional homes do not incorporate a data backbone, every system must have its own data network. From the doorbell to HVAC control to computers to security systems everything runs on separately installed wires and hardware. A new system should provide a platform that allows technologies to be easily integrated into the home in a non-disruptive, non-intrusive manner. This platform should also provide for as much sharing of infrastructure as is feasible.

The scarcity of skilled labor and the complexity of typical construction have led to serious lapses in quality. A new approach should allow for an overall decrease in labor component of building cost, reversing, or at least correcting, the 80/20 labor ratio. Furthermore, the system should allow for most of what labor remains to be performed in the controlled environment of a factory, and should be divided by functional components rather than guilds. The on-site labor should therefore be minimized and simplified. All necessary labor should be as formulaic and straightforward as possible. It should not require extensive training or skill. These criteria will allow quality to increase while keeping cost low.

A factory-manufactured system will also offer the opportunity for strong branding. Branding of homes or home components would help the consumer to accept the new product, and would provide them with a clear accountability path. Imagine BMW enters the home industry. Consumers who associate their own values with BMW would now be much more likely to purchase a manufactured home. Also, it would be very important to BMW that the quality of the home live up to their name. They would ensure that a quality product was being sold and they would provide good customer service when things went wrong. Most likely they would even provide a warranty.

All of the criteria mentioned so far are already of concern to the housing industry. Unfortunately, shackled by the current manufacturing method, they are unable to bring them into proper balance. So, another way of looking at this system is that it should allow companies the ability to better balance the above dimensions of design with cost and each other: customization (size, layout, aesthetics, technology, energy), adaptability/upgradability, new technology, quality/performance, and manufacturing and assembly efficiency/speed.

The solution will likely come from outside of the housing industry, because the industry is so set in its ways. It must then be easily taken up and built upon by multiple firms in a profitable manner. This thesis presents work being done towards this end in the MIT Media Lab's Changing Places consortium, or House_n.

Chapter 2: Theory/Rational

2.1 Historical References

“The problem of our epoch is the problem of the house.”
Le Corbusier (1919)

Over the past century many great architectural thinkers have addressed the problem of reinventing the way houses are built. They have noted the advances in other industries and suggested that they might be applied to homes, or merely found insight in houses themselves and how their inhabitants interact with them. Overall they have agreed that the moderately priced house presents an important and difficult problem.

In 1923, Le Corbusier, perhaps the greatest architect of the 20th century, wrote, “A new epoch has begun...we must create the mass-produced spirit. The spirit of living in mass-construction homes. The spirit of conceiving mass produced homes [4].” No doubt he was responding to the success mass-production had brought the automobile industry and others.

Mies van der Rohe added detail to Le Corbusier’s statements in 1927, “Economic reasons demand the rationalization and standardization . . . If one limits only the kitchen and bathroom as standardized rooms . . . and the remaining living area with movable walls, I believe that any justified living requirements can be met [5].”

Frank Lloyd Wright, the designer of some of America’s great and innovative homes offered this about the homes of those who could not afford his designs, “The American small house problem is still a pressing, needy, hungry, confused issue . . . The house of moderate cost is not only America’s major architectural problem, but the most difficult for her major architects [6].”

These men and others saw that while most architects were content to focus on the needs of the rich, there were important things that could and should be done for the average homeowner. These men were proposing that great design and quality in a home could be brought to the masses through industrialization just as Henry Ford brought the automobile to the masses with the Model T.

2.2 Past Efforts

Almost as long as there have been visionaries posing the problems of the house there have been inventive colleagues proposing solutions. Unfortunately, there has been little lasting change to the industry. However, there are important lessons to learn from these attempts, both in why they were proposed and why they did not have an enduring effect. In understanding them it can be seen that due to recent research and industrial advancements there now exists an opportunity for a new approach to succeed.

Buckminster Fuller created the Dymaxion House as the vessel in which the people of the future would live, Figure 2.1. He said, “We are blessed with technology that would be indescribable to our forefathers. We have the wherewithal, the know-it-all, to feed everybody, clothe everybody, give every human on Earth a chance [7].” While the Dymaxion House did not become the typical home it brought up important issues. For example, that a single aesthetic style, how ever well thought out, cannot be successful over the long term and across the population. It may seem obvious that it cannot, but influential people have continued to create systems meant to be the perfect design.

In 1957, in conjunction with MIT, Monsanto conceived of another perfect home unit that could be sprinkled across the world to meet everyone’s needs, Figure 2.2. It was the Disneyland Home of the Future, and that was where it stayed, one of many “homes of the future” doomed by its single-minded approach.

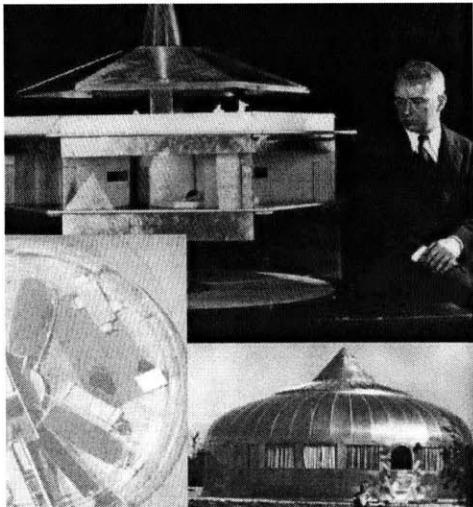


Figure 2.1 The Dymaxion House
Buckminster Fuller’s masterpiece, the Dymaxion House, made important architectural and technological strides, but failed to become popular, because it only provided for a single aesthetic.

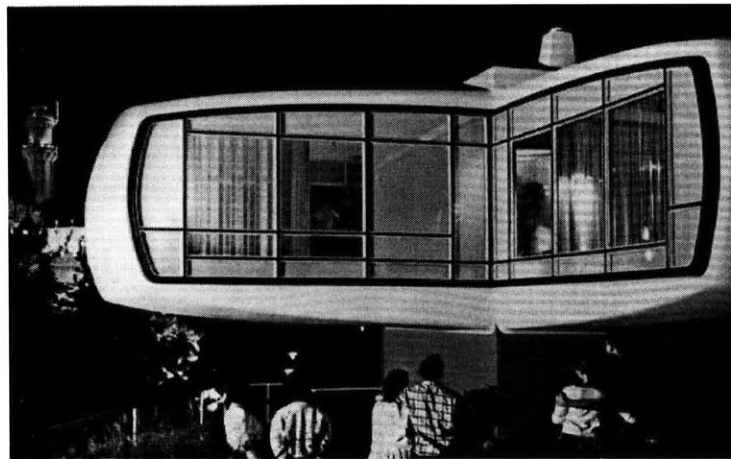
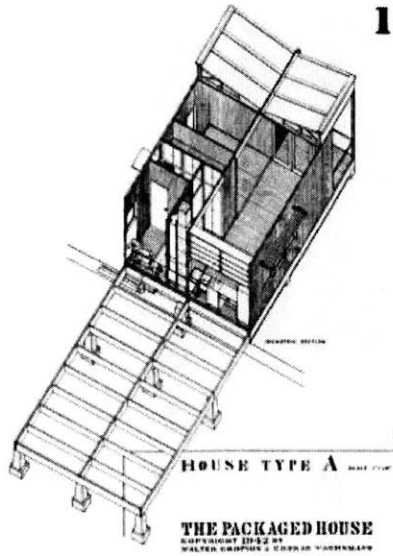


Figure 2.2 The Disneyland Home of the Future
The Monsanto Disneyland Home of the Future again showcased new products, technologies and exciting architectural ideas, but also could not meet the needs of the public, because it did not allow for variation.

In contrast, Walter Gropius developed the Packaged House in the 1940’s, Figure 2.3. It was a factory based, mass-production system to manufacture highly customizable homes. He wrote, “It is by the provision of interchangeable parts that (we) can meet the public’s desire for individuality and offer the client the pleasure of personal choice and initiative without jettisoning aesthetic unity [4].” He had created what Corbusier and others had extolled. It failed spectacularly. He built a factory designed to produce 10,000 houses per year. Unfortunately they quickly discovered the system could not economically offer customized solutions. Personalized homes took far too long to design, and custom manufacturing created a logistical nightmare that the factory of 1945 was not prepared to deal with. Eventually the company was forced to only produce a few standard models that looked cheaper than a conventional home, cost more, and offered less personalization. When the company shut down, less than 200 homes had been produced [8]. Other postwar industrialized housing efforts were similarly unable to

overcome the seeming contradiction of a mass-produced, customized home. They either did not have the resources and design to produce a sufficiently flexible system, or their design and manufacturing was made so complicated by their attempts to make any design possible that it was too expensive to succeed.

Gropius / Wachsman
 General Panel
 Packaged House
 (1942-1946)



I

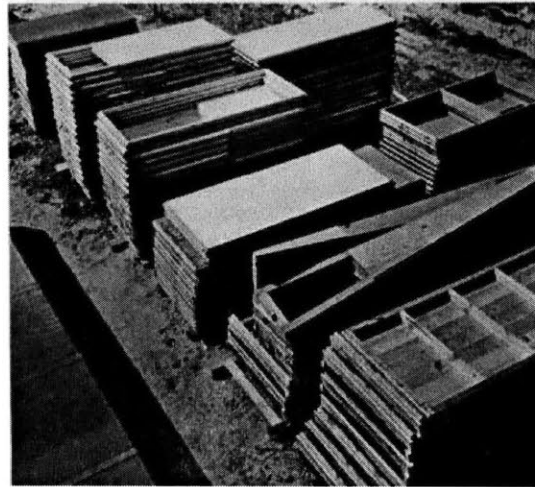


Figure 2.3 The Packaged House

The Packaged House was an extremely ambitious, well intentioned attempt to bring the advantages of mass-production to the construction industry. Unfortunately, the industry of the 1940's was ill prepared to deal with the difficulties presented by manufacturing a customized product. The result was a product which looked cheaper, cost more, and was actually less flexible than conventional construction.

Twenty years later John Habraken, chair of the MIT Department of Architecture from 1975-1981, conceived a much more sophisticated approach to provide manufactured homes. At the time industrialized housing faced problems of relentless monotony, no occupant input in the design process, and perhaps most striking: a failure to benefit from industrialization. Habraken proposed a radical new approach, dividing the home into two parts: support and infill. He described support as the communal part of the building containing the structure, services, etc., and infill as the private portion of the building that is tailored to the needs of the occupant and changed over time. Habraken's influential book, "The Systematic Design of Supports" led to what is now called Open Building [9]. Open Building is popular today in the Netherlands, Japan, and Finland, but its adoption has been hindered by the major changes in the design and construction process it requires, and by the use of proprietary systems and sub-systems that often result in increased construction cost.

From these efforts it can be seen that improving the way housing is built is not a task to be taken lightly. The solution cannot rely on a single aesthetic or a manufacturing system that is

beyond the abilities of the current industry. Furthermore, even with a well-conceived approach it may not be possible for a single company to provide the variety and capacity to be successful. Fortunately the advanced computer assisted production facilities of today are capable of producing products in great variety without great cost and new ideas which provide for many companies to work together in an open source manner may finally allow the industry to change. The Internet, computer assisted design, CNC machine tools, advanced supply chain management, six sigma, just in time production, new materials, new production techniques, and other tools and ideas position the industry to succeed where it has failed in the past.

2.3 Current Products

There are a wide variety of products currently available which approach some aspect of the chassis + infill agenda. Unfortunately, none of them achieve all of the goals of this proposal and most are not very successful.

The most popular of these systems in the United States have been those that address the shortage of skilled labor. Modular construction is one such effort. Modular construction moves most field operations to the controlled environment of a factory, eliminating weather concerns and allowing more efficient quality control. This industry represents 7% of the total US housing market [10]. Modular homes are built in large three-dimensional sections, which are typically 95% complete when they leave the factory [11]. The modules are then trucked to the site and placed on a permanent foundation by a crane. These homes are generally indistinguishable in quality and appearance from conventionally built homes. Unfortunately, part of being indistinguishable from conventional homes is not offering an efficient method for adapting over time or for integrating technology. Also, these homes are not able to provide the consumer with a customized solution, usually offering even less choice than traditional site-built options. Despite being manufactured in a “factory,” these homes still do not take advantage of many of the technological and organizational advances that are in use in other industries. Essentially the homes are “stick built under a roof” using many of the same manual methods that are used by their site-build counterparts [12]. One of the biggest problems is finish work. Studies have shown that 55% of all factory labor is used for finish, and 70% of all rework is finish related [13]. Even worse is that a great deal of time is still spent performing on-site finish work, missing one of the most important opportunities of modular building, reduction in delivery time due to greatly reduced on-site finish work [14].

Another method is to use smaller modules and assemble them on site. This is referred to as panelized construction. Roof trusses, wall frames, and Structured Insulated Panels or SIPs fall into this group. ASBS, Bardon, Enercept, and Precision Panel are some of the companies in this area. Again, this solution attempts to address the labor shortage by moving some of the work into a factory. Unfortunately because this system is also entrenched in site-built methods, the gain in efficiency is nowhere near what it could be with a system designed specifically for this method of construction. As well, the most complex and problematic field operations are still performed on-site, in the conventional manner, such as: installation of windows, doors, exterior and interior finishes, drywall, and all mechanical, electrical, communication, and plumbing systems. Furthermore, these systems only address labor concerns. They do not provide for

customization, adaptability or the incorporation of technology. The building produced is generally generic, fixed once built, and low tech.

There are also a variety of interesting structural technologies, which may offer benefits for reducing labor or customization and adaptability, but they are not systems approaches. In order to be effective they need to be designed into a complete building approach. These technologies include prefabricated concrete forms by Reward, engineered wood framing by companies such as International Paper, inflatable tubing tent systems by Aerotube, and aluminum extrusion framing by 80/20, Bosch and others.

There are a few complete building system approaches, but they tend to produce either non-customized unchangeable buildings or temporary structures that cannot be used as a permanent residence. Metalfit produces a prefabricated system using laminated wood framing for structure, and insulated panels for walls. This system provides for simple construction, and some customization. Unfortunately it produces a building that is fixed once built, uses traditional finish techniques, and does not provide an efficient method for dealing with utilities or technology. A company called Shelter Systems produces fabric skin buildings which use prefabricated structural elements and are quick and easy to assemble on-site, but the system does not allow for services, and is only usable as a temporary structure. Perhaps the most advanced system available today is produced by Specialist Structures. The system uses aluminum extrusion for structural members, and prefabricated snap in panels between structural elements. The system incorporates clip on raceways for power and data systems, and does not require any on-site finish. The system can be easily transported and quickly assembled. Unfortunately, it is non-permanent, non-residential, does not allow for an integrated HVAC system, and can only provide a very specific non-mainstream aesthetic.

The labor crisis and the inability of the current housing industry to provide customization, adaptability, and quality, makes a shift to an advanced manufactured system approach inevitable. No system currently exists which fills this void, but there have been many steps in the right direction. It is only a matter of time until a sufficiently developed system emerges which can meet the need of both manufacturers and consumers by taking advantage of current technology and industrial concepts.

2.4 Hypothesis

To efficiently provide customized and adaptable housing a system must be developed that carefully applies principles of modularity to a manufactured product. In order to achieve high quality at low cost the system must be manufactured. However, the fact that the system is mass-produced cannot be allowed to hinder customization and adaptability. Figure 2.4 illustrates how taking a consumer focus leads to the goals of mass customization and adaptability and how in turn those goals lead to the need for modularity. It is important to note that modularity is not a reference to modular housing as it currently exists or to “standard building modules”, but a reference to modularity as it is used in the automobile and computer industries (among others) to achieve variety and the ability for upgrade without sacrificing cost. The consumer demands personalized solutions, which are too expensive to provide unless the manufacturing system is mass customization. The consumer also wants to be able to modify their living space as their

needs or resources change or simply for re-sale purposes. Therefore, the system must be adaptable. Embodied in the definition of mass customization is that a completely integrated mass produced product can never provide the necessary level of choice to truly enable customization. For example, it is clearly impossible to successfully manufacture 100 million completely different products. However, if the product were made up of only 8 modules and there were 10 options for each module then there would be 10^8 or 100 million possible configurations. For comparison, there are about 100 million homes in the United States, and around 1 million new homes built every year. This is why modularity is both necessary and sufficient to provide mass customization. Adaptability requires modularity to allow for non-destructive change. If walls can be moved and replaced, then it is no longer necessary for remodeling to begin with demolition. Figure 2.4 also references “open source”. This is a crucial component of the Chassis + infill concept. Having the system be open source means that many companies will be able to work separately on various parts of the system with confidence that the system will function as a whole. This is made possible through standardized interfaces. This is crucial to providing the variety of modules necessary for true customization. Economic and political realities in this industry prevent one company from being able to produce the entire system on their own. This can be cited as the reason some earlier attempts at mass-produced housing mentioned above were unsuccessful. This concept is explained more fully in section 2.5.

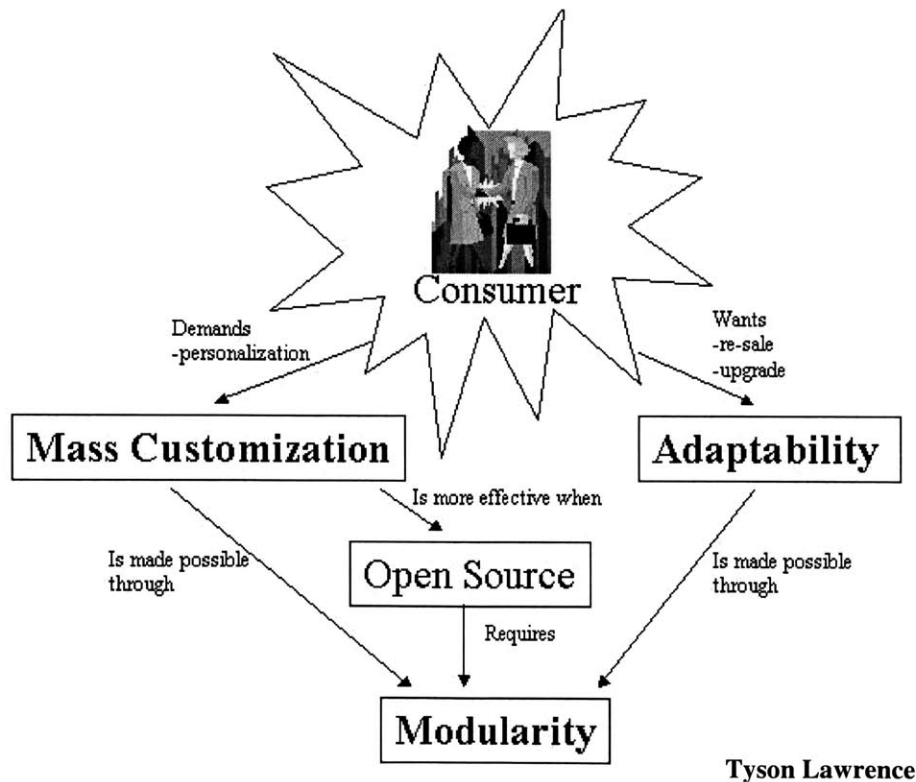


Figure 2.4 Hypothesis Flow Chart

The system takes a consumer-driven approach. This leads to the recognition of needs that lead to the goals of mass customization and adaptability. Mass customization and adaptability require modularity to be successful, and making the system open source allows for greater variety.

It is clear that the system should incorporate modularity, but if this division into modules is not handled carefully the system can very quickly become too complicated and expensive to be feasible. For this reason the building is first divided into two main notional components: chassis + infill. The chassis is the standardized, mass produced part of the system and provides the structure and services. The infill is the customized part and makes up the walls and floors and parts of the building the homeowner sees and interacts with. Figure 2.5 illustrates this division showing photographs of the parts of a typical home, which would fall into each area. On the left, the chassis includes the structure, power systems, data network, and HVAC distribution in one integrated structure; plumbing is also handled in the chassis, but in a different manner than the other components. The chassis is standardized and uniform from building to building allowing it to be mass-produced and allowing the infill that attaches to the chassis to be interchangeable between buildings. On the right, the infill is the wall and floor components of the home. The infill creates spaces, defines the interior and exterior aesthetics and finishes, and contains the technology to be used in the home. The infill is what defines the home for the user, the chassis merely contains the, always necessary, behind the scenes support structure. There are infinite possibilities for types of infill. They could be constantly innovated by competing companies, and, as long as they maintain the standard interface to the chassis, be interchanged with and used beside older modules and modules from other companies.

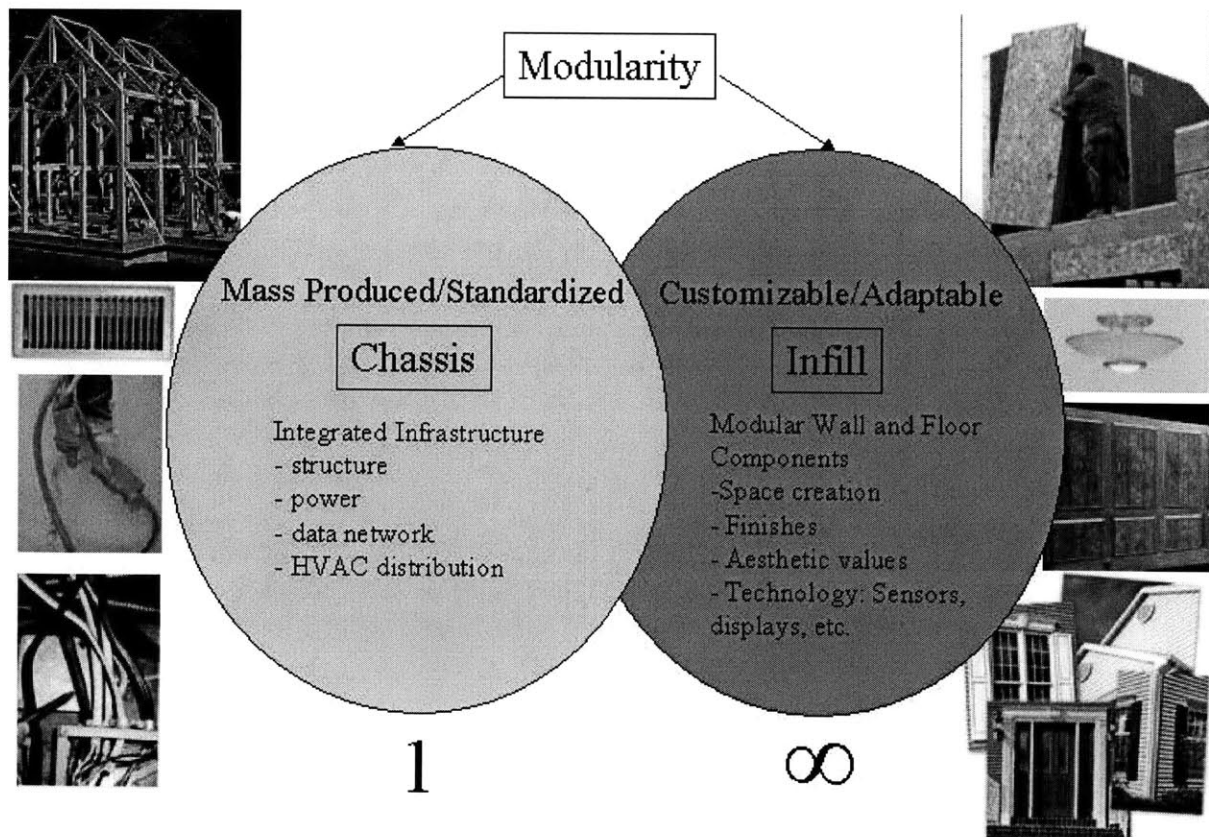


Figure 2.5 Chassis + Infill Modularity

The home is divided into two main notional components: Chassis + infill. The chassis is the standardized, mass produced part of the system and provides the structure and services. The infill is the customized part and makes up the walls and floors and parts of the building the homeowner sees and interacts with.

Tyson Lawrence

2.5 Open Source

One of the great new ideas in industry that the housing industry should leverage is the concept of open source. The open source operating system Linux has proven that a complex system can successfully evolve without the control of a single entity, and still be stable. By creating standard interfaces or ports, and dividing systems into modules and providing everyone with as much information as possible the system can be modified and augmented without disrupting the core or kernel.

This concept has also provided success to the computer hardware industry. By dividing the system into components by function, and creating standardized interfaces between those modules, a host of benefits have been reaped. First, components may be mixed and matched to meet individual consumers' needs and preferences. Dell computer exploited this opportunity to become the world's largest PC manufacturer. Furthermore, the separation into modules allows hundreds of manufacturers to independently innovate their products with confidence that they will successfully integrate with products from other companies. As long as the standardized interface is maintained, devices may have any function, and any implementation.

In the automobile industry, well thought out modularity is becoming a key to success. Integrated modules, for example the entire dashboard display and control, provided by tier-1 suppliers that are interchangeable across vehicle platforms, allow for lower defect rates, more options, and lower cost. GM is examining the logical conclusion of this concept with Hy-wire, a fuel cell concept that places all of the mechanical systems into a standardized chassis, which can then be used for all vehicles. Interchangeable body components, seating, and user interface technology allow each car to be customized by individual and by purpose. Separating the car into modules by purpose rather than trade or material allows mass customization to be provided in an efficient manner, because, when customization takes place, only the specific interface must be exchanged rather than some larger part of the system. In the worst case of a completely mass-produced product to change anything the entire product must be exchanged. This is the situation the car industry is trying to move away from. Currently they must produce two entirely different products to provide a cargo bed vs. seating, etc.

The home should also be divided into components by function. The primary division is between the support systems that are always needed and the parts of the system the user interacts with and might want to change. This division was described extensively in Section 2.4. It is chassis + infill. This division allows the chassis to be a mass-produced, integrated commodity product providing the home with structure, and services. The chassis, or at least the connections between it and the infill, are standardized. The infill allows for customization and innovation, there are infinite possible types of infill. Not only does the infill not need to be defined now, it should not be. Because the interface is standardized the infill can be allowed to take shape over time in hundreds of independent shops and factories. In the following chapter an example chassis will be described in detail to demonstrate that such a system can be created. The infill that works with this chassis is technically simple and is intentionally left open-ended because the potential range is infinite.

The open source building approach allows the players in the industry to operate more independently, focusing on their core-competencies. The modularity of the system decouples one player's decisions from the others, allowing everyone to work more efficiently. Manufacturers can focus on perfecting their component and offering options the consumer wants. Building designers can focus on the unique programmatic and environmental context of a building without being concerned with the engineering. Most importantly occupants can concentrate on tailoring their environment to their needs and values. The additional cost, risk, and coordination errors normally associated with "one-off", highly engineered structures are avoided because the system itself is engineered, so each individual solution doesn't have to be.

2.6 Functional Requirements

The Axiomatic Design approach was chosen to organize the design of this complex system. First, the system was approached as a whole, and then the chassis was examined in more detail. Axiomatic Design organizes design into domains. The customer domain, functional domain, and physical domain are the most important in this case. The records in each domain are customer needs or attributes (CA's) in the customer domain, functional requirements (FR's) in the functional domain, and design parameters (DP's) in the physical domain. The theory is also ruled by two axioms. The axioms are formally stated as:

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

Axiom 2: The Information Axiom. Minimize the information content of the design.

Using the construct of domains and the two axioms, the design can be fully described and defined. The functional requirements spring from the customer needs, but it is important to note that they are not the customer needs. A customer need is stated as what the customer wants, the functional requirements are what the product must do in order to meet the customer needs. The design parameters are the key physical variables that satisfy the functional requirements.

The customer needs address the function of the entire system. Figure 2.6 shows the high level, system wide, customer needs, functional requirements, and design parameters. It is important that these functional requirements are necessary and complete. They must fully define what the system must do without violating the independence axiom. These functional requirements and associated design parameters may then be decomposed into layers of greater detail. Eventually the functional requirements and design parameters will reach leaf nodes and cannot be decomposed any further. Each leaf node corresponds directly to a physical attribute of the system. Figure 2.7 lists the first level of decomposition of FR's and DP's relating to the chassis and chassis to infill interface [15].

Customer Need 'Ideal' residential experience		Functional Requirement 'Ideal' residential space		Design Parameter Conscientious design	
CA1	Personalized solutions	FR1	Mass customization	DP1	Modular design
CA2	Change over time	FR2	Adaptability	DP2	Reconfigurable
CA3	Solve information problems	FR3	Technology infrastructure	DP3	Accessible accommodation
CA4	Trouble-free ownership	FR4	High quality	DP4	Superior construction
CA5	Physical protection	FR5	Physical strength	DP5	Structural components
CA6	Comfort	FR6	Controlled space	DP6	Mechanical system

Figure 2.6 Customer Needs, Functional Requirements, and Design Parameters

The design of the chassis + infill system is described in terms of what the customer needs, what the system must do to meet those needs, and the physical characteristics of the system that will allow it to meet those functional requirements.

FR1 Mass customization 1.1 Flexible physical approach 1.2 Consumer driven design 1.3 New business relationships FR2 Adaptability 2.1 Daily/Monthly change 2.2 Yearly change 2.3 Lifetime change FR3 Technology infrastructure 3.1 Power distribution 3.2 Data distribution (100mps) 3.3 Space for sensors 3.4 Power connection anywhere 3.5 Data connection anywhere FR4 High quality 4.1 High-quality materials 4.2 High-quality design 4.3 High-quality manufacturing 4.4 High-quality assembly FR5 Physical strength 5.1 100lbs/sqft –floor 5.2 900lbs/ft –beam vertical 5.3 97,200lbs –column 5.4 400lbs/ft –beam horizontal (wind) FR6 Controlled space 6.1 Limit effect of external temperature 6.2 HVAC distribution 6.3 Keep out water	DP1 Modular design 1.1 Chassis + Infill 1.2 Computer design platform 1.3 OSBA DP2 Reconfigurable 2.1 Reconfigurable infill 2.2 Movable infill 2.3 Movable chassis DP3 Accessible accommodation 3.1 Power raceways 3.2 Data raceways 3.3 Sensors in infill 3.4 Electrical busway 3.5 Data on busway or wireless DP4 Superior Construction 4.1 Pultrusion (mold, pest, fire resistance) 4.2 Design for design 4.3 Design for manufacturing 4.4 Design for assembly DP5 Structural components 5.1 U-floor components 5.2 Structural pultrusion beam section 5.3 Structural pultrusion column section 5.4 Structural panel to beam attachment DP6 Mechanical system 6.1 Insulation 6.2 5"x12" duct 6.3 Weather Seal
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Figure 2.7 FR's and DP's 1st Level of Decomposition Affecting the Chassis

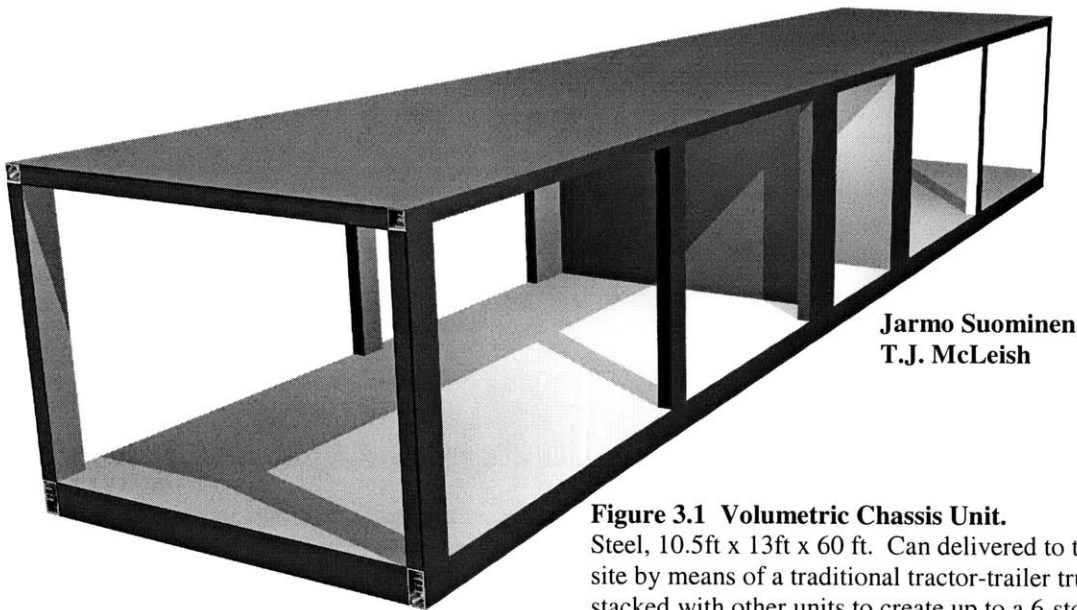
The chassis must meet a great many functional requirements. This list shows the first level of decomposition of these functional requirements. A few design parameters such as 5"x12" duct may appear to be leaf nodes, but in fact there are further FR's associated with that DP. For example, the duct must travel vertically and horizontally, it must turn corners, everywhere it must be sealed, and it must be accessible for cleaning.

Chapter 3: Extended Examples

The functional requirements developed in the last chapter led to the development of two example systems. The two systems address the consumer needs and market situation in unique ways to provide solutions in different sub-markets. However, they are based upon the same basic theory.

3.1 Volumetric Chassis

The first example addresses the multi-family apartment or condo market in buildings, typically three to six stories tall. This is becoming an increasingly important market in the residential industry as land becomes too expensive in many areas for single-family homes to be economical. Manufactured systems are already being applied in this market, but not as effectively as they could be. Because the proposed system is similar to some of what is being done in the industry already it could be implemented in the very near future, perhaps in one to two years.



Jarmo Suominen,
T.J. McLeish

Figure 3.1 Volumetric Chassis Unit.

Steel, 10.5ft x 13ft x 60 ft. Can delivered to the building site by means of a traditional tractor-trailer truck and stacked with other units to create up to a 6-story building.

The chassis in this case would consist of a 10.5ft x 13ft x 60ft box unit, Figure 3.1. The chassis unit is a uniform, factory manufactured, component. It provides the structure to the building and has integrated services installed in the factory, such as plumbing, electrical wiring, data wiring, floor and ceiling components including finishes, and attachments for exterior façade elements. The size of the unit is chosen to provide a typical room size on each side of a double loaded corridor. The size is also affected by the need to stay within highway transportation limits. Further, when two units are placed next to each other there is enough space underneath for two rows of three parking spaces with two-way traffic between. This last point is very important, because almost all building of this type incorporate parking, and many are required to do so, Figure 3.2.

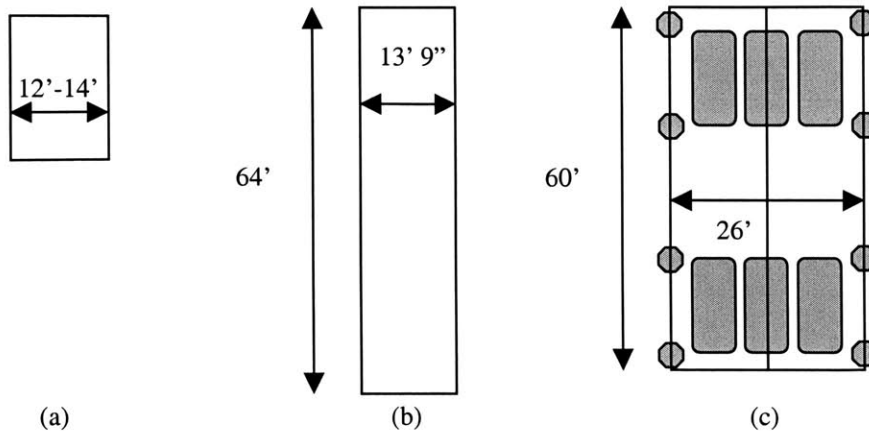
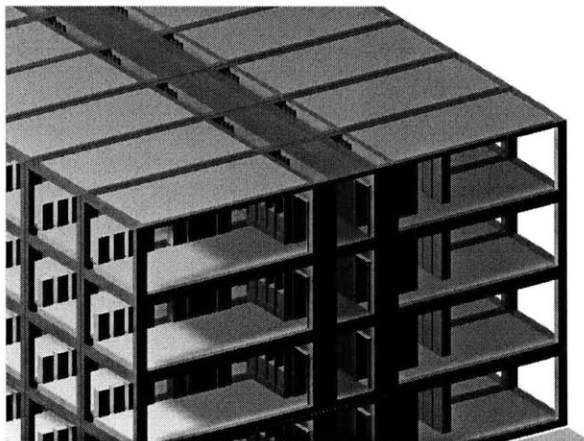


Figure 3.2 Volumetric Chassis Unit Rational

(a) shows a typical room size, (b) shows the government restriction for transportation on the highway without a permit and escort, (c) shows the space required to park 6 cars with 2 way traffic between. The combination of these three module sizes leads to the 13'x60' module shown in Figure 3.1.

To build a building from these units they are trucked to the site on standard tractor-trailer trucks and then simply stacked next to and on top of each other, Figure 3.3. Exterior façade is then applied to protect the building. This construction process is not unique; in fact it is growing in popularity in this market and others. Figure 3.4 shows a hotel being built using this same method by Deluxe Homes of Pennsylvania. Deluxe uses this technique extensively for everything from hotels to single family houses. Unlike the systems used by Deluxe and other builders, the chassis + infill system allows for customization, and easy reconfiguration. While typical modules are delivered to the site with the interior completely fitted out, usually including finishes, the chassis unit is delivered without any interior walls or finishes aside from the corridor walls, which double as wet walls for the kitchen and bathroom. This allows the owner of the building to wait until a buyer is present to decide the size, interior layout, and finish of each apartment or condo, Figure 3.5.



Jarmo Suominen

Figure 3.3 Volumetric Chassis Building.

Chassis units are stacked to build a building shell, leaving the interior to be fitted out with infill once a buyer is present to provide customization information.

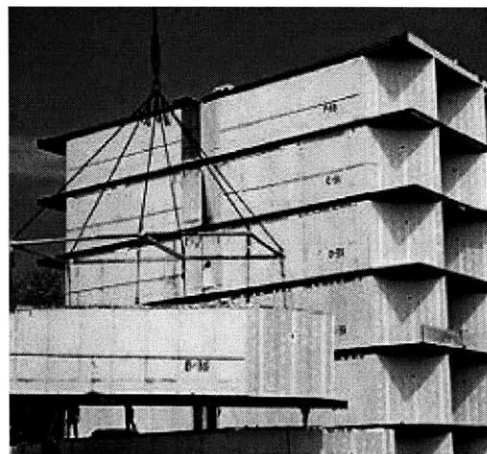


Figure 3.4 Deluxe Homes Hotel.

Completely finished hotel units are stacked to build the building. The interior is fixed at the factory months or years before the building is finished.

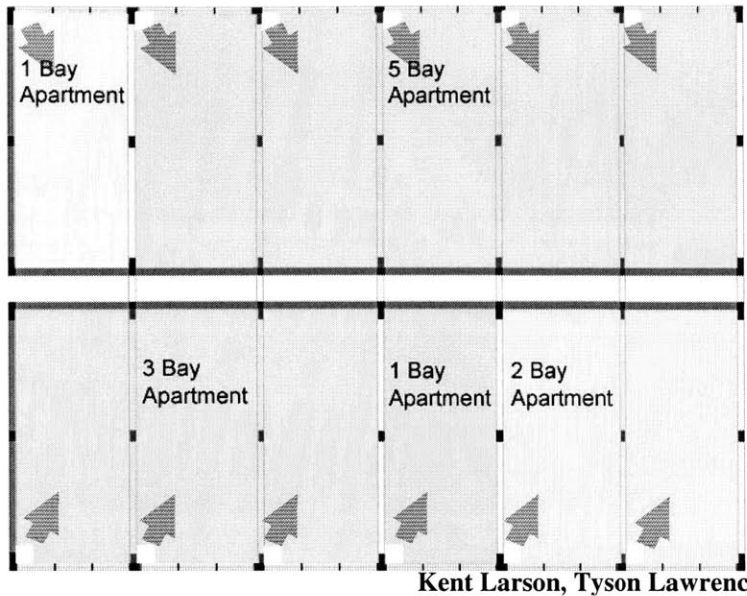


Figure 3.5 Volumetric Chassis Apartment Division.

Size of apartments can be customized by placing a demising wall between any two chassis units. Each side of every chassis unit is served by it's own highly efficient distributed HVAC unit.

An example of a possible customized apartment is shown in Figure 3.6. As can be seen in the picture, even double height space is possible by purchasing two units above one another and removing the intervening division.



Kent Larson, Tyson Lawrence

Figure 3.6 Volumetric Chassis Example Apartment.

Once the buyer is present they can customize the size and appearance of their apartment, even purchase a double height space.

Aside from leaving the interior to be customized once the buyer is present the chassis + infill system is also unique in its efficient handling of the necessary utilities. All of the utilities are installed into the chassis units in the factory, and the infill are simply plugged in and unplugged for reconfiguration. The chassis units are connected to exterior utilities by vertical shafts with a single connection point for each chassis unit and no utility connections between chassis units. Within the unit all of the plumbing is concentrated on the “wet wall” which is the corridor wall installed in the factory which also serves to provide shear strength to the structure. The kitchen or bathroom is simply attached to this wet wall where necessary with simple connectors. This does fix the bathroom and kitchen on the corridor wall, but that is always the

case in all but the most extreme designs. The other utilities are run throughout the space through the steel beams that make up the structure of the unit, Figure 3.7. A power bus provides an easy attachment to provide infill walls with power and low bandwidth signal. High bandwidth signal may either be wireless or run through a provided raceway and plugged in where needed. The space also contains gas and hot and cold water piping to a distributed water heater/air conditioner/heater unit, placed at the exterior façade for venting reasons. In the space that is left, ductwork can be placed for ventilation and heating/cooling, and, if desired, light fixtures.

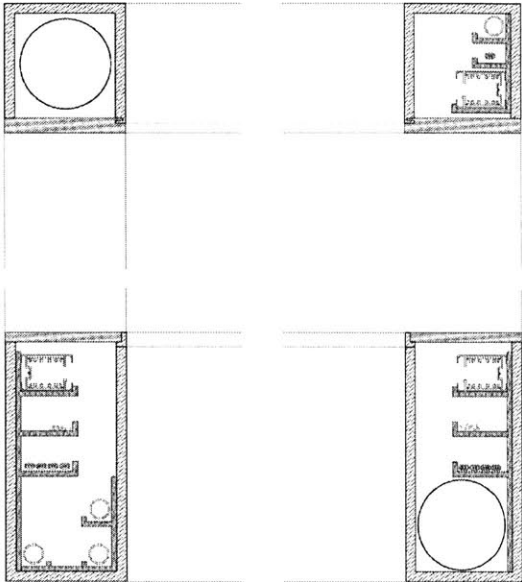
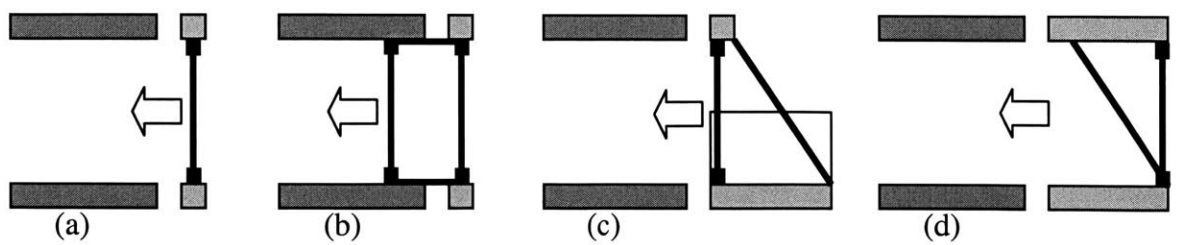


Figure 3.7 Volumetric Chassis Integrated Utilities. All of the utilities are integrated into the structural chassis unit and are installed efficiently and easily in the factory. In this diagram, representing a single unit apartment, the top left beam of the chassis unit holds a duct to carry air from the HVAC unit to the interior space. Below that duct, in the lower left beam, hot and cold water, and gas are run to the HVAC unit. The lower left beam also carries an electric busway for easy power and low bandwidth signal connections, as well as raceways for power and high bandwidth data wiring. The bottom right beam carries the same electrical and data distribution systems for infill on the other side of the apartment, and an exhaust vent for removing air from the living space. The top right beam carries the same busway to serve fixtures in the ceiling, a power raceway, and piping for the sprinkler system.

T.J. McLeish

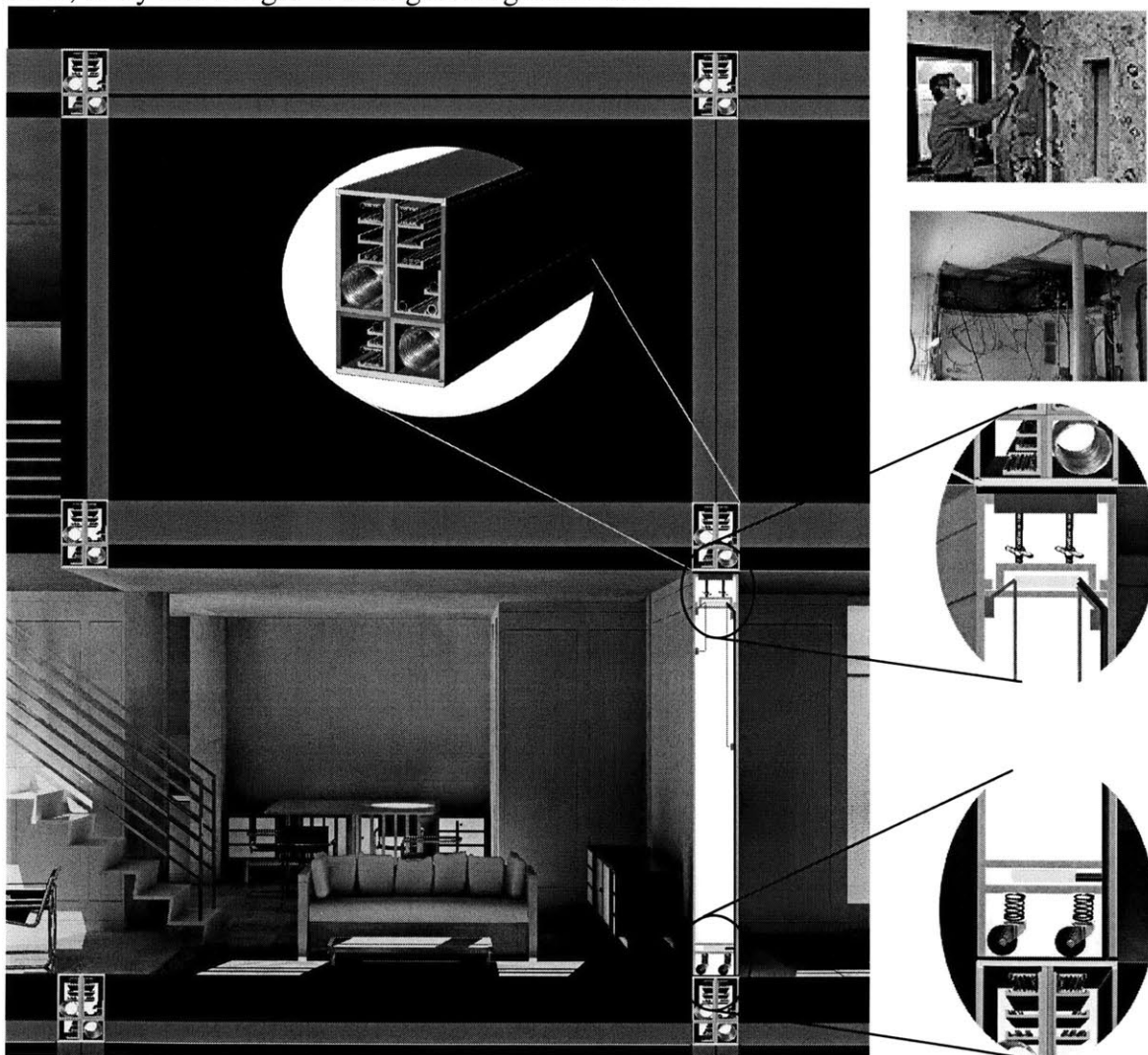
When the building is built the exterior façade would be sealed to protect the interior from the elements. However, the exterior façade modules would be removable and customizable at the time of purchase for an extra fee, due to the need for a crane. Multiple apartments could be customized at once to reduce the cost. The modules would attach by means of cleats at the corners of each chassis unit. These cleats would allow for flush window modules, stepped in greenhouse units, balconies, or stepped out room extensions of up to six feet, Figure 3.8.



Tyson Lawrence

Figure 3.8 Exterior Module Possibilities. (a) Flush window module, (b) Stepped in greenhouse unit, (c) Balcony, (d) Stepped out room extension, up to six feet.

The interior of each apartment would be fit out quickly and inexpensively by using infill modules designed specifically for this purpose. These infill could come in a wide variety of shapes and sizes as long as they fit in the specified ceiling height, and had standard connectors for attaching to the power bus, or wet wall when applicable. They might include walls, cabinets, doors, counters, fixtures, and appliances. All interior infill would be brought up by means of the elevator and rolled or carried to their assigned location. They would be fixed in place in a secure but non-permanent manner to allow for easy reconfiguration. One possible type of infill is illustrated in Figure 3.9, with two pictures of a traditional wall being moved for contrast. In this particular case a wall is shown that can be rolled into place on integrated casters. The wall is then fixed in its location by simple screw jacks, which press against the ceiling and force the casters to compress up inside the bottom of the unit on springs. The infill may be connected to power and data by directly attaching it to the bus in the chassis structure, to specified plugs in the floor, or by attaching it to a neighboring infill unit.



Kent Larson, Tyson Lawrence

Figure 3.9 Interior Infill Example.

In this example an infill wall component has integrated spring mounted casters, which allow it to be wheeled into place. Once it is in the desired location screw jacks are applied which press against the ceiling compressing the wheels into the body of the unit and fixing the wall in place. To move the wall again simply release the screw jacks and roll it to its new location. Two pictures of how a typical wall is moved are shown for contrast.

The only part of the interior that would not come as a small, easily movable unit is the bathroom module. Because the bathroom is generally fixed by the location of the wet wall, is not moved in almost all reconfiguration scenarios, and is a fairly complex area of the living space. It is more economical to make it a single large module that is installed in the factory. What this means is that, similar to the exterior wall module, the bathroom may only be modified by the use of a crane, for an additional fee. Figure 3.10 show several possible layouts using the same bathroom location illustrating that in most scenarios the bathroom is not changed.

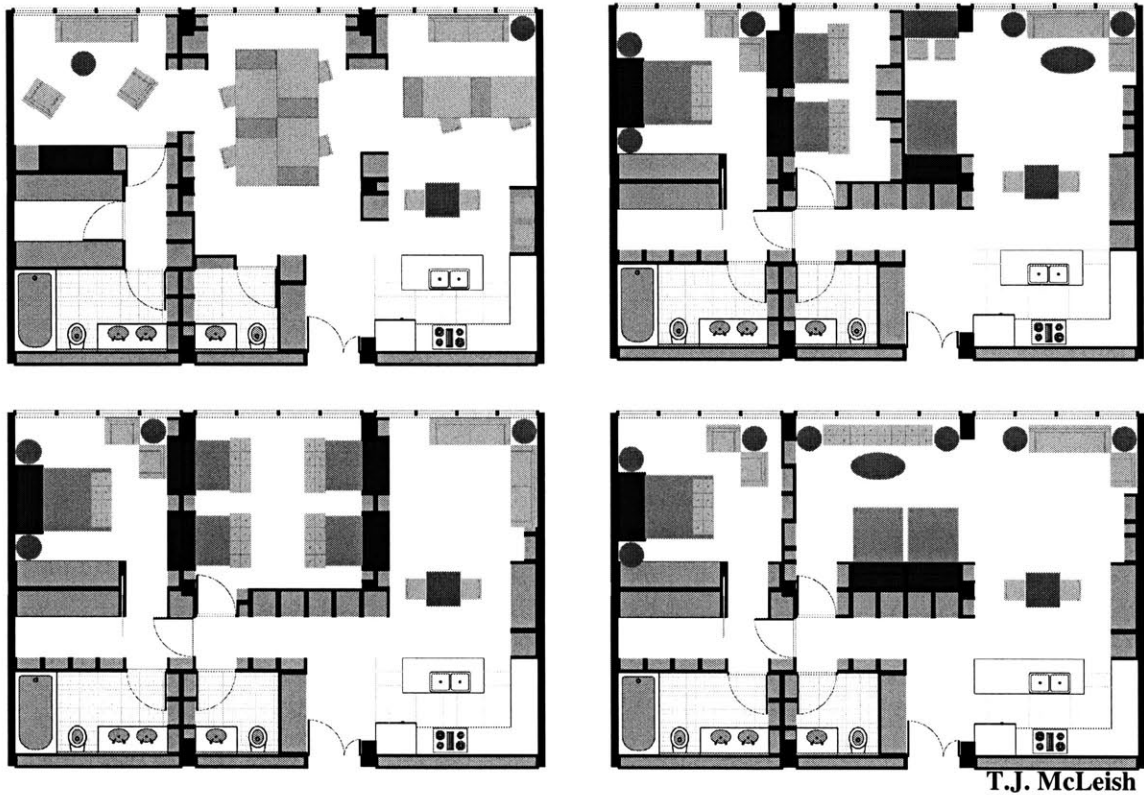
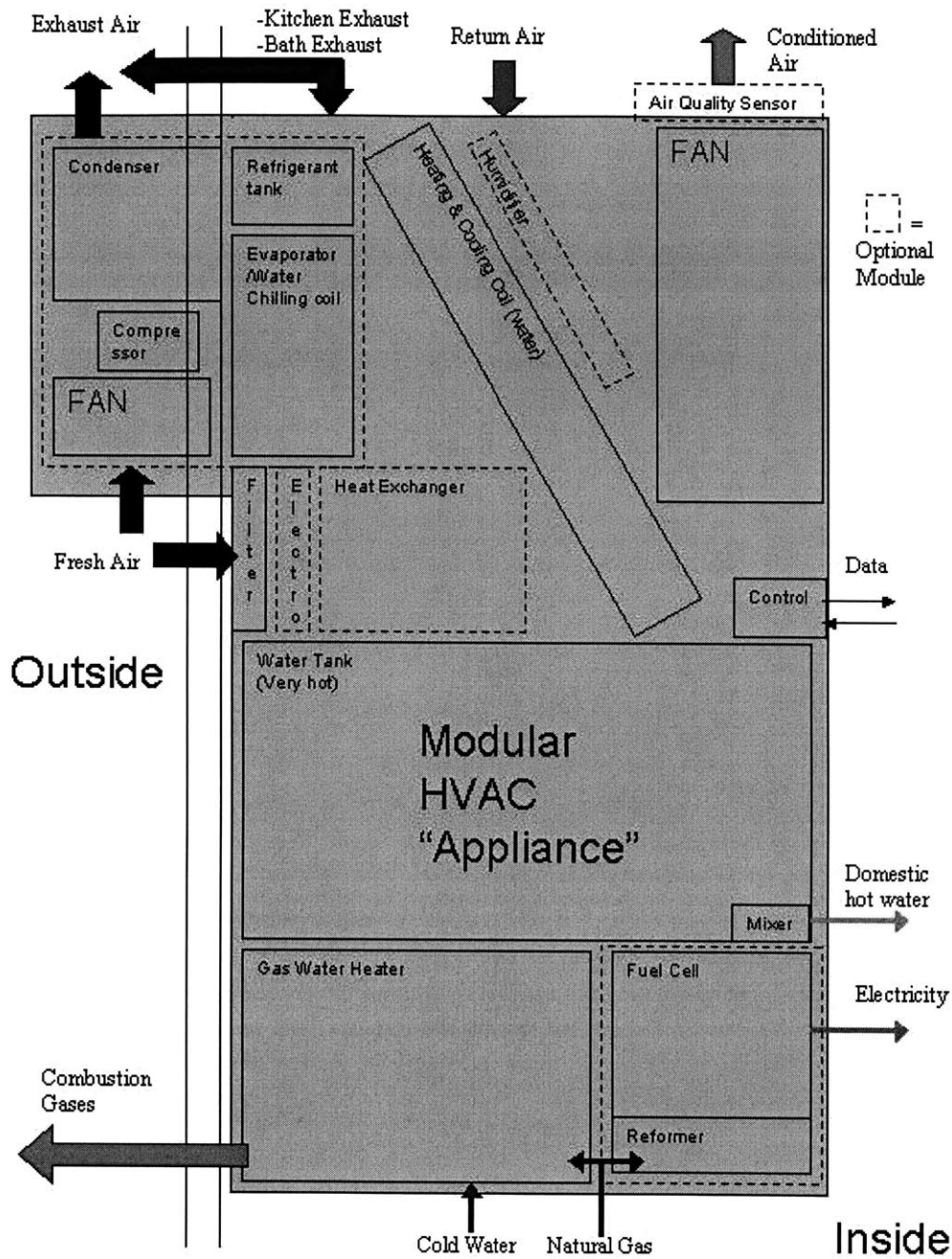


Figure 3.10 Bathroom module example layouts.
All of these layouts use the same bathroom despite significant custom differences.

The mechanical system for each chassis module is installed in the factory, and consists of small, distributed units, one on each end of every chassis unit. These modular HVAC appliances are just large enough to heat and cool the space on one side of the chassis unit and can provide enough hot water for one bathroom or kitchen. The integrated HVAC and hot water unit is approximately two feet square and eight feet tall and is located at the exterior face of the chassis box for ventilation. Gas and cold water are carried to the unit and hot water, and warm and cool air is carried from the unit, through the chassis structure. A diagram of the integrated mechanical system is shown in Figure 3.11.



Tyson Lawrence

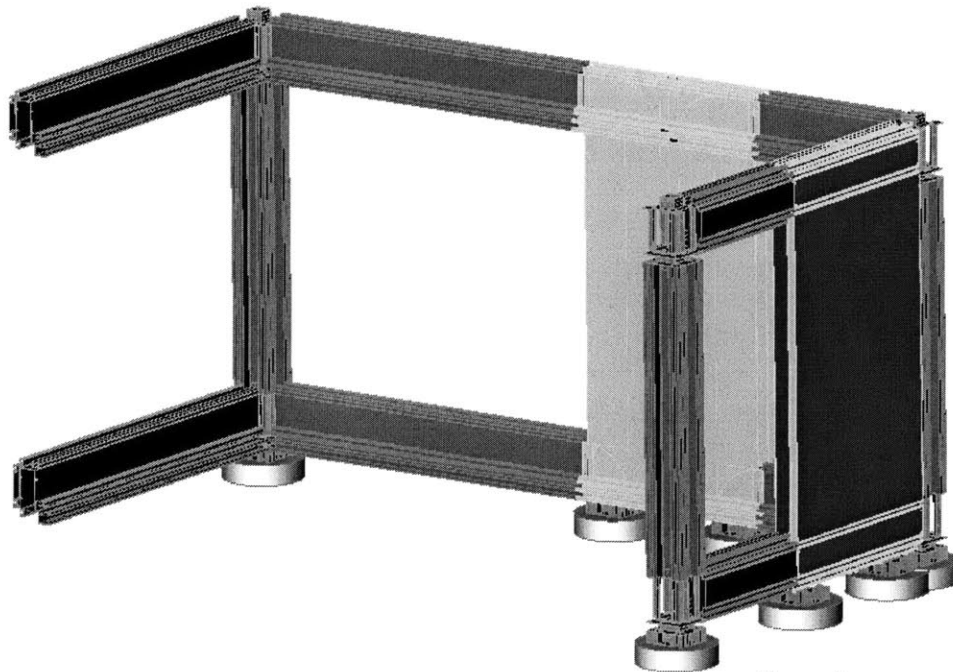
Figure 3.11 Modular HVAC Appliance.

This is a schematic diagram of the proposed distributed HVAC/hot water unit. Products that approach this are currently on the market, but nothing that is exactly right. The system could even include a fuel cell to provide some electricity to the apartment, and harvest the naturally generated waste heat to help heat water.

3.2 Post and Beam Chassis

The second example system addresses the single-family home market in buildings from one to three stories tall. This system could be extended to other markets including small multi-family dwellings or other structures less than four stories tall, but it is primarily designed with the single-family home in mind. By dividing the structure into smaller pieces, the post and beam approach allows the overall layout of the building to be customized as well as the interior floor plan and exterior façade. This system offers greater opportunity for customization, but in turn it is more complex and requires more on-site labor. Because the approach is a significant departure from what is currently practiced in the market it is a more long-term concept, perhaps 10-20 years out.

The chassis in this case would consist of columns (posts) and beams, Figure 3.12. The material of the chassis is a pultruded polymer reinforced by glass fibers. Pultrusion is a process similar to extrusion, but with the material pulled through a die rather than pushed through. The pultrusion was chosen for its resistance to environmental conditions and its high strength to weight ratio. Because the beams and columns are pultruded they may have a complex shape without significantly increasing the cost and they can be easily cut to any length as they emerge from the die.



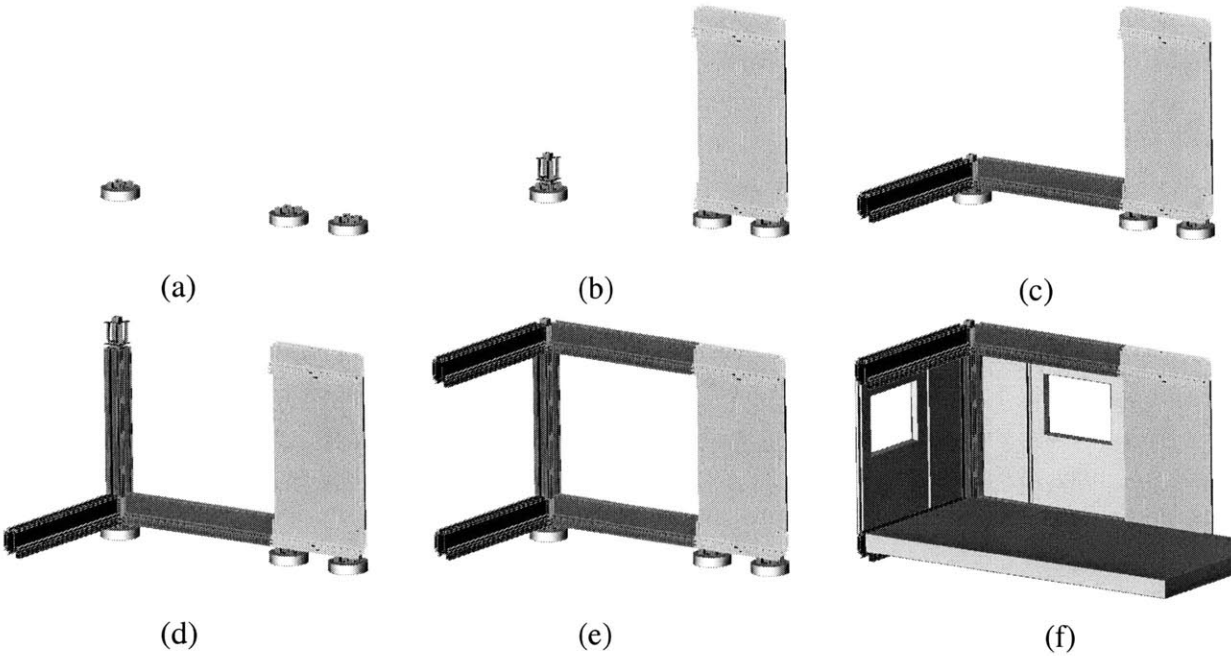
Tyson Lawrence

Figure 3.12 Post and Beam Chassis.

The post and beam chassis is made up of columns (posts), beams, and connectors to attach the columns and beams to each other. The large panel structures are risers, which serve two functions. The first is to bring the services, which are embedded in the chassis beam, vertically. The second function is to provide diaphragm shear strength to the building, lessening the load on the connectors.

As can be seen in Figure 3.12 the beams and columns are linked by specially designed connectors. These connectors make a structural connection as well as provide for the continuation of the utilities, which are integrated into the beam. The large panel structures are risers, which serve two functions. The first is to bring the services that are embedded in the chassis beam vertically. The second function is to provide diaphragm shear strength to the building lessening the load on the connectors.

To build a home using this system a traditional foundation is laid. Slab, pilings, or a basement are all acceptable. Figure 3.13 (a) shows a piling foundation with attached brackets. Connectors and risers for the first floor are then mounted to the foundation by means of the brackets, Figure 3.13 (b). Beams can then be mounted between connectors or between connectors and riser panels, Figure 3.13 (c). Next, columns are added and second floor connectors are attached at the top of each column, Figure 3.13 (d). Second floor beams stretch from connector to connector or connector to riser, Figure 3.13 (e). Finally, infill panels are added to fill in the walls and floors of the building, Figure 3.13 (f), Figure 3.14.



Tyson Lawrence

Figure 3.13 Post and Beam Chassis Construction Steps.

(a) Piling foundation with attached brackets, (b) 1st floor connector and riser mounted to foundation, (c) Beams are mounted between connectors or between connectors and riser panels, (d) Columns are added and second floor connectors are attached at the top of each column, (e) Second floor beams stretch from connector to connector or connector to riser, (f) Infill panels are added to fill in the walls and floors of the building.

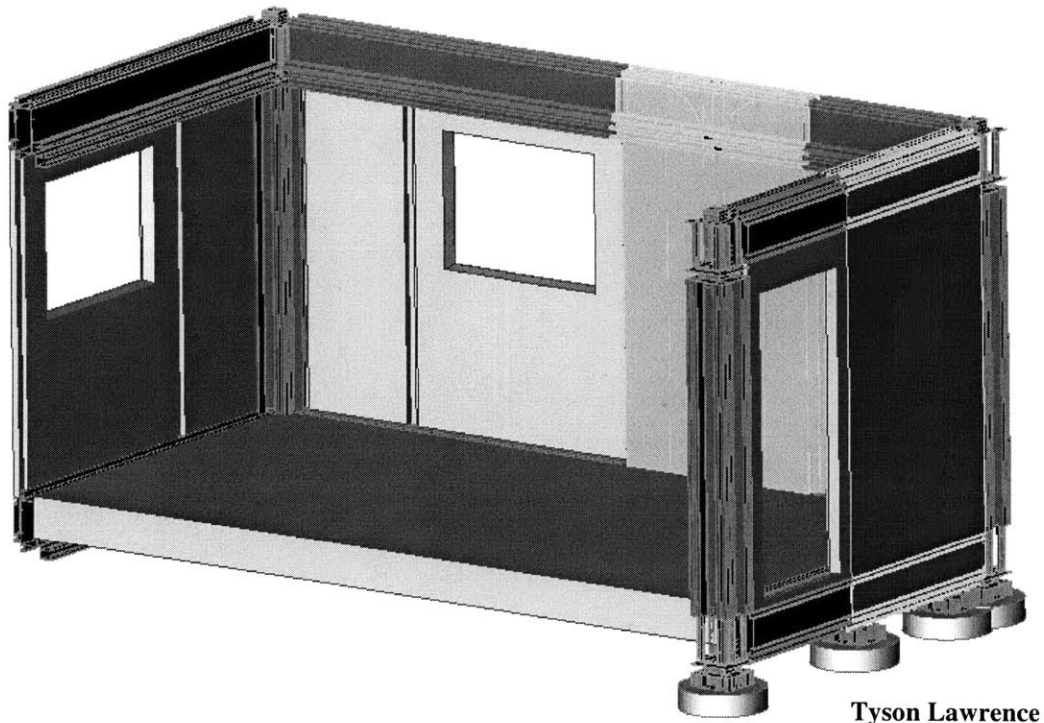


Figure 3.14 Post and Beam Chassis Building With Panels.

The infill panels finish the building and define the interior and exterior aesthetics. They can be made any width and attached in any location as long as their widths add to the length of the beam. In most cases panels would probably be one of a few standard sizes to allow for easy replacement and rearranging.

The key feature of this approach is that, like the volumetric chassis, the building is easily customized without a great deal of difficult on-site labor, and can be easily changed over time. This is possible primarily because the utilities and structure, which represent a large part of the expense in any building, are standardized and consolidated into the chassis. The other most significant building cost is usually finish work, which can be performed efficiently in a factory during the production of the infill.

The utilities integrated into the chassis consist of power wiring, a busway that provides power and low bandwidth signal, data wiring, and an HVAC distribution system. The chassis also must provide structure, insulation for the HVAC duct, physical connections for the attachment of infill walls and exterior façade, and weather seals and flashing. This is achieved with a carefully designed pultrusion profile, Figure 3.15.

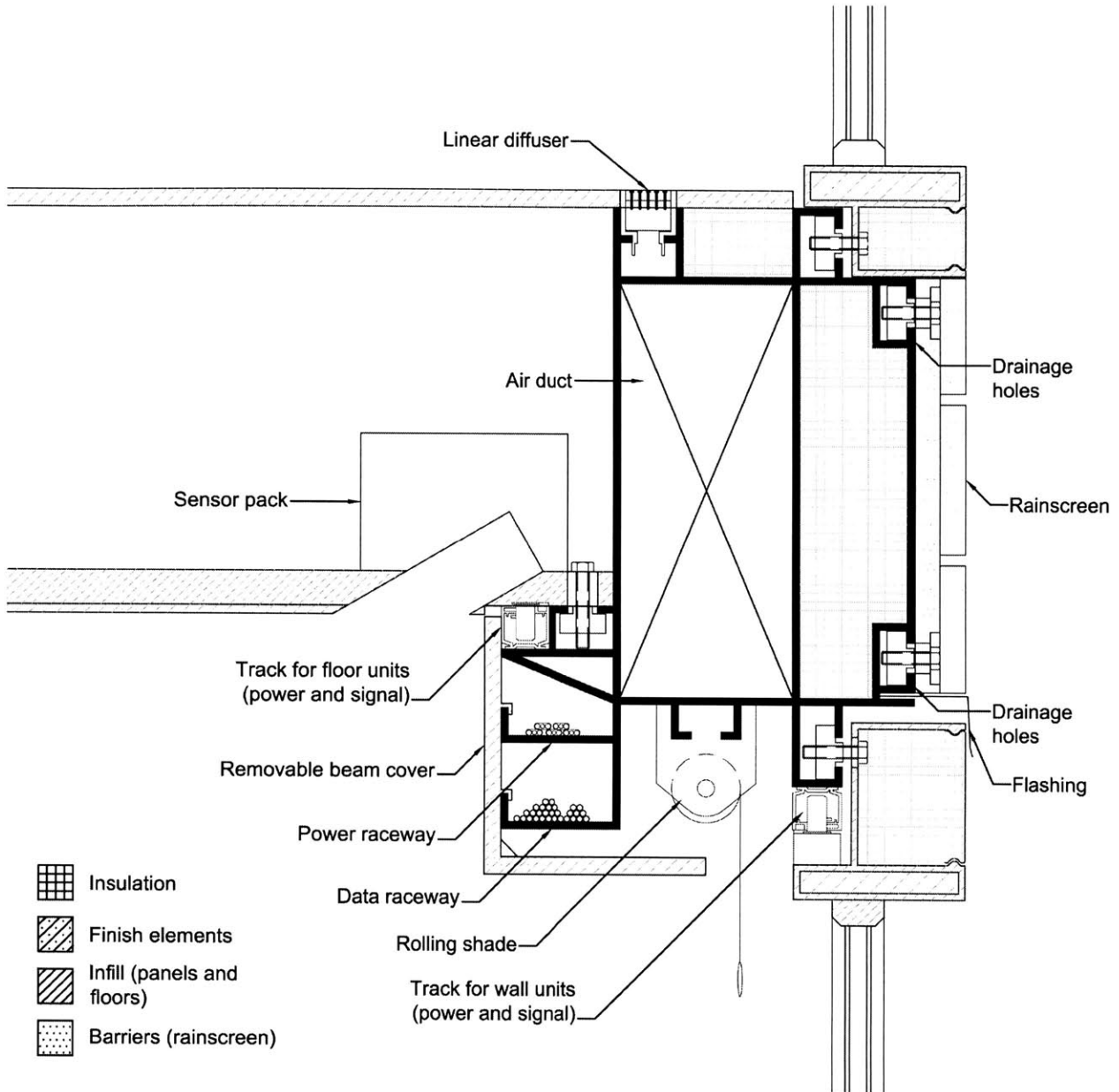


Figure 3.15 Beam Section

Stephen Form, T.J. McLeish

The beam provides structural attachment points for the infill floor and wall panels. The wall attachments are flashed and sealed to protect against water infiltration. The profile also provides an HVAC distribution system with a large duct space and a bracket for holding a linear diffuser. Power and data are brought throughout the home through provided raceways, and infill elements may be easily attached to power and low bandwidth data by means of tracks or busways.

The interior infill for the post and beam chassis would be the same as those used in the case of the volumetric chassis, except that the connection to the power and data bus would now be at the ceiling rather than at the floor, Figure 3.16. It would be very straightforward to design infill that would work in both instances. The exterior infill for the post and beam chassis is structurally attached to the beams above and below by four Hilti connectors. The bottom attachment is self flashed by the beam, and the top has an insertion point for flashing. In

addition to the flashing all joints would have neoprene seals to keep out moisture. The sides of the panels are bolted to each other by means of a small plate that completes the seal plane started by the two beams. The beam attachments are made from the exterior, but the panel-to-panel connections could be made from the interior to relieve any security concerns Figure 3.17 .

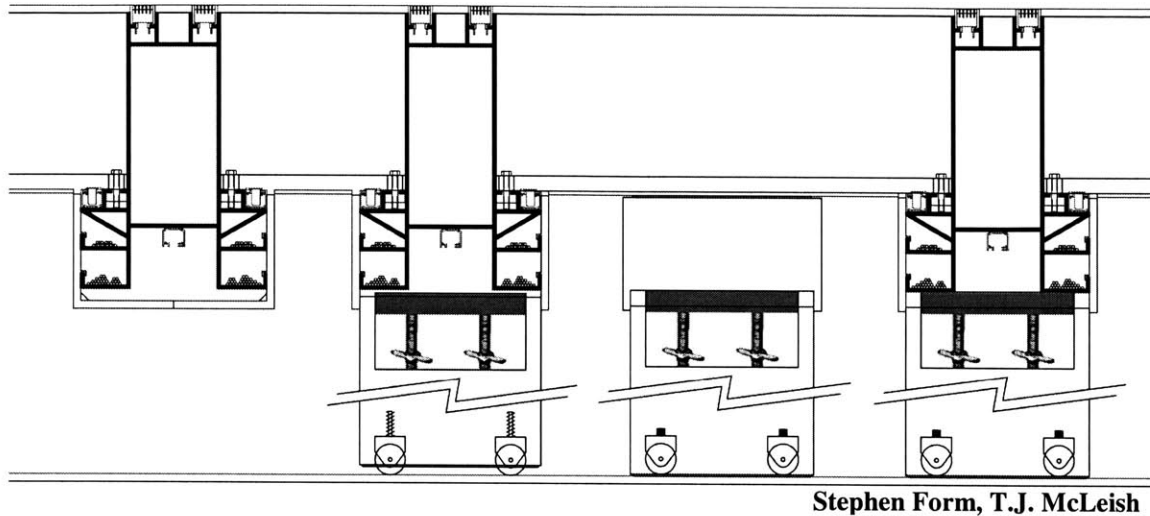


Figure 3.16 Interior Beam and Panel

The interior beam for the post and beam system is symmetrical, carrying power and data raceways on both sides, and supplying a central power and data bus for the attachment of interior panels. Interior panels attach in the same way they did in the case of the volumetric chassis, by pressing against the floor and ceiling. The only difference is that since the ceiling and beam height are not the same in this case, and adapter piece is necessary.

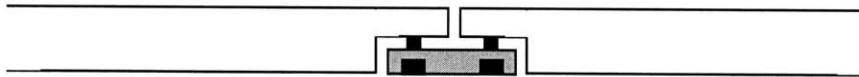


Figure 3.17 Panel to Panel Connection

The panels are attached to each other using the same Hilti pushbutton connector, shown in black. A plate which completes the seal plane started by the beams above and below is attached from the inside, shown in gray. This seal plate can be fastened from the exterior for ease of construction or from the interior for security, so that panels cannot be removed without prior access to the interior of the house.

Infill could range from plain walls to windows and doors to cabinetry and appliances. Infill could also range from completely fixed to very adaptable. One manufacturer may sell infill with interior and exterior finish installed permanently at the factory. Another may sell infill with removable interior and/or exterior finish. Infill might provide fixed power and data outlets, modular outlets that could be moved or swapped out, or no outlets at all. Some manufacturers may provide for hanging art and some may not. Infill might include technology like a television or microwave. Again, they could be permanent or modules that could be swapped out. All infill will be required to perform some basic functions, for example hold themselves up, provide acoustic separation, and in the case of exterior infill provide insulation and resistance to the elements. Ultimately, there is an infinite variety of possible infill and the market will show what types will be successful and which will not.

The concept of infill was explored in the Changing Places Consortium through the creation of a laboratory infill element to be installed in the PlaceLab. The PlaceLab is an apartment scale laboratory to examine subjects in the home environment. The purpose of the infill element is to provide a platform for a large number of sensors while also serving as normal furniture and not appearing “technological”. The result was a cabinet, which appears to simply be fine furniture, but in fact contains a large variety of sensing infrastructure, Figure 3.18. The cabinet contains a network of sensors and makes a power and data connection to the rest of the house through a single panel. The value of the chassis + infill concept became clear during this exercise. By decoupling the cabinet from the base building it was possible to build it separately in a more convenient location and then transport it to the site. This was useful for the prototype, it will be even more useful for the 15+ cabinets to be installed in the apartment lab. Furthermore, because it is designed separately from the structure of the building it may be replaced if necessary allowing for adaptability and upgrade.



Figure 3.18 PlaceLab Infill Cabinet

On the left the cabinet appears to be simply a fine piece of furniture. On the right the true nature of the cabinet is revealed as an enclosure for an extensive sensing infrastructure.

Chapter 4: Design Description

The post and beam chassis was chosen for a more detailed investigation, because it is the further reaching of the two systems. It more fully takes advantage of the theory and more completely meets the goals. However, the analysis for the volumetric chassis would have many similarities. As described in Chapter 2, the detailed infill design is purposely left undefined. The chassis and chassis + infill interface are the crucial elements that must be established to demonstrate that the approach can be a success. To meet the goals of mass customization, adaptability, and incorporating technology there are many things required of the chassis. The chassis must provide structure, power distribution, data distribution, HVAC distribution, insulation, simple assembly and disassembly, be able to create many geometries, etc. The chassis + infill interface must allow physical attachment anywhere, electrical attachment anywhere, data attachment anywhere, a reliable weather seal, etc.

4.1 Leaf node functional requirements

The design began by decomposing the high level functional requirements (discussed in Chapter 2) to find the leaf node functional requirements (FRs) that lead directly to physical attributes of the chassis. In the beginning the design parameters (DPs) were mostly choices waiting to be decided through discussion, research, calculation, and experimentation. The FRs and the DPs under consideration were listed along with analysis that could be used to help decide merit, references, risks, and countermeasures for each DP. A sample of this early stage functional requirement chart is shown in Figure 4.1. All of the charts can be found in Appendix A.

Functional Requirements					
Beam					
FR	DP	Analysis	References	Risks	Countermeasures
Carry weight of floor/roof and panels (100 Lbs/ft ²) (L/360 Acceptable deflection)	Pultrusion	find I, E, basic beam bending	mach. Hand	failure, creep, stress concentrations, holes cut for ventilation/plumbing	thicker walls, careful section design
	Steel, Aluminum protrusion	find I, E, basic beam bending	mach. Hand	cost, creep, stress concentrations, holes cut for ventilation/plumbing	thicker walls, careful section design
	natural resin	find I, E, basic beam bending	mach. Hand	failure, creep, holes cut for ventilation/plumbing	reinforce with multi-directional fibers?
	wood	find I, E, basic beam bending	Creative pultrusions	failure, creep, rot, holes cut for ventilation/plumbing	protect, overdesign
provide insulation (R-30 max DOE rec.)	1" aerogel	cabot	Kent	cost	assume mass prod.
	9.5" of Fiberglass	cabot	Kent	too thick	Increase beam size
Carry power (120V, 20A)	standard wiring in raceways	length req?	Kent, MIT elec	accessability /onsite labor	put wiring on inside under snap on cover
	separate with connectors	# of connectors?	Kent	cost	get standard conn. Assume mass prod.
	standard wiring in raceways	length req?	ken wacks kenn@alum.mit.edu	accessability /onsite labor	put wiring on inside under snap on cover
	separate with		ken wacks		get standard conn.

Figure 4.1 Early Functional Requirement Chart

The functional requirements were set, but the design parameters were as yet undecided. This chart included analysis, references, risks, and associated countermeasures that could be used to help decide the appropriate DP.

The components of the chassis are very limited. There is the beam, the column, and the riser. These are what must be defined. However, while the number of components has been kept low, there are still a very large number of connections and interfaces to deal with, as well as different scenarios for each. This is essential to creating a flexible system. The connections can be divided into two major groups, physical connections and service connections.

The physical connections are:

1. Beam to column (top) – straight wall, inside corner, outside corner, T, X
2. Beam to column (bottom) – straight wall, inside corner, outside corner, T, X
3. Beam to beam (no column) – inside corner, outside corner, T, X
4. Beam to foundation
5. Beam to panel (top)
6. Beam to panel (bottom)
7. Beam to finish
8. Beam to outer finish
9. Beam to floor
10. Beam to roof
11. Beam to riser
12. Column to panel
13. Column to finish
14. Column to outer finish
15. Column to riser
16. Riser to panel
17. Riser to floor
18. Panel to panel
19. Floor to Floor
20. Roof to Roof

Originally, some additional interfaces were also considered. For example, panel to finish, panel to outer finish, floor to finish, and floor to ceiling finish. These interfaces could be factory installed permanently, they could be permanently installed on-site, or they could be removable. Velcro was examined as a means of attachment. Clips were considered; even 3M removable adhesives were a possibility. However, because one of the main tenants of the system is that it would allow for a wide variety of infill, interfaces within infill should not be defined any more than colors should be. The only parts of the wall panels, floor, and roof that are defined are the edges at which they must interface with the chassis or other infill. The connections between infill must be defined to allow separately designed and manufactured infill to be installed adjacently.

The service connections the system must accommodate are:

1. Power (AC + DC?)
2. Signal – high bandwidth
3. Signal – low bandwidth
4. HVAC
5. Plumbing

This service connection list is a simplification, because it is only a list of the types of services, not the actual interfaces across which those services must connect. This is partly because at this point in the design it had not been determined across exactly which physical interfaces these service would need to run. Ultimately it was decided that the power and signal would need to bridge between the riser, beam, wall panels, and floors, including panel to panel connections. The HVAC would only span the riser and beam, and plumbing would go between the riser and floor only.

The following sections examine the physical attributes or design parameters the chassis must have to meet the six high level functional requirements of the system. The options considered and the decision-making process will be discussed for each attribute.

4.2 Mass Customization

In order to provide for mass customization the chassis must allow for many possible geometries. The chassis as designed allows any geometry within the following limits:

1. The geometry is rectilinear.
2. The building may only be up to three stories tall.
3. Beam spans may be any length between 3' and 15'
4. Ceiling heights are 9'
5. There must be one riser for every 300sqft, and risers should be evenly distributed and perpendicular wherever possible.

This allows for a wide variety of designs including the majority of homes available today and an infinite number of new designs. It does not allow for any design, but most designs that do not fit into these limits would already have been an expensive custom designed structure. This system is meant to meet the needs of the average consumer, so providing for eccentric designs is not necessary, and in fact should be avoided in order to keep the system as simple as possible.

The geometry must be rectilinear, because the connector, which manages the beam to column interface, only allows connections in six perpendicular directions, Figure 4.2.

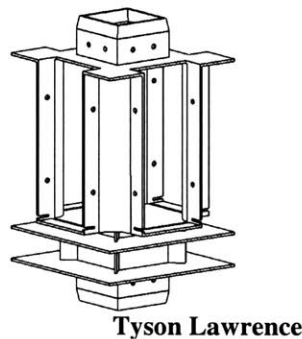
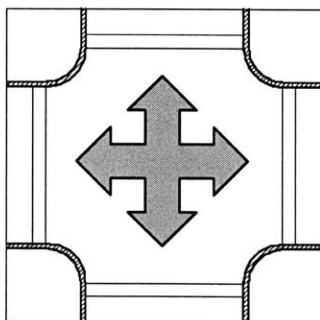


Figure 4.2 Connector Geometry

The connector only allows rectilinear attachment, limiting and defining what homes may be designed using the system.

It may be possible to create non-ninety-degree connectors, but for the initial introduction of the system only the one connector would be provided for simplicity. How the connector achieves continuation of the technology infrastructure will be discussed in section 4.4, ease of assembly and manufacturing in section 4.5, and continuation of HVAC and protection from the elements in section 4.7.

The limits on building height, beam span, and column placement are for strength and ease of assembly reasons, which will be discussed in sections 4.6 and 4.8. Beams may be easily created in any length because of the manufacturing process. As the finished beam is pulled through the mold it may simply be cut at the desired length. Because beams may be any length, and panels may be any width the beam must allow physical attachment anywhere. This means that the system cannot use point connectors such as ordinary bolts or rivets. Instead the beam incorporates T-slots similar to those used by 80/20 and Bosch aluminum extrusions, Figure 4.3.

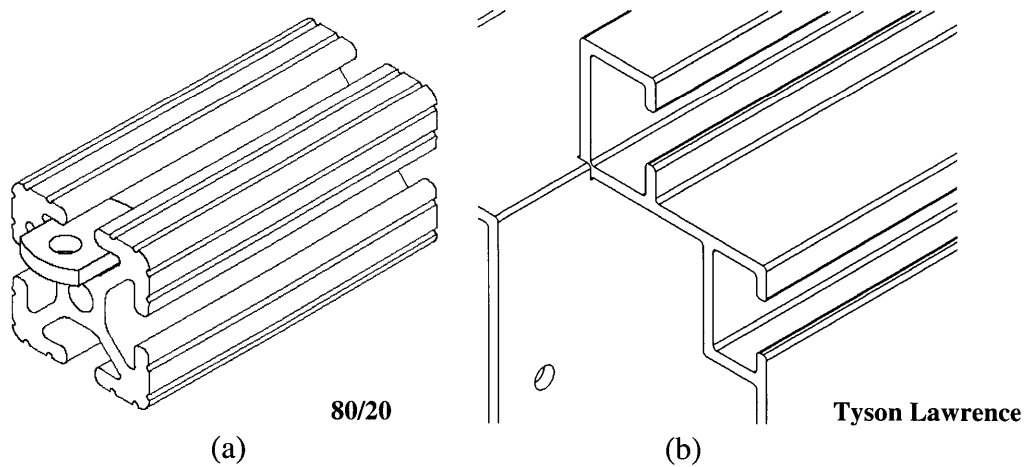


Figure 4.3 Beam to Panel T-slot

(a) An 80/20 aluminum T-slot extrusion, which inspired a similar structure in the chassis. (b) Two of the T-slots integrated into the pultrusion beam. The T-slot allows positive physical connection to be made anywhere along the length of the beam.

Columns are made using the same pultrusion process as the beams. The limit on ceiling height is set not because it is difficult to customize column lengths, but to allow panels to be interchangeable between buildings. Double height spaces are allowed.

The frequency of risers is dictated by a variety of factors, the area an HVAC duct can serve, the number of wires that should reasonably be run through beams, and shear strength requirements. The limiting factor is the HVAC.

4.3 Adaptability

To provide adaptability the chassis must be reconfigurable, even more importantly the connections between the chassis and infill must allow for easy reconfiguration of infill. Adaptability must take place on four time scales, daily, monthly, yearly, and lifetime. Daily and monthly change, for example changing an office into a bedroom, will be generally be limited to reconfigurable infill elements, because moving infill or chassis components would usually be too disruptive to do on a daily or monthly basis. Thus, the chassis is only concerned with yearly and lifetime change.

Yearly change might involve changing the sizes, position, or number of rooms. This requires infill components be moved, which means that the chassis and infill must be easily attached and detached. This is made possible by using non-destructive removable connectors. The connector that was chosen is the Hilti pushbutton MKN-FX, Figure 4.4. The pushbutton allows the infill to be removed and reattached by a single person with basic tools and access only from the front of the T-slot. The electrical and data connections between the beam and infill can be unplugged without disrupting the system. This will be explained further in the following section on technology infrastructure. If the desired change requires exterior panels to be moved inside, or visa versa, special panels which could convert from exterior panels to interior panels would be used, the creation of such a panel would be straightforward.

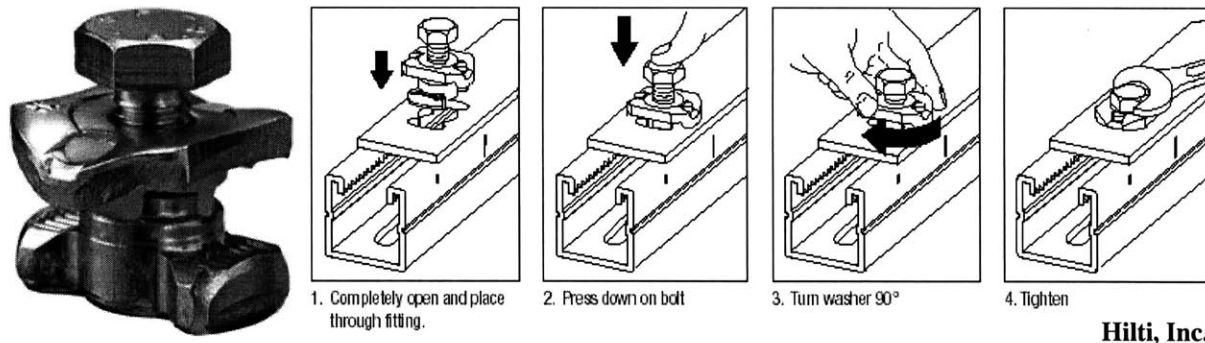


Figure 4.4 Beam to Panel Connector: Hilti MKN-FX

The MKN-FX pushbutton can be attached and detached with only basic tools and access from only one side.

Lifetime change would include major changes such as adding rooms or floors and other changes to the chassis. Change to the chassis is much more difficult and dangerous than change to infill because the chassis is providing the structure to the building. Using the same pushbutton fasteners to attach the beams and columns to the connector accommodates this kind of change. To make a change any part of the building supported by the chassis elements to be modified would first be removed or supported by a temporary structure. The chassis could then be physically taken apart much in the same way an infill panel is removed from the chassis. The power and data systems would need to be partially uninstalled, because there are no connectors at beam to beam interfaces due to labor, heat, and data loss concerns. So, to remove a chassis element wires would have to be cut or removed. However, it is an unusual circumstance that a chassis element is removed, most lifetime changes would not require any dismantling of the system, because they are generally additions not subtractions.

4.4 Technology Infrastructure

The technology infrastructure is becoming an increasingly important part of housing, as the home becomes the center for ever more complex activities including, work, entertainment, communication, health care, and commerce. These activities can be enhanced and improved by the proper use of various kinds of technology, but only if the necessary infrastructure is installed or can be easily installed. Homeowners are already demanding the parts of this infrastructure they understand. According to a forecast by Parks Associates market research firm, the market for prewired homes will be worth \$1 billion nationally between 2000 and 2004, and half of all new homes will be prewired by the end of 2004 [16]. This means the chassis must accommodate infrastructure and make it easily accessible for future upgrade. Integrated raceways provide an, automatically assembled, easily accessible, area for power and data wiring. A removable cover, which doubles as molding, hides the raceways. Various types of sensors may be an important part of the home of the future, but except for those monitoring some part of the chassis, such as the HVAC system, sensors would come installed in infill, so that they could be easily modified and upgraded. Power running through the chassis must be connected to the sensors and other technology, including lights, which could be part of the infill. Because the location and width of infill panels is uncertain, electrical connections are made via a busway, similar to the tracks used for track lighting. Fixed plug locations would require excess plugs and clumsy extension cords. Data must also be brought to the infill. Low bandwidth data can be brought on the busway by means of integrated signal wires or with a power line carrier. High bandwidth data cannot be sent on the busway due to interference issues. It can be handled wirelessly, or if necessary be plugged manually into the infill and run back to the service gateway through the raceway much as it is done now in most homes and offices, but without the difficulty of drilling holes and fishing wires.

The power and data raceways are incorporated into the beam and riser. The two are always kept separate and shielded from one another to minimize interference. The beams bring wiring horizontally to every location, and the risers bring the wiring vertically, Figure 4.5. The frequency of risers would limit the number of power wires running through the average beam to one or two and there would generally be less than twelve data wires even if every infill panel was home run with its own Cat5 wire. However, the maximum number of wires that could fit through the provided raceways is: 25 (12-gauge, 20-amp, Romex, 3 conductor) power wires with 40% fill for heat dissipation, and over 200 Cat5 (or Cat6) wires with 90% fill. It is not expected that the raceways would ever need to be used at full capacity, but the extra space allows for contingency and hand space. It is important to note that there are no connectors in the raceways. All of the wires are home runs from the service gateway to the point of connection, to a busway, or rarely, directly to an infill component. This requires that the cabling be installed in the field, but is necessary, because otherwise the large number of connections would cause heat problems and data loss. The high bandwidth data wires could also be organized in an star network with switches located in risers, but it is unlikely that enough high bandwidth, non-wireless, connections will be needed to make that topology worthwhile.

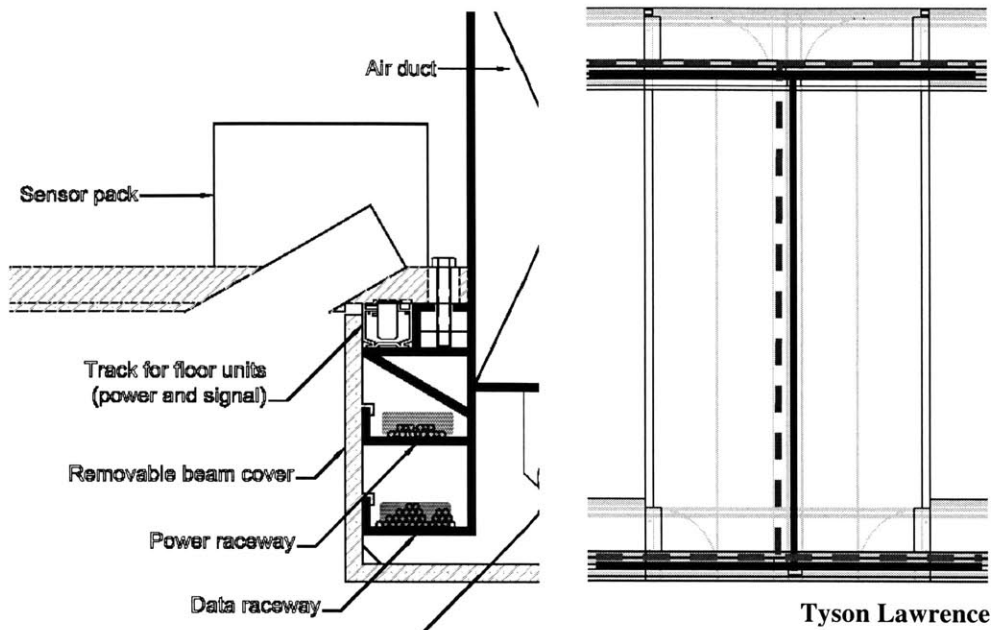


Figure 4.5 Power and Data Raceways

The power and data raceways bring wiring throughout the building and are easily accessible for repair and upgrade by means of a removable cover along all areas of the raceways horizontal and vertical. No fishing of wires is necessary.

The most difficult parts of the raceway system were the riser detail and the connector detail where beams and columns come together. Originally the cabling was to be brought vertically through the column, but keeping the data and power wiring separate from each other and the HVAC duct, which also had to run through the connector, made the connector far too complicated and required a specific connector design for each scenario (corner, T, X), Figure 4.6. Instead a universal connector was designed which left open, but separated shelves where the cables could be run in any horizontal direction, Figure 4.7. The column may still be used to bring cables vertically by drilling holes through the shelves (interference is minimal when wires cross at 90 degrees), but primarily cables are now brought vertically through the riser, relieving the complexity of the connector. Wire management vanes assure correct bending radii.

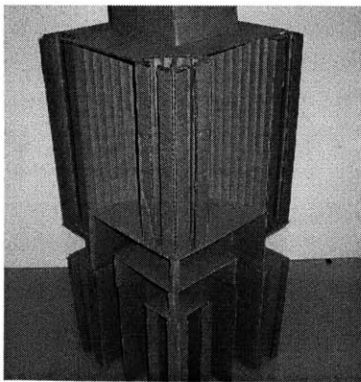
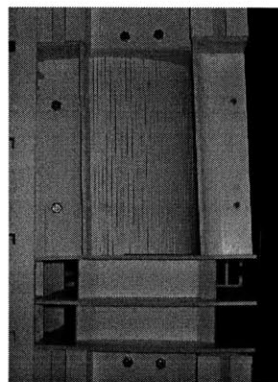


Figure 4.6 Connector Model - Cardboard

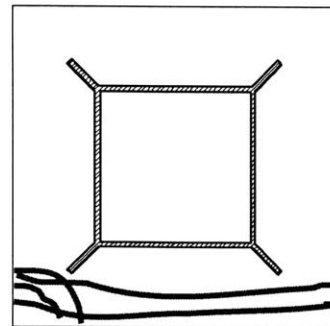
This model proved bringing the data and power wires through the connector both vertically and horizontally was too complicated.



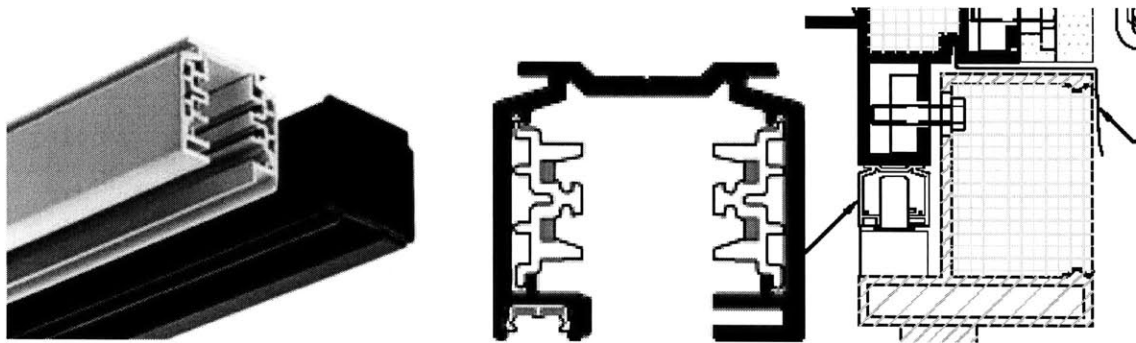
Stephen Form, Tyson Lawrence

Figure 4.7 Connector Model - Foamcore

This model shows the simplified design that was arrived at after learning from the other model, sketches and discussions.



The power interface to the infill is an electrical busway, Figure 4.8. The busway shown here is made by EUTRAC[®] and incorporates low bandwidth data wiring which can be used as the data interface to the panel. The four power conductors of the EUTRAC[®] can provide three 20 amp circuits, separate phase with a shared neutral, or, in circumstances where a shared neutral is not desirable, two completely separate 20amp circuits. There are many busways available, but with other busways a power line carrier would have to be used for data signals. Power line data transmission can be more expensive and has problems with interference when appliances are connected to the power line. This busway is only designed for track lighting, but there is nothing that technically prevents it from being used for appliances as well. All that would need to be done is to design a 20-amp connector, perhaps modeled on the very similar Starline busway made by Universal Electric.



Stephen Form

Figure 4.8 Power and Data Busway.

The EUTRAC[®] four 20amp power conductors, and two conductors for data. The busway is used to make connections from the beam to wall panels and floor components. It allows connection to be made anywhere along the length of the beam.

The systems shown here do not define what type of data network, or for that matter power system, must be used. This is intentional. The data network may change dramatically as technology is developed. The chassis + infill system will be able to change and be upgraded easily due to the simple nature of the system, extra space allotted, and easy access. These factors all contribute to meeting the second functional requirement, adaptability. The power system could even be changed to a higher voltage or DC power, to allow home generation, with very little difficulty. However, the data system that should be installed, given current technology, has been considered.

Of the utility networks, one of the most important will be the data network. This network will be used for entertainment and environment control, computing, communication, security, facilitating advanced cooperation between appliances, and perhaps most importantly for relaying sensor and control signals. To make infill easy to install and reconfigure, there cannot be hardwired control connections between components, such as lights and light switches or HVAC and thermostats, instead these connections are stored as software bindings. There are a broad range of network options available that could meet these needs. Keeping in mind each function has specific bandwidth, control, and connection requirements. For the purposes of this analysis wireless communication systems are assumed to be auxiliary to a wired system. Totally wireless solutions may be explored at a later date, but at this time they do not seem feasible.

As a first pass at choosing a data network the options can be divided into three basic levels. First is the current popular system for home use, in which each function of the complete data network is supplied by its own wiring network. Phone, TV, audio, computer, lighting control, security, sensing are all independent networks. There are tens to hundreds of wires in each beam and column, bandwidth is limited, control requires home runs to expensive dedicated central hardware control equipment, and connectivity is limited to a few predetermined points. Second is the ideal system in which all of these functions and potentially many others are networked by an intelligent distributed computing system embedded in the structure of the house. This system would require only a single data wire to be run in each beam or column, have essentially unlimited bandwidth, be controlled by distributed computing, and allow connectivity by any appliance at any point with a simple universal connector. The third level is somewhere between the current system and the ideal. It would require a minimum number of different wires in each beam and column, have sufficient bandwidth for all foreseeable applications, allow for software control, and provide connectivity at many points.

Current System

The current home networking market is dominated by expensive systems based on the current connector and data transfer protocol standards in each functional area. Since each functional system has been developed independently each has its own network protocol, cable, and connectors, bandwidth is tailored to each specific task. Control is achieved by centralized hardware usually located in a switching box in the basement, and connectivity consists of device specific jacks at a few predetermined locations through out the house. For example the television network works as follows. The data from CATV or satellite comes into the house in the basement on a high bandwidth coaxial cable. It is then amplified and divided into a few new coaxial cable lines. These lines are run to each room in the house where a television that is to receive broadcast service is located. All of the channels are brought to each television location and channel control is performed there by the television tuner or set top box. If the user wants to be able to view an input device such as a DVD player or video camera in multiple rooms a new coaxial cable is run from each input device back to the central control in the basement. Now the control box in the basement must perform a patch panel service to control where the input signals are sent. In high-end systems this can be automated and controlled by a separate data network running from a control panel in the living space to the central control box. A wiring closet containing some of the connections required by the current system can be seen in Figure 4.9.

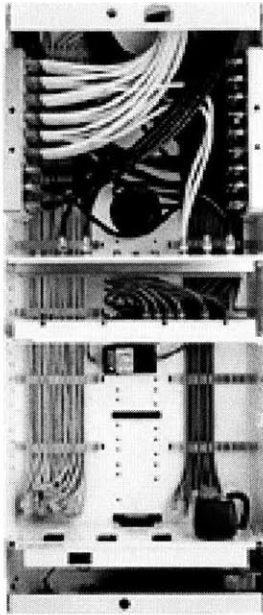


Figure 4.9 Basement Switching Enclosure

This enclosure, made by Leviton, supplies some of the hundreds of wires needed to support a home using the current system

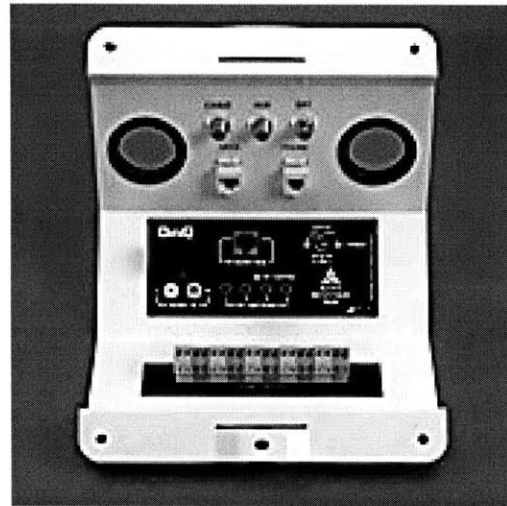


Figure 4.10 Connection Point Panel

This complex panel, made by OnQ Technologies allows a myriad of devices to be connected, each by a different connector, and supplied by a separate wire.

Generally there is only a single set of input and output jacks in each room requiring the television to be placed in a specific location or for long extension wires to be run around the room. Each of the functional areas in the current system have a similar setup: dedicated wiring home run to a centrally located controller that may be remotely controlled by the user by using a separate data network. Figure 4.10 shows an example connection panel with all of the various output jacks required for various devices/networks. Since there are so many types of wire, most companies recommend some variation of structured wire to minimize cost and confusion. Structured wire is simply a bundle of some of the required cables. There are a number of companies that sell and install systems of this type including the following:

[AMX Corp. <http://www.amxcorp.com/index_usa.asp>](http://www.amxcorp.com/index_usa.asp)

[Future Home Systems <http://www.futurehomesystems.com/>](http://www.futurehomesystems.com/)

[Greyfox Corp. <http://www.hometoys.com/toys/greyfox/greyfox.htm>](http://www.hometoys.com/toys/greyfox/greyfox.htm)

[Greenfern Corporation <http://www.greenfern.com>](http://www.greenfern.com) (software)

[Crestron <http://www.crestron.com/default2.asp>](http://www.crestron.com/default2.asp)

[Home Automated Living, LLC <http://www.AutomatedLiving.com>](http://www.AutomatedLiving.com) (voice control - phones)

[Home Automation, Inc. <http://www.homeauto.com>](http://www.homeauto.com) (security and utility control)

[Home Director <http://www.homedirector.com>](http://www.homedirector.com)

[OnQ Technologies <http://www.onqtech.com>](http://www.onqtech.com)

[X-10 \(USA\) Inc. <http://www.x10.com>](http://www.x10.com)

Ideal System

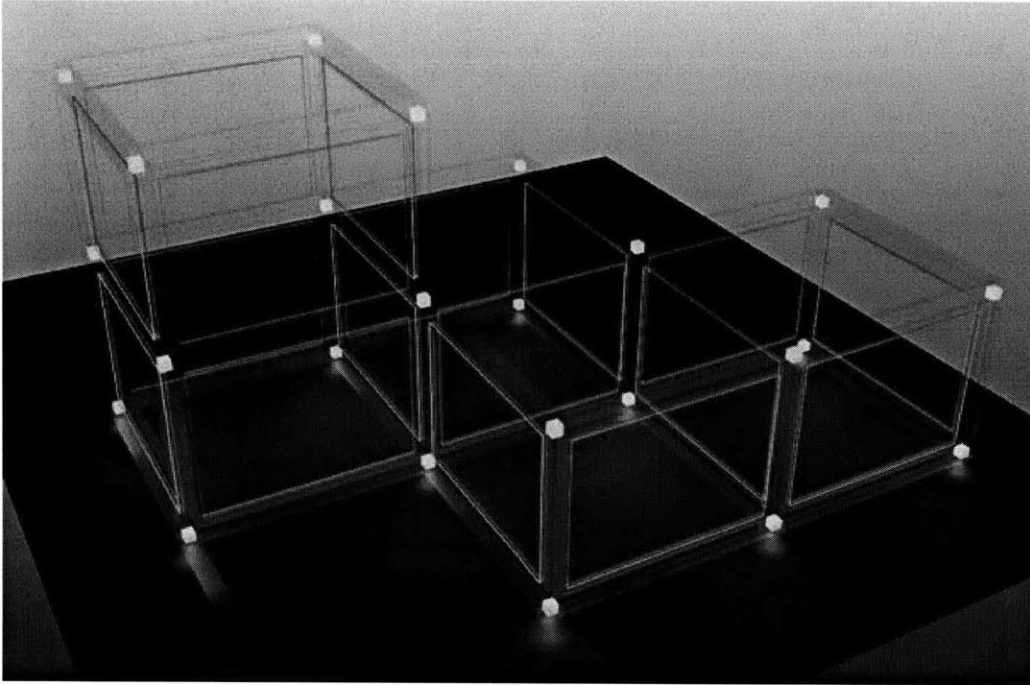


Figure 4.11 Ideal Network

T.J. McLeish

The white boxes in the rendering represent the chips in the distributed computing network. Between these network control chips runs the single wire onto which appliances may be connected.

Unconstrained by what is currently available, requirements can be set for an ideal home data networking system. First, it should be completely integrated so that all of the functional systems in the house run on a single network. Therefore there should only need to be a single wire in each beam and column, and a single plug for all connections. This wire should come already installed in the beams and columns so that no on-site cable pulling is required. The network should provide unlimited bandwidth to all devices. This may require the use of fiber optic or other advanced cable, however it may also be possible to supply sufficient bandwidth with nothing more than enhanced category 5 copper wire. The actual cable that should be used depends on how networking, compression, and cable technologies develop, and of course on the bandwidth requirements of new appliances. Perhaps the most significant differences between the currently available network systems and what we can expect to develop is intelligent control. The ideal network would only send data exactly when and where it is needed. It would provide attached appliances with information about their location, function, and what other appliances and systems are connected to the network. The network would be automatically configuring and all appliances would be “hot plug and play” such that they could be attached and detached from the network in any location. When a new appliance is connected it would automatically begin performing its designated task without disrupting the system or performing any special installation tasks. Furthermore the relationship between appliances attached to the network would be easily re-configurable. For example if the user wished to install a new wall sconce, and a corresponding switch all they would do is attach the sconce and switch to the wall and plug them into the system. Then later if they wanted to change the relationship between the wall switch and the light fixture there would be a simple intuitive procedure such as touching the switch with a control device and then touching the new light it should control. The system

should allow connection at any location within the house. This type of system does not exist, but distributed computing networks are being developed that demonstrate many of these functions on a smaller scale. It is only a matter of time before such a system will be commercially available.

During the development of the chassis + infill system some time was spent examining possibilities for novel building network structures and protocols that would provide for easy design, construction, and reconfiguration of a chassis + infill building. This examination focused on how to deal with creating and maintaining control connections that were not hard wired from component to component, but rather stored as software bindings. To do this, each infill component is equipped with a microcontroller to maintain bindings. The microcontroller holds a list of components that it is “connected” to, and can communicate with other devices through the data network provided by the chassis.

A number of functional requirements were identified as essential:

1. Robust - Since building control is vital, the system must be reliable and resilient to a wide variety of failures.
2. Intuitive User Interface – The system should have convenient and simple user interfaces.
3. Self-maintaining - Since these networks would be used by untrained users, the system must be self-maintaining.
4. Size - The size of devices must be small enough to be unobtrusive.
5. Inexpensive - The circuitry and operations must not drastically increase the cost of electrical networks

Guided by these functional requirements Deva Seethram and H. Shrikumar developed a State-Coherence Protocol for distributed control. It consists of three layers, named Get, Set, and Go, running on top of a diminutive TCP/IP network.

In the bottom-up order, they are as follows:

1. GET - An idempotent transaction protocol, which ensures that control transactions occur exactly once per interaction, without race conditions, over-writes or data corruption due to distributed actions.
2. SET - A coherence protocol, which operates over GET, and brings together all the nodes in a distributed control or coordination context and ensures that they operate in unison, with a distributed consensus about the results.
3. GO - A concurrent programming language for the application layer using a distributed programming model based on the concept of program devolution. Devolution is an innovative distributed programming technique that allows the application designed to easily build complex applications involving thousands or even millions of nodes, without being burdened with the need to program and manage each node.

In the continued development of this theme, they are developing systems to evaluate these ideas and improve the implementations. The current implementations, GSG 1.0 and c@t are described further in [17] and [18].

To further develop the ideas into something that could effectively be used in a chassis + infill building, an architectural scale model was designed and built in conjunction with T.J.

McLeish, Figure 4.12. In this model, devices compute their own address based on their physical location relative to a root node (cornerstone). The infrastructure provides locational cues to the components. The components use this information to establish meaningful bindings.

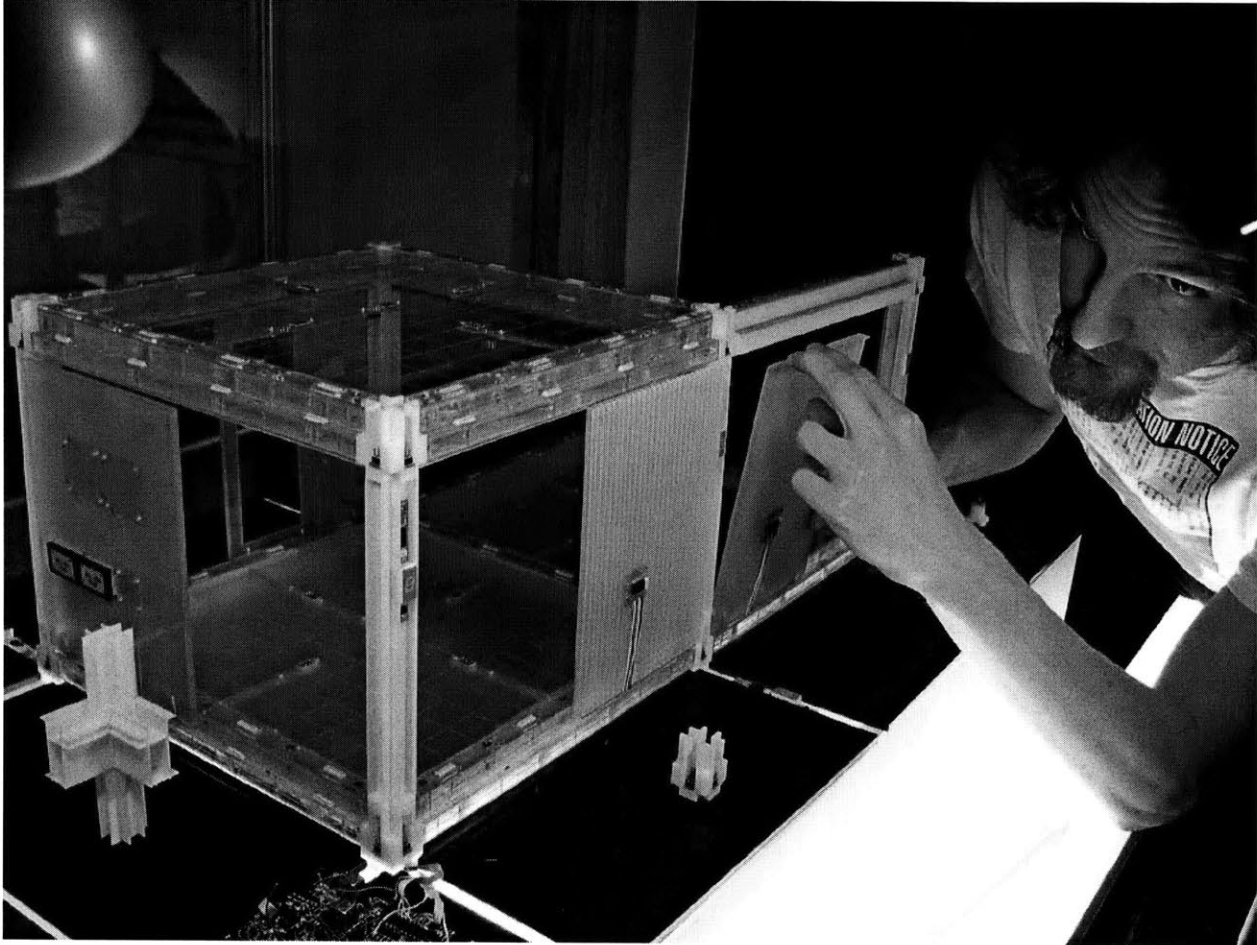


Figure 4.12 Architectural Network Model

In this model, devices compute their own address based on their physical location relative to a root node (cornerstone). The infrastructure provides locational cues to the components. The components use this information to establish meaningful bindings.

This network structure has not been developed sufficiently to be installed in a home, but it demonstrates how a novel structure combined with the chassis + infill system can offer new possibilities for efficiency of design, assembly, and reconfiguration.

Compromise

Obviously in the real world the options are constrained by what is available. However, the popular current design is cumbersome and does not provide all of the functionality desired. What is needed is a compromise system that achieves as many of the features of the ideal system as possible using currently available technology. Hopefully, by the time chassis + infill might come to market something closer to the ideal system, perhaps incorporating Neil Gershenfeld's Internet 0, would be available. However, in order to provide for prototyping and avoid relying on a non-existent technology, a compromise system is outlined using currently available technology. This compromise requires a minimum number of wires to be run in each beam and column, provides sufficient bandwidth for all foreseeable applications, allows for software control, and provides connectivity at many points throughout the house. Of the networking technologies currently available the most promising is Ethernet. Ethernet has many advantages including low cost, high bandwidth, and flexibility. There are thousands of products built to work on Ethernet networks and there are new products being introduced everyday. In addition Ethernet may be used on a number of cable types. The supply of digital media to the house would be a single mode fiber optic cable providing almost unlimited bandwidth. Where necessary commercial service delivery systems would be converted to Ethernet. Within the house the network would be distributed from this gateway point. Most of the home systems only require very low bandwidth and could be handled by the data path integrated into the power busway. A few \$90 TINI boards manufactured by Dallas Semiconductors would manage the 1-Wire protocol on the busway and provide connection to the TCP/IP where necessary. High bandwidth data could be delivered to the few locations it was needed wirelessly, or if wireless were undesirable devices could be homerun much as they are currently, but without drilling holes or fishing wires. To create a completely flexible wired system, multimode fiber optic could be run to switches placed throughout the house in risers. From each switch Cat5 wire would run to standard RG45 jacks placed in the beams at 3-foot intervals. This would allow every wall panel to connect to the network and if necessary panels could have their own switch or hub to provide further access points. If there were one switch, per average sized room (12ft x 12ft) the beams would carry a maximum of eight Cat5 wires. The riser with the switch at its crown would carry two fiber optic cables, one for sending data, and one to receive data. The network would provide dedicated 100Mbps to each access point.

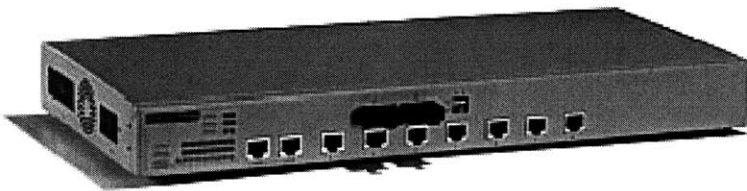


Figure 4.13 Gigabit Switch
8 port 100Mbps ST switch with 1 port Gigabit Ethernet, SC connector, 1000Mbps, by Cisco Systems.

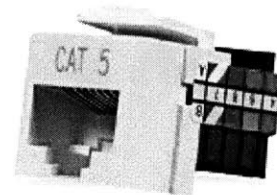


Figure 4.14 RJ45 Jack
Standard RJ45 Cat 5 Jack, by Leviton, Inc.

If gigabit Ethernet was required the Cat5 wire could be replaced with Cat6 wire or more multimode fiber. However, because each access point has a dedicated 100Mbps line the need for more bandwidth is unlikely to come up. Even HDTV, the highest bandwidth function anticipated, only requires 20Mbps max. The control of the system would be performed at the

gateway in the basement, where telephone, television, Internet, and alarm services would enter the building. The central gateway would connect each access to point with the service it requests. This would prevent the network from being unnecessarily swamped by hundreds of digital television channels when only a few actually need to be displayed. The user control could be performed at a PC or at an Ethernet ready control panel programmed to communicate with other appliances installed on the home network. In order to provide maximum flexibility and upgradability, overall system control should probably be performed with software on a PC. However individual or groups of systems could continue to have recognizable standard controls. For example, lights could be controlled by a light switch attached to the network, and television could still be controlled by an IR remote, by means of an IR receiver connected to the network. This network does not provide all of the features of the ideal network. For example, each beam must carry multiple wires and the wire will not be preinstalled. There are two separate networks, high and low bandwidth instead of one unified network. The appliances will almost definitely require some configuration in order to communicate properly with the rest of the network and reconfiguration probably will not be very intuitive. Also, since this network is central rather than distributed it cannot provide location information to each appliance and there is risk of a single point failure bringing down the entire network. Despite these definite limitations this system comes far closer to providing the ideal data network than the current system.

4.5 High Quality

The chassis allows superior construction through high quality materials and a system design that is easy to work with. The first group who will interact with the system is designers. They may be professionals, or homeowners designing with the aid of a computer platform, but either way the system should be structured to make their task as simple as possible. The second group to deal with the system is the manufacturer. The system should be as easy and cheap for them to produce as is feasible. Finally, and most importantly the system should be transparent to assemble in the field. It should require very little training, and be very difficult to do incorrectly. Many of the same simplifying principles apply to all of the interested parties, so they may come up repeatedly. A glass reinforced polymer pultrusion was chosen for the beams and columns over wood, steel, aluminum, and natural resin systems because of a variety of benefits.

Pultrusion is a process for making a composite material from an advanced polymer and reinforcing fibers. For this system fire-retardant polyester is used in conjunction with glass reinforcing fibers. The most important feature of this material is that it has a higher strength to weight ratio than steel, aluminum, or wood allowing structural members that are stronger than what is typically used while also being light enough that workers can install them without heavy machinery. Another important aspect of the material is that it facilitates the creation of the complicated profile that is necessary for integrating HVAC, wiring, and structure into one reusable component. A complicated profile increases the fixed costs of creating a mold, but does not significantly affect the marginal costs. Furthermore the volume to strength ratio of the pultrusion is in the right range. Wood requires too much volume to get the required strength. A beam that was strong enough to span 15 feet under 900lbs/ft of force with a duct, raceways, insulation, and mechanical connections incorporated into it would be far too large. A similar profile made from steel or aluminum would be so light gauge that they would not be able to resist impact. If a wall panel was banged into the beam during assembly it could deform and be

unusable. The pultrusion has a low thermal conductivity so it does not act as a thermal bridge between the interior and exterior. The pultrusion also does not rot or corrode, is unaffected by pests and moisture, does not expand excessively with temperature change like aluminum, and perhaps most importantly is dimensionally accurate and stable unlike the low quality wood that is being used in the industry today. There are many advantages of pultrusion, however there are still a few concerns to work out. The first is that it has a very low glass distortion temperature (160°F) and could experience a decrease in structural properties in a fire. Second, it is currently a specialty product and as such is very expensive, however there is nothing fundamentally expensive about it (e.g. the large amount of energy required to produce aluminum) so the price can be expected to decrease dramatically if it were used widely. These concerns will be discussed in more detail in Chapter 5, Evaluation.

The chassis is designed to allow for quick and easy design of high quality houses. This is made possible by minimizing the part count (there are only five parts and one fastener used in the chassis), and providing a system that is pre-engineered such that as long as the designer stays within the design limits mentioned earlier and follows a few other simple guidelines, the structure and mechanical systems are automatically worked out. The parts of the chassis are the interior beam, exterior beam, column, connector, and riser.

These components were arrived at after many months of consideration and experimentation. They are chosen to minimize part count and part complexity. Initially a single symmetric beam was designed for both interior and exterior applications. This eliminated choosing which beam to use and allowed a beam to continue from the exterior to the interior or to be used as an exterior piece and then later as an interior component. Some of these early symmetric beam designs can be seen in Figure 4.15. Unfortunately the function of the interior and exterior beam was determined to be too different for one component to perform both functions well without undue complexity.

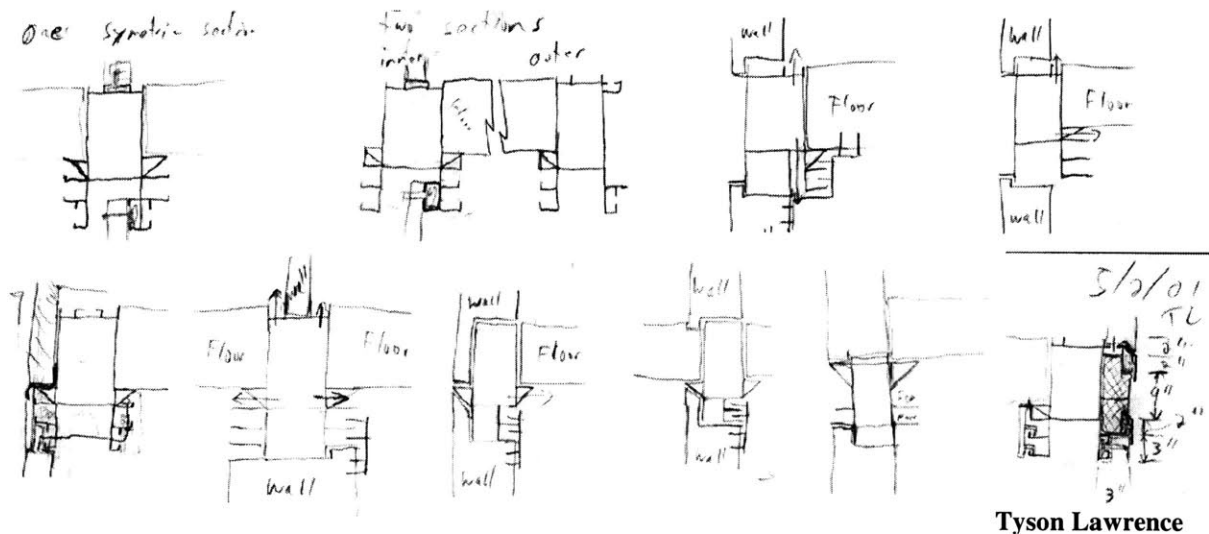


Figure 4.15 Symmetric vs. Asymmetric Beam

A single symmetric beam would be convenient, but the functional requirements of the interior and exterior beam are simply too divided.

Additionally, the connector and riser were not initially part of the design. Mitering the beams and simply setting them on top of the column was experimented with, a connector piece that was integral to the column or beam was considered. In the end the connector was created as a separate part so as to concentrate the complexity in one part and leave the beams and columns as simple as possible. Before the riser was part of the design, all the utilities were brought vertically through the columns and the connection between beams and columns was a moment connection. This system overloaded the column and made it unnecessarily complex, but the real impasse was that the connector was required to somehow handle transferring a large air duct and separate data and power wiring to the beam while maintaining the structural strength of a moment connection. Forcing the connector to perform so many functions was simply not feasible. Some of these early designs can be seen in the section 4.8 about the prototypes built.

Design of a home using chassis + infill will be highly efficient, because other than the five final components, the rest of the house is infill, and can be filled in however and wherever desired, without respect to structure or the mechanical systems. It is likely that the same basic chassis layout could be used to provide hundreds of customized homes, which vary only in type and placement of infill. The system uses only a single fastener and defines all attachments, effectively eliminating the need for the designer to indicate attachment details. The HVAC system requires only the most minimal of diagrams, and could even be generated automatically by a computer, because it is almost completely defined once the risers and beams have been placed. The electrical and data wiring would only require a diagram indicating circuits, which again could be generated automatically by a square footage calculation, because they are completely defined by the location of the beams and risers. The structural system and insulation requirements have also already been verified. The system could even include guidelines or best practices in paper or digital form to make design even more straightforward.

The manufacturing of the chassis is simplified by many of the same factors that make the design process simple. The minimum number of parts and the simplicity of the parts are the most important factors. The columns and beams can be made automatically with very simple machinery, the profile is pultruded from the die, cut to the desired length, eight slots are drilled or punched, and in the case of the beam three inches is cut from the parts of the profile surrounding the duct. The riser and connector are the most complicated parts. The connector could be molded with a complex mold. The riser would need to be assembled from several parts. The top and bottom of the riser are modified beams; the intervening area consists of two flat sheets of reinforced polymer composite with dividers in-between, which separate ducts, raceways and plumbing spaces. Holes would be cut and snap in covers molded to allow access to the raceways and plumbing space. Because the components are all manufactured in a factory many processes can be automated, and what labor is needed can be efficient.

The ease of assembly is one of the key functional requirements of the system. It is crucial to helping relieve the labor crisis, improving quality, allowing customization, allowing adaptability, and keeping cost reasonable. The assembly should not require extensive training, allowing a single assembler to do all of the tasks required to complete the chassis system rather than requiring a framer, an electrician, a plumber, a data network installer, a plasterer, a painter, etc. The assembly must be difficult to perform incorrectly, providing guidance with physical or digital components. Again, the same concepts that helped design and manufacturing help

assembly as well. There are only five components, and a single fastener used throughout the system. To learn to install the system the assembler needs to learn what each of the five component is used for and how to install them, how to lay wire in the raceways and connect it to the busway, wireless port or infill, and how to attach infill to the T-slot and busway. The system is years simpler to learn than the traditional construction system. Furthermore most components physically cannot be installed incorrectly. A beam cannot be installed as a column, and a connector must always be used to attach a beam to another beam.

The connector attaches to beams and columns in a tongue and groove fashion with the Hilti pushbutton, described in section 4.3, providing a positive union, Figure 4.16.

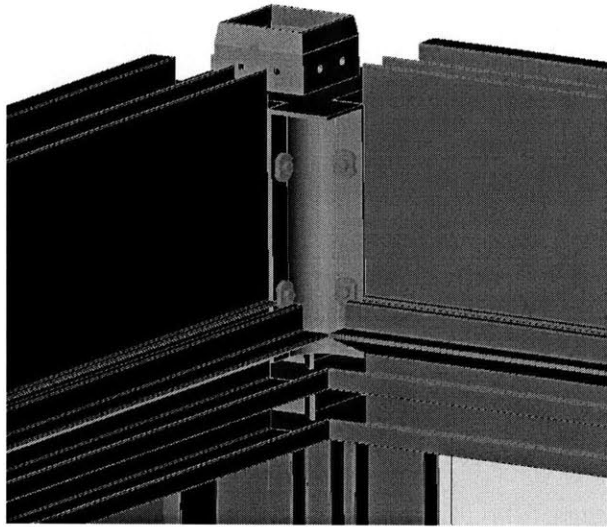
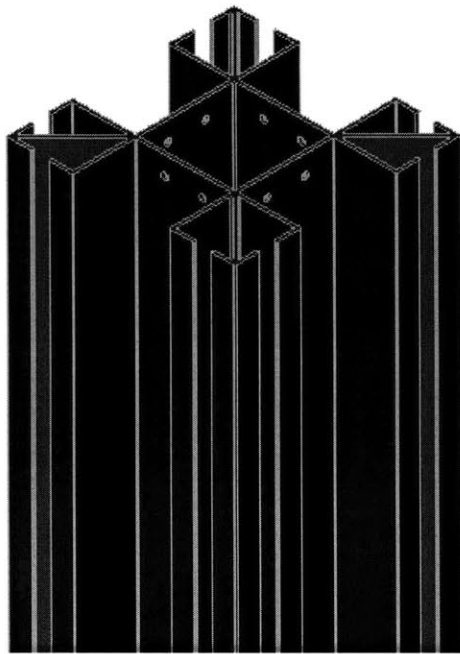


Figure 4.16 Connector Detail

The connector makes structural attachment to the beams and columns by means of a tongue and groove connection reinforced by Hilti pushbutton connectors. The raceways and ductwork continue around the corner unhindered.

Tyson Lawrence

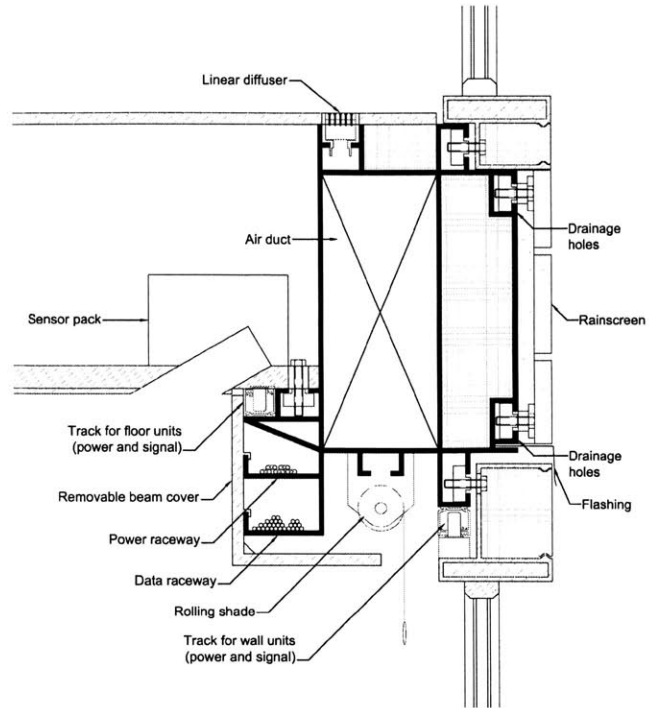
The beams and columns have incorporated T-slots, which accept the same pushbutton connector to be used to connect wall, floor, and roofing infill panels. Figure 4.17 shows the column. The beam profile also provides connections for an optional rainscreen. The rainscreen is a porous structure that protects the building from driving rain and pressure differentials, and offers the opportunity to create a monolithic exterior façade. The floor is also attached to the beam in exactly the same manner with the same connector, Figure 4.18. It is this uniformity and minimization of connections that helps the system to be much more labor and time efficient on site. In fact, the same connectors are used throughout the system for all physical connections, for example to attach panels to each other.



Tyson Lawrence

Figure 4.17 Column Profile

The column is primarily a structural part, but the flanges in the corners also accept the same Hilti pushbutton connector to provide linear attachment points for sealing the building from the weather, by attaching a bracket to which panels can seal to, and for attaching interior and exterior finishes.



Stephen Form, T.J. Mcleish

Figure 4.18 Beam Section – Easy Assembly

The beam incorporates attachment points for panels above and below, floor infill, and an optional rainscreen all with the same t-slot structure and Hilti pushbutton connector. As the physical structure is assembled, the chassis automatically creates an HVAC distribution system, power and data cabling raceways, and a system to connect power and signal to infill.

Because the components of the system will be manufactured from computer generated designs by CNC machines they can be easily tagged with color codes and labels as they are manufactured, showing which parts attach to which and where they go: essentially build by number. The parts could even have simple digital components attached in the factory, which would know if they were installed incorrectly, and could sound an alarm.

Not only is the physical structure easy to assemble, but also as it is assembled, the power, data, insulation, and HVAC systems are automatically created. Components such as light switches and lights would not need to be hardwired to each other, instead they would each simply be connected to power and signal and their relationship to each other stored as a rewriteable software binding as explained in section 4.4. These bindings could be made automatically if the components contained some simple intelligence, or they could be easily made by anyone, using a tool such as a laser pointer. First point at the switch and then at the light(s) it should control. The HVAC system would be created as the physical components are assembled, the insulation, and finishes would be factory installed so that they would not require any on-site effort. The foundation would, at least initially, be the same as a conventional home. The home would be leveled on the foundation using laser levels and adjustable brackets. The home would be trued to ninety-degree angles by temporarily attaching cables across opposite corners and tightening the cables until a laser sight verified accuracy. The angle would then be

fixed by fastening the shear panels, and the cables could be removed. All in all the chassis + infill system will be very formulaic to install, despite the high level of customization!

4.6 Physical Strength

The strength of a chassis + infill home must be equal to or greater than a conventional home. This should not be difficult, because of the advanced materials and robust connections that are used. Assuming a live load of 100lbs/sqft the beam must be able to support 750lbs/ft (to accommodate an 15' floor span on each side) with deflection less than half an inch ($L/360$). The column must be able to support a maximum (unusual to say the least) 67,500 lbs assuming three floors of four 15' beam spans. The beam should also be able withstand 400lbs/ft of horizontal force to endure hurricane force winds. In addition to connection details, infill panels would have, as part of the defined criteria they must meet, a minimum wind loading value. Infill floor panels would have to meet a live load of 100lbs/sqft and provide diaphragm strength to prevent warping of the building.

The profile of the beam is primarily defined by the functions it must perform, such as provide HVAC distribution, wiring raceways, physical T-slot connections for panels and optional exterior finish, support the floor, and provide space for insulation. The strength of the beam can be tuned by changing the wall thickness of the profile and by changing the polymer and reinforcing fibers used. Spreadsheets were created to examine these factors, see Chapter 5, Evaluation.

The most likely failure mode of the panel connection point would be shear under wind loading. A simple calculation based on the shear area and the shear modulus can demonstrate that the connection will be able to withstand more than the generally accepted amount of force. More detail on the strength of the chassis can be found in Chapter 5, Evaluation.

4.7 Controlled Space

Some of the most common homeowner complaints relate to how well the space is controlled. Leaks, drafts, improper temperature, and lack of ventilation, are problems which must be avoided. Furthermore the system should be environmentally and economically friendly in terms of the heating and cooling systems.

In order to limit the effect of external temperature, the space is insulated and sealed. The chassis incorporates insulation, and the wall and roof infill would have to meet minimum insulation requirements. The infill manufacturers could offer a range of insulation options by geographic region and as part of the customization, but some minimums could also be set to ensure the home would be environmentally responsible. The interior is sealed off from the exterior by factory sealed joints around doors and windows, and double silicon seals between all site assembled components.

To provide proper ventilation, heating, and cooling, without creating excessive noise, a 4"x11" insulated duct, is brought to every 150sqft area, and a large area linear diffuser is used to let the air into the room. This should provide a complete air exchange every 9 minutes with air

speeds less than 500cfm, at the low end of the industry standard. The space integrated into the pultrusion is 5"x12" and is lined with a half inch of insulation to keep sound and condensation to a minimum. The air is brought vertically from the HVAC unit by risers, Figure 4.19. There are two ducts brought to each floor per riser, thus, if a riser is included for every 300sqft, each duct will supply 150sqft. Cabling and plumbing are also brought vertically through the riser. The air and cabling brought through the riser are distributed into the beam, the air for the floor above the beam, and the wiring for the floor below. Keeping the air designated for the floor above the beam allows the risers to decrease in width as they move up through the house. The plumbing only needs to be run in specified risers and will output directly to the kitchen or the bathroom through the riser and floor. There is also separate plumbing for the sprinkler system that is built into every floor module.

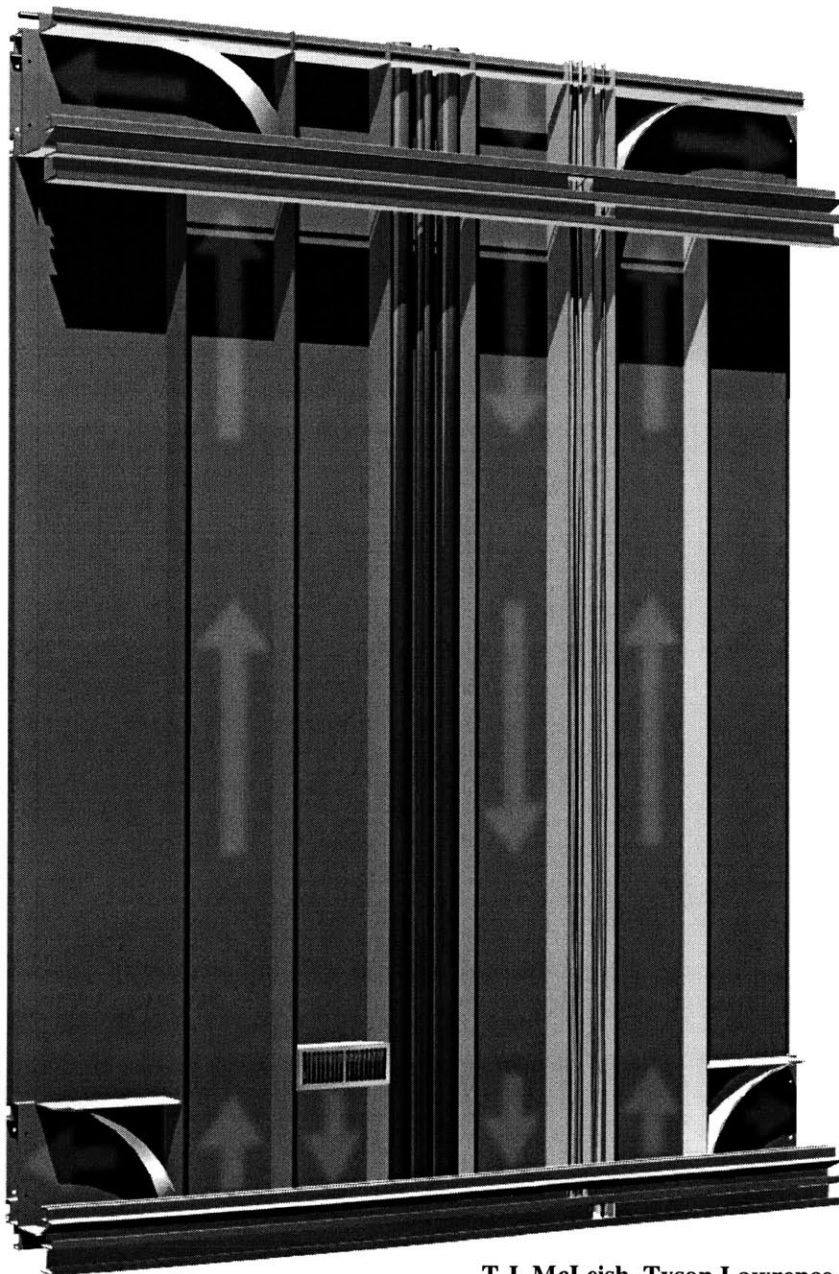
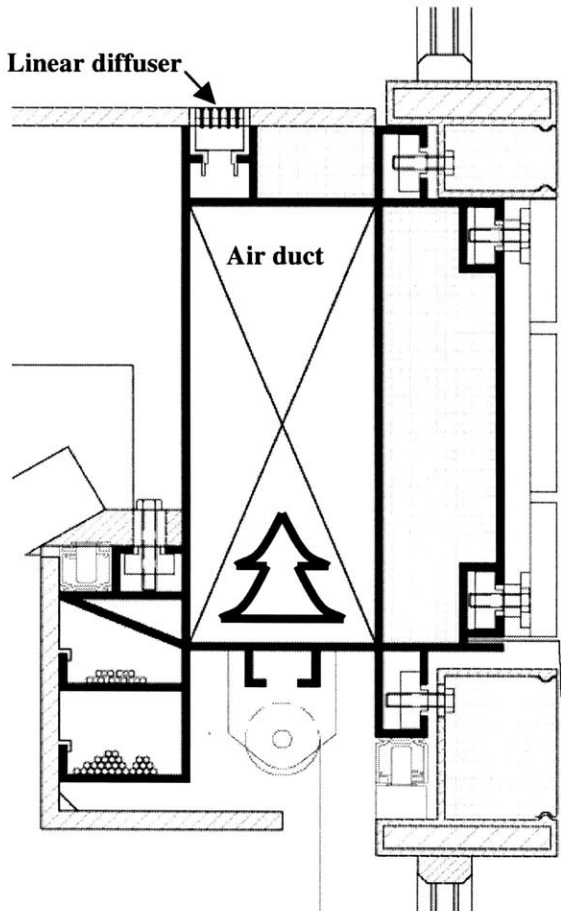


Figure 4.19 Riser Detail

The riser brings air, plumbing, and power and data wiring between floors. The outside ducts serve the first floor beams; the ducts next toward the center serve the second floor beams. The inside ducts are returns, one for the first floor, left, and one for the second floor, right. The wiring raceways and floor support integral in the beam continue across the riser. Power and data wires are brought vertically through separate shielded raceways, on the right side of the diagram between the return from the second floor and duct serving the right side second floor beam. They may be accessed by removable covers and have outlets into the horizontal raceways on each floor. Plumbing, shown in the center of the diagram, also has a separate area, which can be accessed by means of a removable panel on the wall or through the floor.

T.J. McLeish, Tyson Lawrence

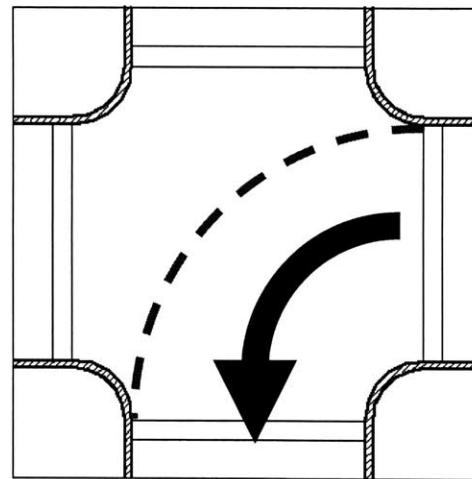
Air is carried horizontally through the HVAC duct integrated into the beam, Figure 4.20. Air flows from beam to beam unobstructed through the connector. A large open space allows for airflow in any of the four possible directions. After the universal connector is located a curved vane may be placed within the open space to direct the air in the correct direction. This allows the same connector to be used for any scenario of beam attachments, Figure 4.21.



Stephen Form, T.J. McLeish

Figure 4.20 Beam Air Flow Diagram

Air is carried horizontally through the integrated duct in the beam section, and released into the living space through an integrated linear diffuser.

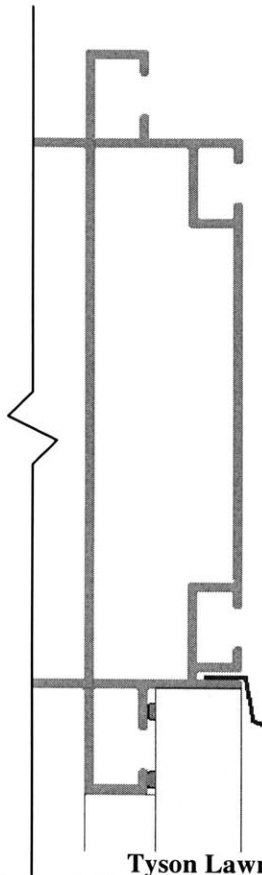


Stephen Form, Tyson Lawrence

Figure 4.21 Connector Air Flow Diagram

The universal connector can be modified with curved vanes to direct air to and from any beam.

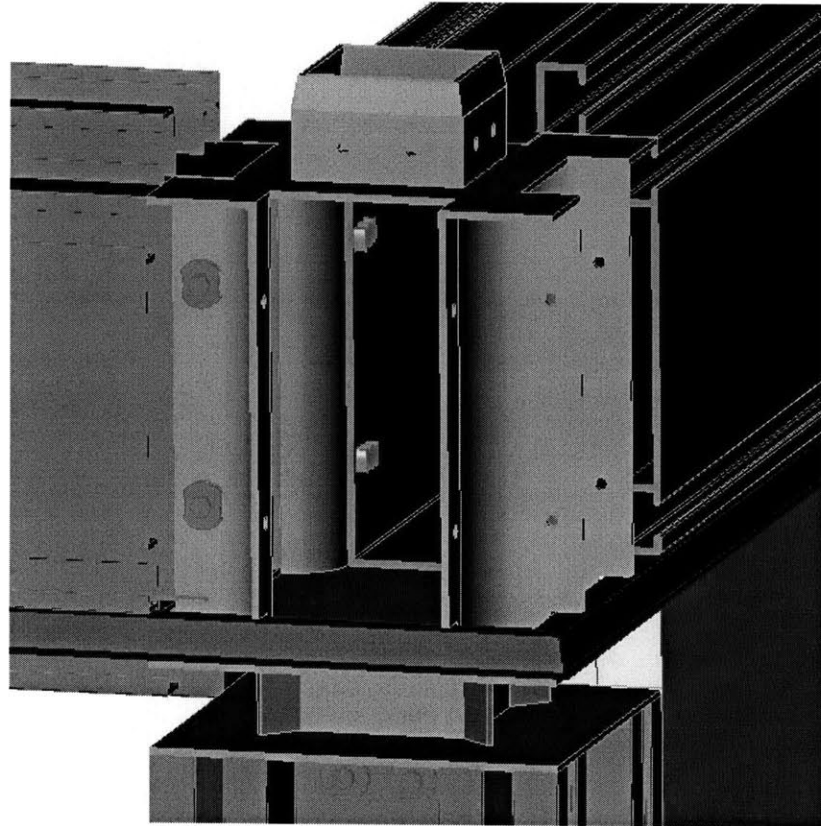
To keep water out of the system all horizontal joints are flashed in addition to the double silicon seal. Figure 4.22 shows how the connection at the top on the beam is self flashed and the connection on the bottom of the beam incorporates a removable flashing component, this flashing continues unbroken around the building, Figure 4.23.



Tyson Lawrence

Figure 4.22 Beam Flashing

The connection at the top on the beam is self flashed and the connection on the bottom of the beam incorporates a removable flashing component.



Tyson Lawrence

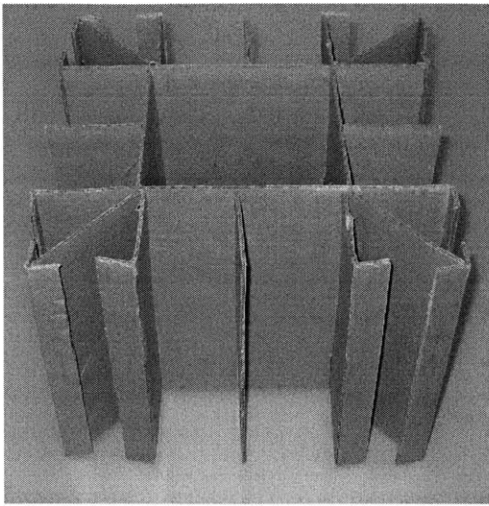
Figure 4.23 Continuous Flashing Detail

The flashing continues around the building over connectors to maintain a positive layer of protection from water infiltration.

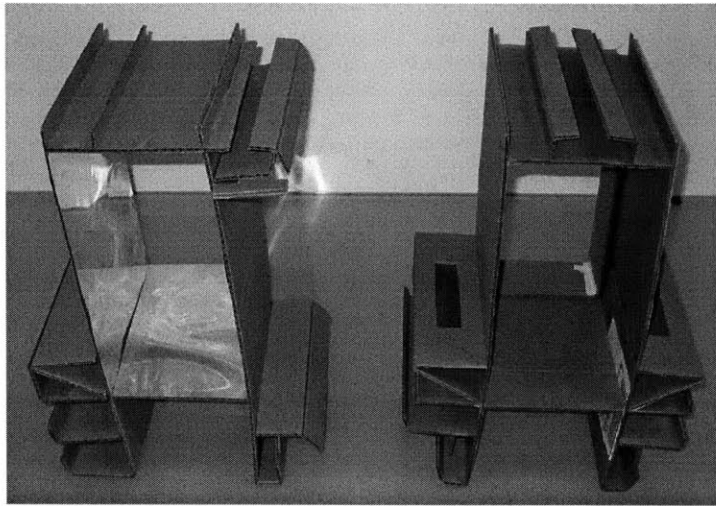
Because the chassis + infill system is factory manufactured, much tighter tolerances can be maintained and quality of seals and insulation assured. This quality assurance will lead to a very well protected space.

4.8 Prototype

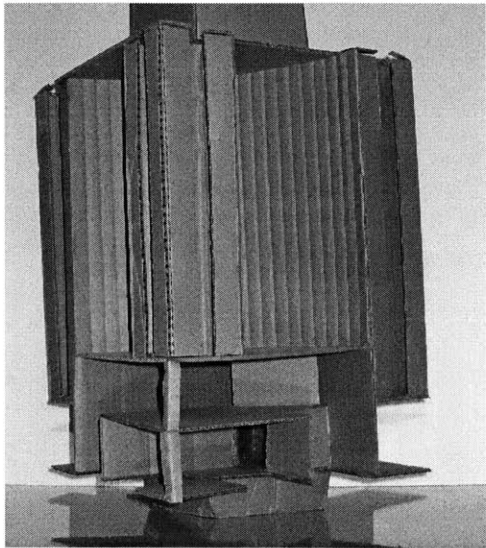
In order to test the ideas developed and have something physical with which to explain the ideas, a full scale prototype was built in addition to the 1/12 scale network model shown in section 4.4. Preliminary sketch models were made from cardboard, and included a first attempt at a column, a symmetric beam, an asymmetric beam, and a connector, Figure 4.24. These sketch models were invaluable for getting a feel for the shape and size of components, and for collaborating with colleagues. They led to the addition and subtraction of details, and the development of a full scale “looks like” prototype made from foam core. The final prototype included two columns, two beams, a connector, an infill wall panel, an infill floor panel, a rainscreen, as well as many of the off the shelf components that might be used in the system. Some of the components included were: insulation, flashing, a Titus linear diffuser, an Eutrac electric busway, and the Hilti connector, Figure 4.25.



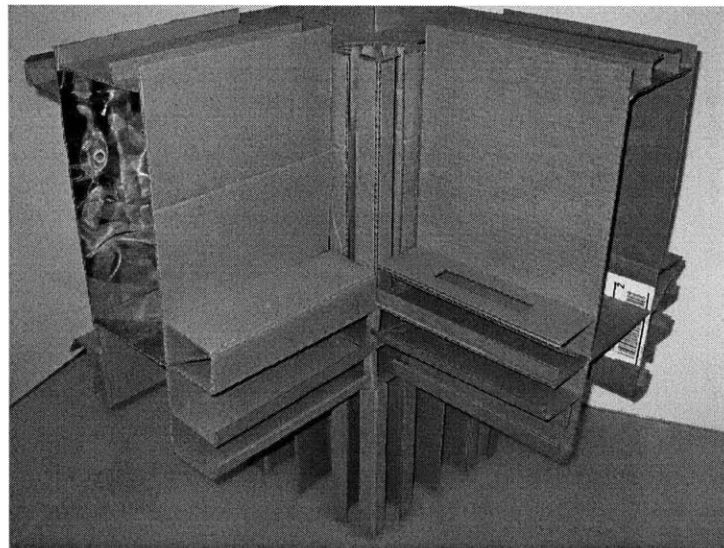
(a)



(b)



(c)



(d)

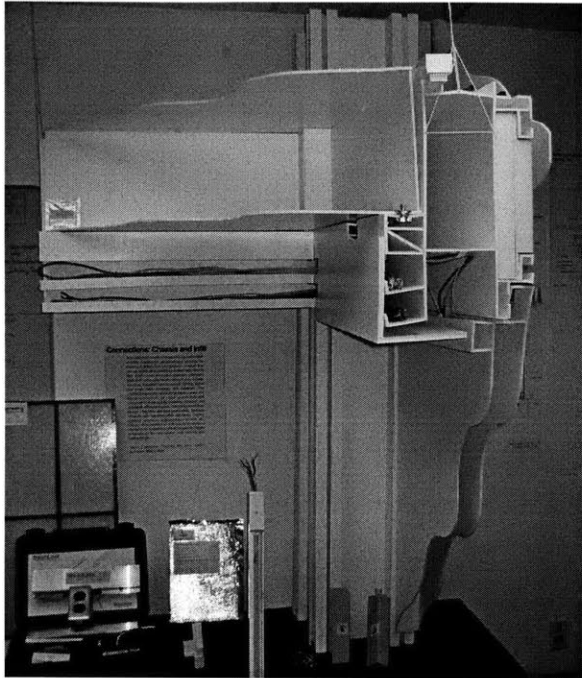
Figure 4.24 Cardboard Sketch Model

(a) The early column model included a pultruded shield to separate power and signal wires, this was later removed in favor of an optional divider.

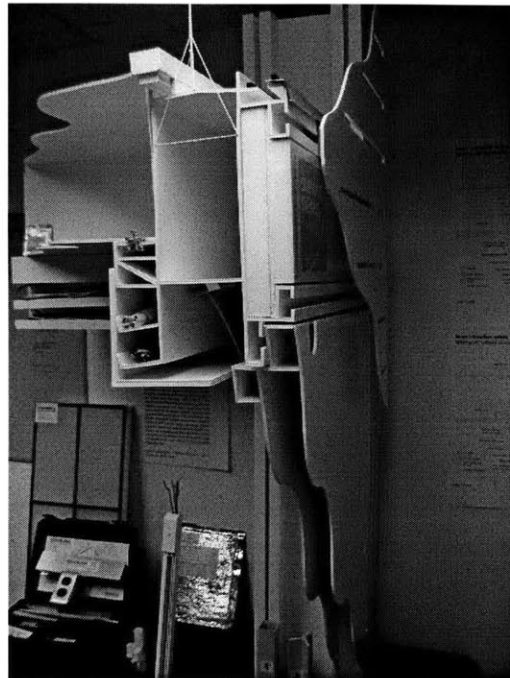
(b) Early columns did not include rainscreen attachments or an enclosed insulation space. The symmetric column on the right has raceways as well as attachments for physical infill on both sides.

(c) The early connector design was too complicated and required a different connector for every corner scenario (corner, T, X, straight).

(d) At this stage the beams connected to the connector by means of specialized fasteners and add on pieces rather than the simple tongue and groove and bolt method developed later.



(a)



(b)

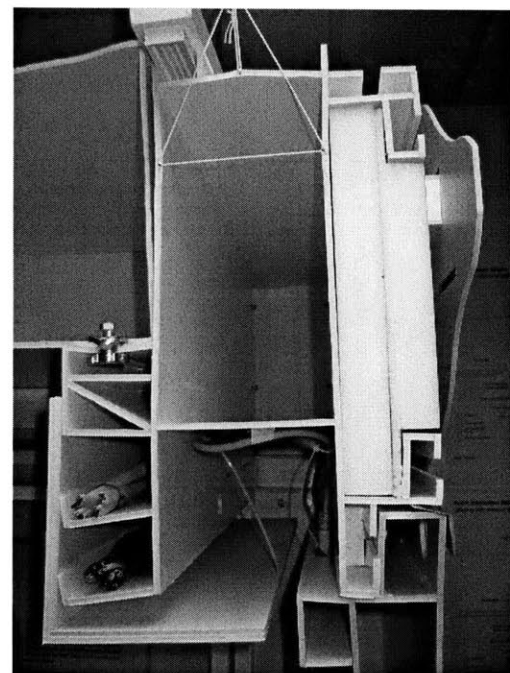
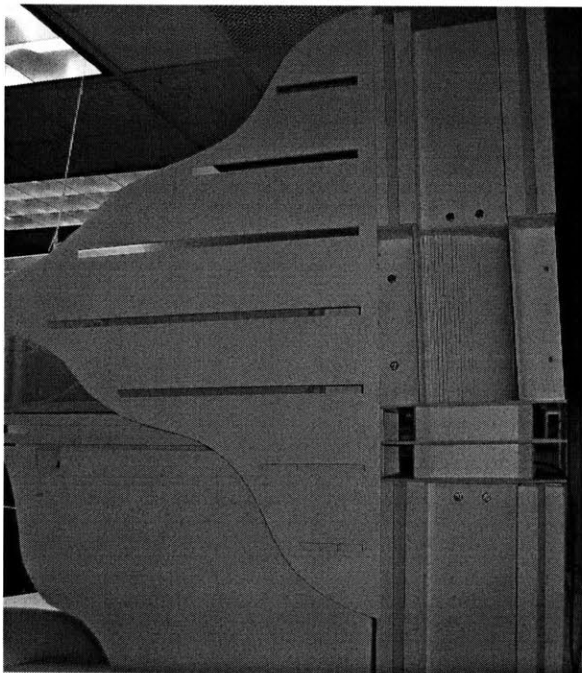


Figure 4.25 Foam core “Looks Like” Prototype

(a) This view is from the inside of the “house.”

(b) The rainscreen and infill attachments can be clearly seen here.

(c) This is the model from the outside of the house” the simplicity of the universal connector, with removable vane, is apparent as well as the ability for the rainscreen (cutaway) to provide a monolithic façade.

(d) This close-up shows all of the components of the beam (except the busway, which could not be mounted for weight reasons). Note the Hilti pushbutton holding the infill floor, and the Titus linear diffuser mounted top left.

Chapter 5: Evaluation

The evaluation of a complex system like this is very difficult, and can never be certain without full implementation of the system into the economy. However, it is important to evaluate those parts that can be evaluated prior to implementation as well as possible. What follows are evaluations by experts in the field of construction, a qualitative analysis and discussion of the aspects of the system that cannot be objectively measured, and a quantitative estimation of those facets of the system that can be calculated. The expert evaluations are the products of 16 interviews conducted with homeowners, architects, manufacturers, builders, engineers, an insurance company, professors, and a local building inspector. The qualitative analysis is an examination of scenarios, which demonstrate the viability of the system on qualitative measures. The quantitative analysis consists of estimations generated from basic principles.

5.1 Expert Evaluations

The industry experts interviewed made many insightful observations about potential problems with the system, but overall were extremely positive. The general consensus was that the ideas behind the system had great merit, and that movement to a system like the chassis + infill is inevitable. "Has tremendous potential!" "This is a forward thinking concept that has merit." "Great concept, very imaginative." "I'm sure that it could be made to work." "Almost something that has to take place to address problems like the unsophisticated workforce." The interviewees saw benefits to their own businesses and to the consumer. A builder commented, "The system would allow improvements in cost, quality, schedule, and in general allow us to be more competitive." A contractor said, "I think the chassis infill system could be used to create my dream house." A wire manufacturer gushed, "I think the chassis infill system would give me more bang for my buck providing a quality product, in a reasonable amount of time, that is customized!" They noted that they were currently faced with real problems and were having difficulty overcoming them with the current manufacturing method. One alleged, "The #1 consumer complaint is home construction." According to the National Association of Consumer Agency Administrators and the Consumer Federation of America, home improvement topped the list of consumer complaints in 2001 with 59% of consumer agencies reporting it as a major complaint area. Household goods followed home improvement as the second most frequently reported complaint, and then auto sales and auto repairs, [19]. This is one indicator that the housing industry is in fact broken; one major problem leading to this statistic is that the renovation or adaptability process is so convoluted and difficult that it cannot be performed satisfactorily. The best builders are unable to participate in renovation, because they cannot transfer their proficiencies well. Instead small contractors struggle and sacrifice their integrity and quality to survive.

The interview process was very informative and rewarding, however it was not a perfect method of evaluation. Each interview began with a thirty to sixty minute explanation of the chassis + infill concept, followed by a discussion period lasting from a half hour to three hours. Each participant focused on his or her business or area of expertise. This is to be expected, and it is fascinating to see how each interviewee picked out how the system would help their area. For example, the insurance group focused on repair and risk, an MEP engineer who deals with

building code on a daily basis focused on how the system must meet code, and the developer commented on cash flow and scheduling. This is why people from all parts of the industry were interviewed. Unfortunately this diversity led to a very small sample from each area. A larger sample size could provide statistical information, while this group can only really be used for insight. Furthermore, because each expert could only spare a limited amount of time, a full discussion of the complex system was not possible. One of the results of this time restriction and perhaps a desire to please the interviewer was a regurgitation of the material presented. When asked what their concerns with the system were many interviewees responded with the concerns that had been mentioned during the explanation of the system. The process chosen allowed for valuable direct discussion of the systems merits, which would not have been possible with a more anonymous or broad method. However, an interview process that involved more participants, allowed for more time, and was administered by an impartial third party, could provide additional insight.

The following describes the comments and concerns brought out during the interview process. Most of the concerns brought up had already been considered within the design, but a few new issues surfaced and changes were made to deal with them.

Acceptance

One of the concerns brought up most often was consumer acceptance. “New is bad,” “Pre-fab homes aren’t as durable,” “The market isn’t ready for versatility like this,” “There is public stigma against modular.” Marketing is a very valid concern and would most likely slow the adoption of this sort of a system. However, if the system provides good value, high quality, and allows for new benefits to the consumer, like customization and adaptability, it is only a question of creating consumer awareness. Consumer awareness can be created by finding high profile lead users, like Bob Villa, and through effective marketing. Andre Chaszar, a structural engineer, suggested first concentrating on performance rather than newness. Another homebuilder suggested that high-end apartments in New York might be a good first market. While expressing some concerns, the experts also had many positive things to say. “Modularity is good for construction.” “Great job thinking through market and trades.” In general they seemed to feel that this was where the industry needed to go, though change can be painful. “Suffolk is already doing something similar, but less advanced, for dormitory construction.” “Already going in this direction – modular.”

Building and Fire Code

Another concern brought up frequently was building and fire code. Because this is a new type of construction it does not fit into the traditional code. Similar to the consumer acceptance if the product is good the code can be dealt with. That is not to say that it is not a concern or will happen by itself, only that it can be dealt with as long as the system is safe and well engineered. The biggest difficulties from a code point of view are likely to be the new material and the possibility of incompliance created by moving infill. The material is structurally satisfactory, the problem will be the risks it poses in a fire due to a decrease of structural properties and out gassing. Michael Grover, a Cambridge building inspector, said “the out gassing is not as much of a concern as the loss of structure, because everything in houses outgases.” Most household rugs, furniture, decorations, and appliances emit toxic fumes when burned, and they generally burn first. The decrease in structural properties at 160 degrees is a concern, but should not

present a safety issue, because it is unlikely to cause a building collapse. First of all, once the home is built the pultrusion would be additionally supported by the infill and would not need to provide as much strength. Further, according to Pultex Pultrusions the decrease in structural properties is minimal. In any case, to deal with this concern and in general add safety, the design was modified to include quick response sprinklers that could activate to extinguish a fire at temperatures as low as 135 degrees. Another fire concern brought up was cavities going throughout the building such as the HVAC ducts and power raceways. This problem is easily addressed by adding fire rated, snap in, walls periodically in the raceways. The HVAC ducts will not need additional fire breaks, because they will already be separated to only serve one or two rooms each. The other code issue involves compliance to codes, such as, outlets must be placed every 12 feet, separate living spaces must be divided by a fire rated demising wall, and egress. The system by no means prevents these regulations from being met, the concern is that because infill is so easy to move homeowners will create illegal and possibly dangerous situations. These concerns can be dealt with through education of homeowners, new regulations concerning reconfiguration, and perhaps infill that prevents a problem, for example putting an outlet in every wall panel or making every wall panel a rated demising wall. One positive note on code issues is that "The system would be transparent to building inspectors allowing them to inspect in half the time. Plus some inspection could be done right in the factory." This would help relieve the strain on building inspectors, and allow them to better ensure safety and quality.

Cost

Cost is also a major concern with any new system. In order for the chassis + infill system to be successful in the marketplace it must have a total cost that is similar to that of a traditional site built home. This is possible if the system reaches the necessary sales volume. By making a number of assumptions, a cost estimate for the proposed system can be generated. Assuming a volume of 1,000 homes, which is equivalent to approximately 750,000 feet of pultrusion, Pultex pultrusion quoted a price of \$1.80 per pound. Assuming economies of scale and advanced production methods the cost of finished pultrusion parts, in ten years, could be expected to drop to almost the current cost of raw materials (approximately \$1.00 a pound), because the process is very simple, and requires very little labor or energy. However, for now \$1.80 is used for estimations. Using this cost per pound the 100 pound 9' column would cost \$180. In the current design beams would cost an estimated \$15 per foot. The cost of a factory produced infill panel is estimated at \$500. The Hilti connectors were quoted at a bulk price of \$33 per box of 25.

Therefore, the entire cost of materials for an average, 2500sqft, chassis + infill home is estimated as approximately \$173,000. As expected this material cost is significantly more than the average material cost for a similar traditionally constructed home, \$62,500. However, the estimators and professionals in the building industry interviewed estimate that the new process will reduce labor and associated costs enough to shift the ratio of labor to materials from 70/30 to 20/80. This would place the cost of the entire chassis + infill building at approximately \$216,000 as opposed to \$208,000 for a traditional home. This savings in labor costs when better engineered materials are used has been observed in other industries, for example companies using busway systems like the one used in the system have observed similar savings for their product as compared to traditional wiring, Figure 5.1. See Appendix I for calculation details.

	Conduit & Wire, Panels & Breakers	StarLine Track Busway & Breakers
Material Cost	\$ 2,830.00	\$ 9,149.00
Contractor Labor Cost	\$10,659.00	\$ 1,500.00
Total Installed Cost	\$13,489.00	\$10,649.00
Savings		\$ 2,840.00
% Savings		21%

Figure 5.1 Cost Comparison for Electrical Busway

This chart shows an installed cost comparison of traditional electrical wiring to the Starline electrical busway system (equivalent to the busway used in the chassis + infill system), published by Universal Electric Corporation. A similar comparison can be made between traditional construction and the chassis + infill system as a whole.

While expressing feelings that the cost must be comparable to that of a traditionally built home, most of the experts were also very optimistic about the cost of the new approach. "After the learning curve, I expect a 15-20% savings could be achieved due to better quality control and lower labor requirements," proffered the president of Tocci Construction. A wire manufacturer observed, "The system would allow an experienced professional to install wiring quickly so it works! That alone is worth a lot of money." A construction manager was excited, because "The new system would allow a large decrease in time spent managing the process." An estimator commented, "Using this system I could make a 98% correct budget estimate, because there is less contingency." The insurance group offered "We would most likely charge the same for a house built using the chassis + infill system as a traditional house" and "Repair costs could be less with the chassis + infill system because parts can be replaced so easily." All around the experts seemed to expect low cost. "It is mass-produced so it will be cost effective." "Many many economic plusses." "I think this system will provide affordable housing." Finally, a professional estimator suggested the system "would save upwards of 30%!"

Industry Acceptance

The cost estimate above assumes a certain volume and level of assembler proficiency. It will take a large capital investment to set up factories and train labor to reach those numbers. Besides efficiencies of scale another reason high production is crucial is to address the acceptance concern brought up earlier. There must be sufficient infill options that the consumer can meet their customization needs. Creating this sort of volume and production facilities would require one of a few very large construction companies to take on the project or for a consortia of companies to work together. Part of the reason getting started will be difficult is that the building industry is very resistant to change. The NAHB is likely to resist the change as well as unions of all sorts. However, most of the builders and manufacturers interviewed did not share this resistance. They expressed desire to be part of implementing a system of this sort. This result may in part be due to self-selection by those builders who choose to participate, but nonetheless it is a promising sign. Their comments included, "I would like to control the sales process from beginning to end with a more direct relationship with the customer and I think this system could help me achieve that," "I would be willing to try and implement a system like this

in order to differentiate myself from my competitors.” “If the cost of components is reasonable I would adopt the system because there is value-added for the customer” “I would reorganize my business to use this system in order to take advantage of the decreased time from start to finish” “I would like to offer this product to my customers. If we got in early the potential is for great profit.” “I could produce infill panels. It would be a new product, but not a big departure. It would compliment what we do now (pre-hung doors, window assembly). I am interested in being an infill manufacturer...” “Not having to fit out the interior of an apartment until the buyer is present would lower my risk considerably.” “Installers would reorganize their businesses to take advantage of this system because it offers a new opportunity to generate money.” If the companies within the building industry are not able to take the initial risk of changing to a new system, one possibility is that a company from another industry that has interest in the home, such as Microsoft, could see the potential profit in the system and take it on, either entirely or by sponsoring a construction firm. In any case a large amount of venture capital will be required to fund the project. One way to reduce the risk involved is to target a contract based market such as the government. Military bases have thousands of homes and re-configuration would be useful due to the nomadic nature of military officers.

Labor

By definition this system would cause a reduction in labor needed, which would likely generate resistance from unions. This fact should not be allowed to prevent the system from being successful; any improvement in efficiency causes a reduction in the need for labor, that doesn't mean that industries should move to the least efficient process possible. Furthermore, the labor shortage is one of the problems the system is designed to address. “The new system may cause a loss of jobs, but that is okay, because there are less and less skilled people available anyway.” “I like how you have built the specialization into the product rather than the labor. This is needed in an era of declining per capita labor pool.”

Standards

Another concern is that traditionally it has been difficult for industries to agree on standards. There have been some significant successes in the computer industry, but there have also been many problems, including companies that have disappeared due to tying their success to a failed standard. Hopefully this will not be as much of a problem in this case because a major university is spawning the discussion, the standards will be non-proprietary, and can be fully agreed upon before manufacturing must start.

Functional Requirements

There were also a number of concerns related to how well the system met some of the functional requirements. Descriptions of how the system meets the functional requirements will be presented in sections 5.2 and 5.3, Qualitative and Quantitative analysis respectively. What are discussed here are the issues that seemed particularly important to the industry experts or that required a change in the system.

Mass Customization

Mass customization is one of the primary goals of the system. However, one construction expert said the system was “too modulated, even if it's just a perception I feel limited.” He agreed that in fact this system would most likely allow him a greater variety of

choice, because the developer sets his choices currently. However, because traditional construction technically allows any geometry and any design and the chassis + infill system puts some bounds on the possible designs, there can be a perception of lost choice. This comes back again to the acceptance problem. The consumer must be educated to understand why this approach offers more choice and is higher quality. Most of the interviewees expressed positive views of the system's ability to provide customization, often expressing that it could be used to build their ideal home. They also suggested that the customization was important and would be valued by the consumer. "I would be willing to invest more time to customize my home." "This system allows homeowners to customize economically." "[The chassis + infill system] combines small components to provide versatility." "I like the flexibility and availability of mechanicals distributed throughout the building." One interesting observation by Jim Sheridan related to finding a home, "I wouldn't have to look at so many places when shopping for a condo. First I could find the geography I wanted, and then customize the interior instead of compromising between the two."

Adaptability

The other primary goal of the system is adaptability. There were some concerns related to this as well. One interviewee commented that while the system was versatile it did not allow for all scenarios, moving a bathroom is difficult, and the type and volume of the home is difficult or impossible to change. For example a single family home cannot become a six story condo building and visa versa. His concern is valid, but to keep the system economically feasible the possible change must be limited somewhat. Another expert made the opposite comment suggesting that it may be cheaper to build and destroy a drywall structure multiple times rather than pay for a rolling infill element. The drywall solution might be cheaper for the do-it-yourselfer who is willing to deal with the mess and disruption demolition of drywall causes if she only moves the wall once or twice. However, if the wall contains electrical or data wiring it can quickly become a very difficult and expensive task. Furthermore, the infill is intended to offer an easy and nondestructive way to make changes that ordinarily would be too difficult and expensive, not just to make what remodeling is already done easier. A third concern related to change addressed component aging. Often new materials do not match old materials. This presents the same problem for the chassis + infill system as for a traditional system. However, the chassis + infill system would make replacing all of the affected material easier. Better materials engineering could also solve the problem, but that is beyond the scope of this paper. Despite these concerns, a majority of the interviewees expressed confidence in the systems ability to provide adaptability, noted it would be beneficial, and expressed a desire to use this function. "It would allow families to stay put through change." "I would use the systems ability to upgrade." "I would like to be able to change my house. Right now I would like to change my upstairs." "I had to move four times to accommodate [new] kids." "I would like to be able to change spaces from interior to exterior." "I would use movable walls to make spaces larger for parties." One builder made an interesting observation that the adaptability of the system would probably be helpful before the building was even finished. "The ability to easily change things would help alleviate one of my biggest problems which is dealing with customer changes demanded in mid construction."

Technology Infrastructure

Concerns related to technology infrastructure were limited to turning radius and connections. Turning radius can be easily provided for with curved fittings at corners. The connections must allow for some misalignment of components, be simple, reliable, and corrosion free. This should not be a problem because the busway manufacturers have already dealt with these problems under similar circumstances. The infill panels will simply use standard connectors on short pigtails to allow for misalignment. One possible area for improvement is the connection between cables and the busway. This could potentially be improved by conversion to a plug system rather than manual wiring, but because there are very few of these connections in a typical house it is not a change that is immediately necessary. The allowances for technology infrastructure generally generated positive feedback. “[The technology infrastructure] allows a house to be cost effectively designed to include modern features.” “I would like more technology in my home, and I think the chassis + infill system would facilitate it.” “The easily accessible raceways would allow the simple replacement of wiring defects.”

Quality

Quality was a major concern, largely because the current modular market is associated with poor quality. Back to acceptance again, it is crucial that the system look high quality in addition to being strong and reliable. “It can’t seem futuristic or shoddy.” “It should seem durable, homey and comfortable.” This is difficult with any component based system because any errors in manufacturing will translate into steps and gaps between components. However, the chassis + infill system is expected to be far superior to traditional modular building because it takes advantage of highly accurate and controllable manufacturing processes and uses smaller pieces, in addition to the efforts mentioned in the last chapter to ensure high quality. Two sixty foot wooden boxes handmade by nailing boards together can be expected to be slightly different sizes, but two three foot panels made by a CNC machine should not have much variation. In addition the system allows for reveals, which hide slight errors, and where necessary slight imperfections can be covered by added finish: for example the rain screen on the exterior. The industry experts offered huge number of positive comments on the possibilities for quality improvements. They agreed that the current situation had a number of problems including materials, design, manufacturing, and assembly. On-site assembly and construction problems were brought up most frequently. Materials: “Wood can warp badly causing misalignment of walls and cracking of finishes.” Design: “As it is buildings are just too complicated, architects can’t keep up and then they screw up.” Manufacturing: “Pultrusion would last longer and provide more value than traditional pre-fab.” Assembly: “Current developer construction needs reform. What they do now can be described with the acronym CATNAP (cheapest available technology narrowly avoiding prosecution).” “15-20% of on-site labor is spent on rework.” “100 things are left incorrect at an average suburban home construction site.” “There are quality and workmanship issues on finishes and details.” “Wiring and piping requires a lot of onsite labor and this system would relieve that problem.” They also expressed confidence that the new system could help with these problems. For materials, the pultrusion manufacturer said “I could produce structural pultrusion to ± 0.005 inches and pultruded panels to ± 0.01 inches.” This is far superior to currently available materials. “Architectural design would be easier because it is systematic, but would still be flexible enough.” “It’s like building and designing with a kit of

parts. An ordered system approach would help architects immensely.” Manufacturing would be better, because “It is made in a controlled environment, so it will be high quality.” Perhaps partly because they knew the most about on-site assembly or because the system is focused on relieving the on-site problem most comments focused on that topic. “I would only have to train one person as an assembler, rather than an electrician, plumber, HVAC, etc.” “The ability to cut out the subcontractor and have more power over quality control would help my business a lot.” A contractor commented, “This system would be much easier to learn than traditional construction because there are fewer details and components.” The wire manufacturer noted, “Staples damage cable, wire is bent at too sharp an angle, cables are connected wrong, and the wrong cable is often used. The chassis’ raceways allow no staples, no incorrect bend radii, and bring the wire to a standard connector” and “raceways remove the need for excessive connections and help with installation time.” Some additional benefits of reduction in labor were noted. “There is less liability when there is less labor, less human error.” “The reduction in labor costs would allow more energy efficient materials, windows, shutters, etc. The home owner would be empowered to help the environment!”

Physical Strength

The physical strength of the system only generated a few minor concerns. One structural engineer noted that the floor must provide diaphragm strength. This was already assumed in the design, but it is important in that all the floors between any two walls should not be removed, an unlikely occurrence, but nonetheless important to note. A more significant concern is that it is difficult to fasten composites and plastics with point connections. However, given the expected loads on all of the connections this should not present a problem. This is precisely why the system was not designed with connectors bearing large structural loads. Instead all major loads are transferred by direct contact and connectors are merely used to keep components from shifting. Another important concern was that in order for components to be strong enough they may not be light enough for assembly workers to move by hand, despite the use of the composite. This will be examined fully in section 5.3. One engineer noted the lack of mention of stairs. This is because like the walls and floors, stairs would be infill, not a required part of the structure, allowing them to be moved and separately engineered. There were also positive remarks on this aspect of the system from the structural engineers interviewed. “The structural system seems reasonable as long as the floors have diaphragm strength.” “If wind loading is okay seismic strength will be okay.”

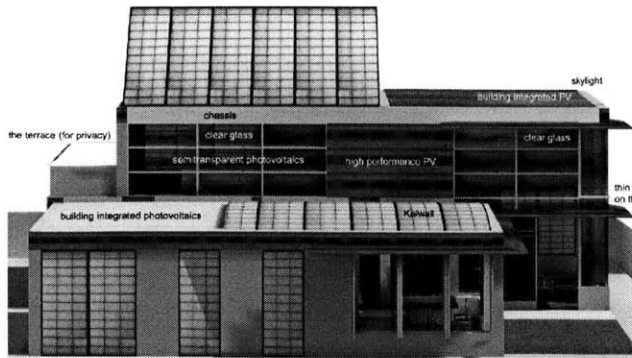
Controlled Space

The final functional requirement, to provide a controlled space, also received attention from the experts. One noted that the beam did not allow for air return. The air return is located in the riser next to the air supply, one per 300sqft. Another engineer was concerned about condensation in air ducts, and another about noise, both of which can be easily addressed by factory installing insulation inside of the ducts. The insulation would not add very much cost. Keeping water out of a system made from removable parts was also a concern. Though not tested, the double rubber seals, flashing, and drainage system should prevent any problems, but if it does not it would be acceptable to simply caulk all joints and remove and replace the caulking when exterior infill is moved. This is not ideal, but could still be easily performed by the homeowner. Overall, the people who dealt with weather sealing felt that the system would need to be tested and carefully detailed, but did not expect there to be a problem.

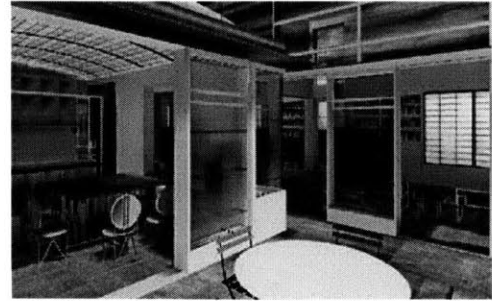
5.2 Qualitative Analysis

Does the system provide mass customization? Adaptability? Important opportunities for technology integration? Higher quality? These functional requirements cannot be calculated or measured without building the system. However, a solid case can be made for each beyond the comments of the esteemed industry experts.

In order to offer mass customization, the chassis must allow for many geometries, see Chapter 4, and the infill system must create the opportunity for many aesthetic possibilities. To demonstrate that this is the case, two very different aesthetics were developed using the system. The first is a modernist aesthetic, which expresses the joints in the system, Figure 5.2. The second shows the same chassis structure with different infill to create a more traditional Greek Revival expression, Figure 5.3. The system offers the opportunity for a wide range of possibilities between these two as well. Even a basic colonial clapboard home could be created by using a clapboard rain screen to create the monolithic façade, Figure 5.4.



Kent Larson



Kent Larson

Figure 5.2 Modernist Chassis + Infill Example

This expression puts the structure on display and expresses the joints giving a cutting edge feel to the home.



Kent Larson

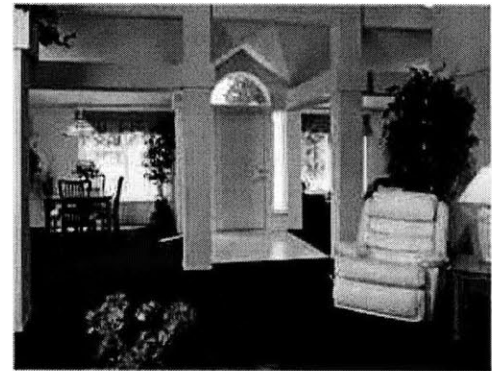


Figure 5.3 Traditional Chassis + Infill Example

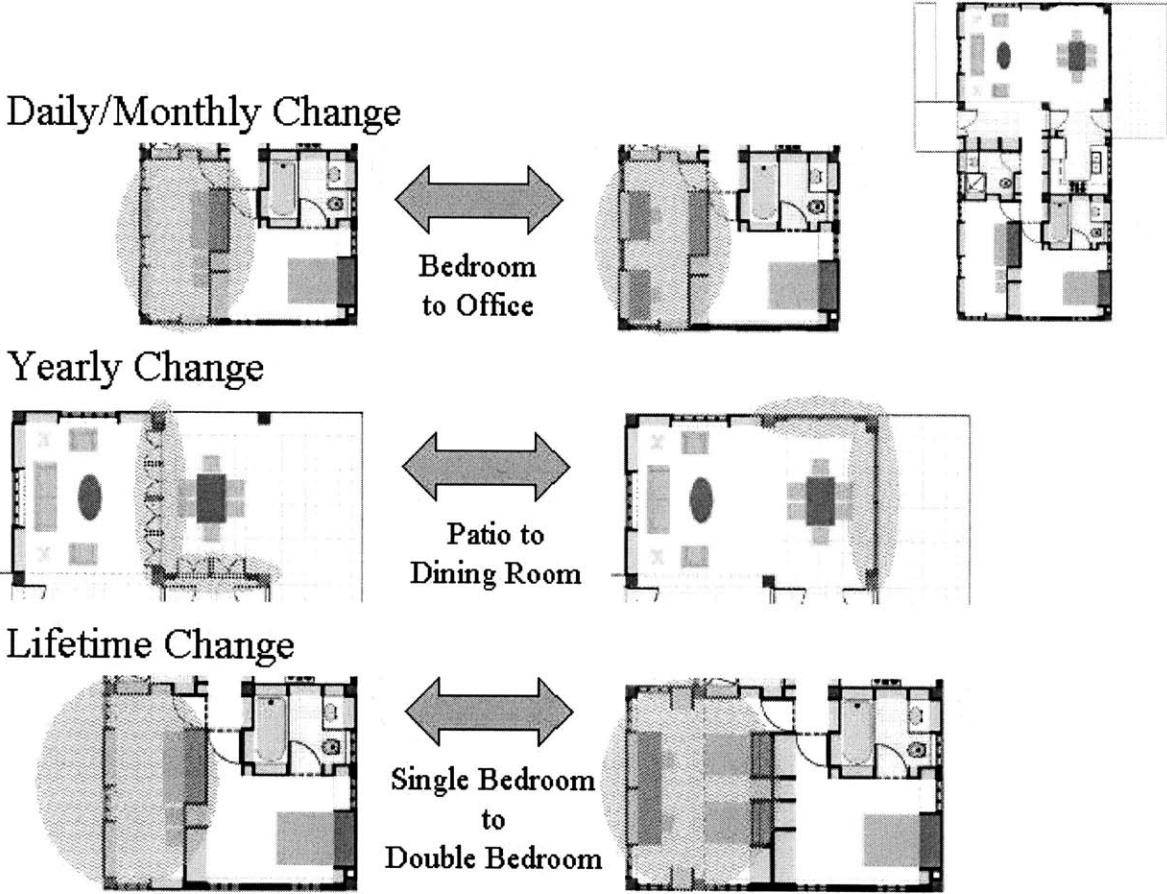
This expression is more traditional, offering a return to fine detail made possible by efficient factory manufacturing. This system uses the same chassis as the home above, only the infill and cover plates have been changed to achieve this very different aesthetic.



Figure 5.4 Clapboard Chassis + Infill Example

This home hides the chassis components behind a monolithic rain screen, giving the appearance of a traditional stick-built colonial house.

The chassis + infill approach also provides well for adaptability. Figure 5.5 shows an example layout using the post and beam chassis and some example changes at three time scales. Daily and monthly change is made possible by using special transformable infill such as foldaway desks and Murphy beds, even swinging walls to create multi-use space. Yearly change would likely involve moving infill to change the size, number, or type of rooms. Windows could be added or moved. Exterior spaces could be made interior. The last timescale is lifetime change. Lifetime change is likely to involve additions and major changes driven by new owners or family members moving in or out. During lifetime change, infill could be moved and exchanged, and chassis elements could be moved or added to create a different structure.



T.J. McLeish

Figure 5.5 Adaptability Scenarios

Using an example layout (top right) three examples of possible change are shown, each takes place on a different time scale. The first example is a daily or monthly change in which a bedroom is converted to an office by means of special transformable infill elements. The second example might happen on a yearly basis to convert an exterior patio to an interior dining room for the winter, by moving infill elements. The last example takes place on a lifetime scale and shows an addition where chassis and infill components are added to make room in a bedroom for a second child.

Adaptability could also include upgrade of finishes, technology, or simply building components. In the volumetric chassis, multifamily example, adaptability would not include additions to the space or structural changes, but could still include transformable and movable infill. Figure 5.6 shows how the volumetric chassis could be adapted to meet the needs of many possible residents or situations.

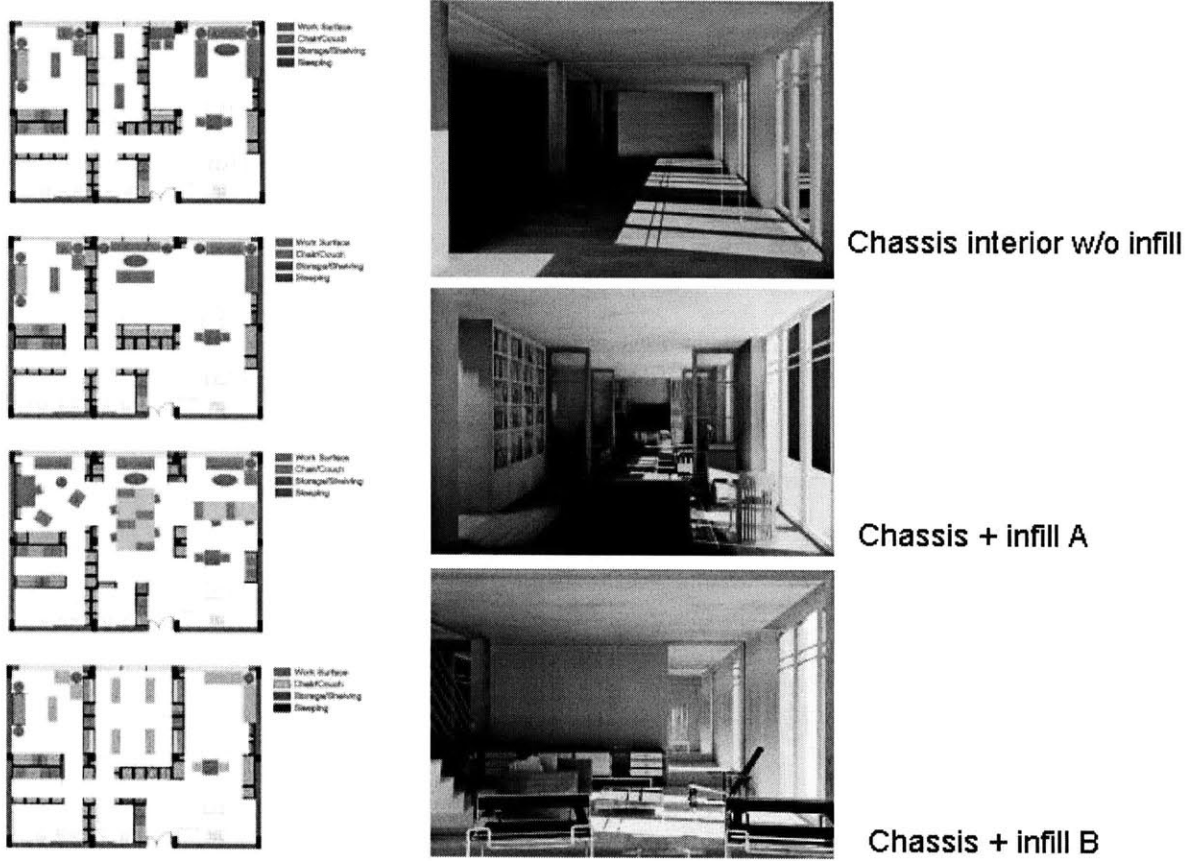


Figure 5.6 Adaptability Volumetric Chassis Scenarios

Kent Larson, T.J. McLeish

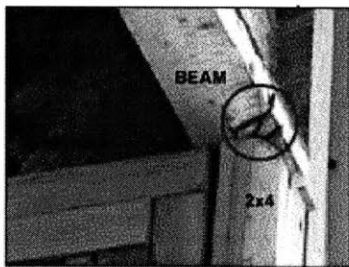
On the left a variety of possible layouts are shown, from an apartment for a family of four on the top, to a couples pad, to a home/office, to a packed economy space for a family of six. The same space can provide for a vast array of uses by moving and changing infill. On the right the empty volumetric chassis space is shown followed by two examples of infill that could fill the space.

Technology infrastructure is an important focus of any forward-minded residential study and the chassis + infill system provides for it well. The chassis brings power and data wiring to all areas in easily accessible raceways, and delivers the power and signal to the infill through simple connections that can be made anywhere along the length of the beams. The wiring can be easily installed during construction (in the case of the volumetric chassis at the factory) or it can be installed just as easily at any time during the building's life. This makes it easy to upgrade the infrastructure as necessary. The factory-manufactured infill allows technology to be embedded in walls and furniture in an inexpensive and unobtrusive way. For example an infill cabinet element might come with sensors already installed. Simply plug that cabinet in and all of those sensors are now part of the home network. A related question is what kind of technology might actually take advantage of this advanced infrastructure. First there are many systems already in the average home that will be made more efficient by sharing a single infrastructure. For example, HVAC control, television, phone, computer, and security system networks. Lighting

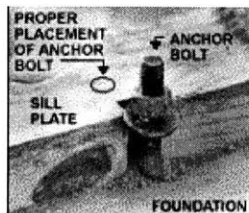
will also take advantage of the network because there will not be any hard connections between lights and switches, or any control systems, because infill elements might be moved. Instead the control elements such as thermostats, doorbells, and light switches will send a data signal telling their respective devices what to do. This allows light switches, other controls, lights, and other devices to be easily moved and re-assigned to one another. Other new systems might include energy management, energy generation, communication, education, and preventative healthcare. Without the chassis + infill system it might be many many years after these technologies are developed that they finally make their way into the average home. However, if they are inexpensive to install because the necessary infrastructure is easy to install or better yet already in place then they will penetrate into the mass market much more quickly.

The system should also provide higher quality than the traditional approach. This is made possible through high quality materials, a system structure that makes good design straightforward, components that are easy to manufacture, and a system structure that is so easy to assemble it is almost impossible to make any significant errors (even if an error is made, because the system is adaptable it may be easily corrected). Due to labor shortages and material quality problems, the current industry is producing very shoddy products. Producing something better will not require anything spectacular. Figure 5.7 shows some serious quality problems discovered in high-end Boston construction. The figure also shows some new materials that may be economically feasible if they were infill rather than specialty products. Currently as specialty products, installing them requires a highly trained and expensive specialist. As infill they could be installed in a moment by anyone, just like any other infill element.

Construction Quality



A load-bearing joist is inadequately supported by a single vertical 2-by-4.



New Possible Finish Materials

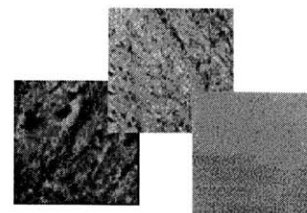
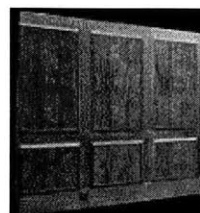
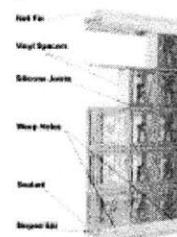
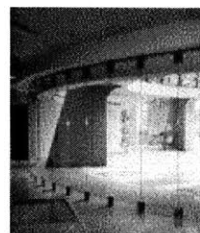
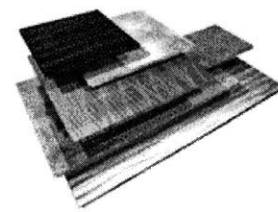
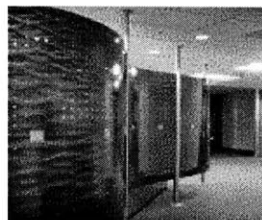


Figure 5.7 Quality Improvements

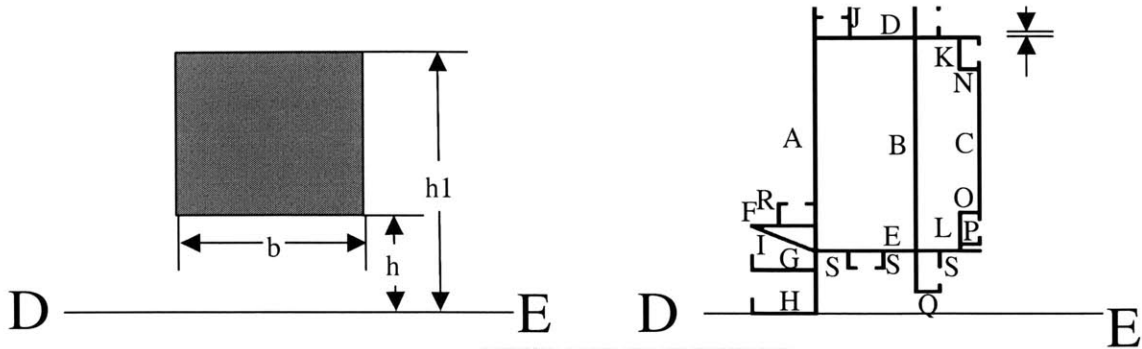
On the left are some examples of quality problems: improper support, storage of materials in snow, and improper attachment to the foundation. These types of mistakes are all too common in the industry today. On the right are some new finish materials, which could become available once labor is removed from their cost.

5.3 Quantitative Analysis

The last two functional requirements, physical strength and controlled space, can be estimated with reasonable confidence. This section will feature some calculations intended to demonstrate that the structural components and mechanical systems of the chassis are sufficient.

A live load of 100lbs/ft has been assumed for every area of the home. This number is generally reserved for public gathering areas, but was chosen to make the estimation conservative. The floor is infill, and as such has not been designed or analyzed except to say that there is 11.5 inches left for the floor, which should be more than enough space to provide the required strength even if traditional joists are used. The beams and columns, however, were analyzed based on the 100lbs/sqft live load requirement and an additional constraint that they not deflect by more than $L/360$. This second constraint is important to ensure there is no perceived deformation and all infill panels can still be easily removed and added. Figures 5.8 and 5.9 show in more detail the calculations mentioned in Chapter 4. The calculations were made by using formulas provided in Pultex Pultrusion's global design manual. They have verified these formulas through extensive testing. The beam bending is very similar to simple beam bending, but the column strength is based heavily on shape in order to account for different failure modes. The shear strength of the flanges onto which the infill panels are attached is 7000lbs/ft. This means that they should have no problem withstanding a wind force over 100 lbs/sqft. The strength of the connections used throughout the system, whether on a T-slot or through a standard slotted hole, is roughly 500lbs in tension and 400lbs in shear. See Appendix H for details. The connector itself can withstand 2000lbs in tension and 1500lbs in shear. The weak point in the connection is the composite. If a better strength to weight ratio was needed an epoxy and carbon fiber pultrusion could be used rather than polyester and glass fiber. This would also raise the glass distortion temperature to 320 °F, but would raise the cost of the chassis 20-30%.

The mechanical systems designed to work with the chassis are also completely sufficient if not exemplary. The chassis provides for three inches of insulation. The infill which covers the majority of the façade can have whatever amount of insulation is desired. Three inches of insulation will provide an R-value of 20 if standard polyurethane foam is used. If Aerogel, an advanced insulating material, is used only a half inch would be required to provide the same R-value. The standard for walls set by HUD is R-19. The HVAC distribution system will provide a complete exchange of air every 9 minutes by delivering 1cfm per sqft. Because there is a duct for every 150 sqft of floor area, and the duct is four inches by eleven inches, after subtracting for a half inch of insulation, the airspeed in the duct will be approximately 500 feet per minute. The linear diffuser will provide so much area that the airspeed out of the diffuser will be less than 100 feet per minute, thus generating very little noise. See Appendix H for details. The weather seal should be tested and modified as necessary to achieve the best seal possible. However, the experts interviewed were confident that the flashing, combined with a single plane, double ring seal with directly applied pressure, should be sufficient. The inner seal will be permanently attached to the infill and the outer seal permanently attached to the chassis, such that even in the case that the seal is kept open for some reason, there still will be no direct path through the seal. Furthermore, the path to the seal will require a turn on each side, making it unlikely that water will find it's way through. Drainage holes will allow any water that comes partway through the water seal structure to drain back out.



Enter values in yellow cells

Results are in red cells

Thickness (t) 0.125 inches

Piece	Bredth (b)	Top dist. from DE (h1)	Bottom dist. from DE (h)	Height (h1-h)	Area b(h1-h)	$h1^2$	Moment $(b(h1^2 - h^2))/2$	$h1^3$	I about DE $(b(h1^3 - h^3))/2$
A	0.13	18.00	0.00	18.00	2.25	324.00	20.25	5832.00	364.50
B	0.13	18.00	1.25	16.75	2.09	324.00	20.15	5832.00	364.38
C	0.13	14.56	5.44	9.13	1.14	212.07	11.41	3088.22	182.97
D	8.59	16.00	15.88	0.13	1.07	256.00	17.12	4096.00	409.29
E	8.59	3.81	3.69	0.13	1.07	14.54	4.03	55.42	22.66
F	3.50	5.19	5.06	0.13	0.44	26.91	2.24	139.60	17.24
G	3.50	2.69	2.56	0.13	0.44	7.22	1.15	19.41	4.52
H	3.50	0.13	0.00	0.13	0.44	0.02	0.03	0.00	0.00
I	4.00	4.00	3.88	0.13	0.50	16.00	1.97	64.00	11.63
J	0.13	18.00	16.00	2.00	0.25	324.00	4.25	5832.00	108.50
K	0.13	16.00	14.00	2.00	0.25	256.00	3.75	4096.00	84.50
L	0.13	6.00	4.00	2.00	0.25	36.00	1.25	216.00	9.50
M	1.50	18.00	17.88	0.13	0.19	324.00	3.36	5832.00	90.49
N	1.00	14.19	14.06	0.13	0.13	201.29	1.77	2855.73	37.41
O	1.00	6.00	5.88	0.13	0.13	36.00	0.74	216.00	6.61
P	1.00	4.19	4.06	0.13	0.13	17.54	0.52	73.43	3.19
Q	1.50	1.25	1.13	0.13	0.19	1.56	0.22	1.95	0.40
R	0.13	6.44	5.19	1.25	0.16	41.44	0.91	266.78	7.95
S x3	0.38	3.63	2.38	1.25	0.47	13.14	1.41	47.63	6.42
Totals				Area (A)	11.57	Moment (M)	96.52	I_{DE}	1732.15

Distance from DE to neutral axis (d)	= M/A	8.34 inches
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Moment of inertia of section	= $I_{DE} - Ad^2$	927.02 in ⁴
------------------------------	-------------------	------------------------

Length (span)	15 feet
Acceptable deflection L/360	0.50 inches

Beam Weight per foot	8.33 lbs/ft
Total Beam Weight	125 lbs
(simply supported at both ends, uniform load)	
Total Allowable load	898 lbs/ft
Less Beam Weight	889 lbs/ft
Live Load max (100lbs/sf)	750 lbs/ft

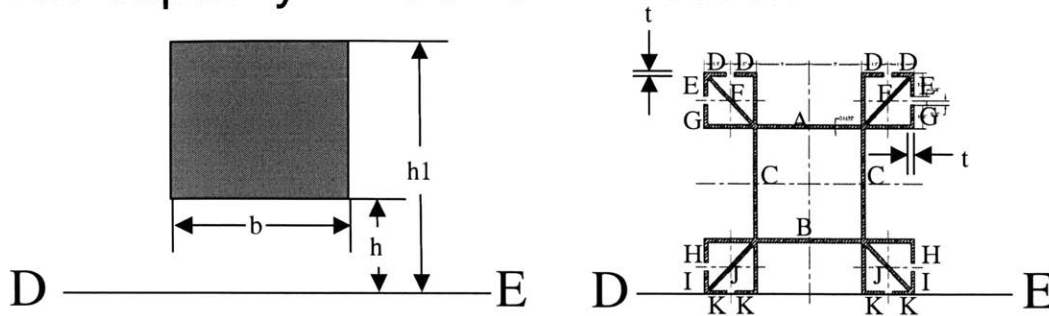
	young's modulus	density (lbs/in ³)	shear modulus
Aluminum	1.02E+07	0.098	
Pultex	2.8-4.0 E+06	0.06-0.07	5.00E+05
Steel	2.95E+07	0.28	
Wood (pine)	1600-2000	0.014	

young's modulus	2.80E+06 psi
density	0.06 lbs/inch ³
Shear modulus	5.00E+05 psi
Shear Area	6.88 in ²
Cost per pound	1.80 \$/lbs
Cost for Beam	224.93 dollars

Figure 5.8 Beam Load Capacity

The beam is both light enough to be installed without heavy machinery and strong enough to withstand the most extreme loads in could be subjected to without deflection over L/360. These numbers have been calculated by finding the moment of inertia around axis DE and applying basic beam bending theory, including shear to determine deflection at the center of the beam, as recommended by Pultex pultrusions.

Load capacity for COLUMN section



Thickness (t) 0.19 inches
 Flange Width (f) 1.3125 inches

Enter values in yellow cells

Results are in red cells

Piece	Bredth (b)	Top dist. from DE (h1)	Bottom dist. from DE (h)	Height (h1-h)	Area b(h1-h)	$h1^2$	Moment $(b(h1^2 - h^2))/2$	$h1^3$	I about DE $(b(h1^3 - h^3))/2$
A	12.00	8.69	8.50	0.19	2.25	75.47	19.34	655.67	249.26
B	12.00	3.50	3.31	0.19	2.25	12.25	7.66	42.88	39.17
C*2	0.38	12.00	0.00	12.00	4.50	144.00	27.00	1728.00	324.00
D*4	5.25	12.00	11.81	0.19	0.98	144.00	11.72	1728.00	209.32
E*2	0.38	12.00	10.69	1.31	0.49	144.00	5.58	1728.00	95.11
F*2	0.38	12.00	8.50	3.50	1.31	144.00	13.45	1728.00	208.85
G*2	0.38	9.81	8.50	1.31	0.49	96.29	4.51	944.80	62.00
H*2	0.38	3.50	2.19	1.31	0.49	12.25	1.40	42.88	6.08
I*2	0.38	1.31	0.00	1.31	0.49	1.72	0.32	2.26	0.42
J*2	0.38	3.50	0.00	3.50	1.31	12.25	2.30	42.88	8.04
K*4	5.25	0.19	0.00	0.19	0.98	0.04	0.09	0.01	0.02
Totals				Area (A)	15.56	Moment (M)	93.38	I_{DE}	1202.27

Distance from DE to neutral axis (d)	= M/A	6.00 inches
Moment of inertia of section about neutral axis (I_N)	= $I_{DE} - Ad^2$	642.02 in ⁴
Radius of gyration of section (r)	= $I/A^{1/2}$	6.42 in
Ultimate compressive stress (σ_{ult})	see apx	21.60 ksi
Allowable compressive stress	= $\sigma_{ult}/3$	7.20 ksi

	young's modulus	density (lbs/in ³)
Aluminum	1.02E+07	0.098
Pultex	2.8-4.0 E+06	0.06-0.07
Steel	2.95E+07	0.28
Wood (pine)	1600-2000	0.014

Length (span)	9 feet
Slenderness KL/r	=short

Acceptable deflection L/360 = 0.30 inches

Column Weight per foot	11.21 lbs/ft
Total Column Weight	100.35 lbs

young's modulus	2.80E+06 psi
density	0.06 lbs/inch ³
Composite bearing str	30 ksi
Cost per pound	1.80 \$/lbs

(assuming pin joints at at both ends)

Total Allowable load	112,042 lbs
max applied load (3 floors)	67,500 lbs

Cost for column	181.50 dollars
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Figure 5.9 Column Load Capacity

The column is both light enough to be installed without heavy machinery and strong enough to withstand the most extreme loads in could be subjected without significant deflection. This strength has been found by using the most conservative of the formulas suggested by Pultex pultrusions.

Chapter 6: Conclusion

6.1 Summary

The problems with the housing industry are real and will only become more pronounced in the future. Good labor will continue to become more expensive and more difficult to find. The quality of wood framing will continue to decrease as the resource becomes more and more scarce. The consumer will learn that the industry can provide more and will start to demand it. They will demand personalization, adaptability, the infrastructure to incorporate the technologies that are important to them, and a high quality product at a reasonable cost. The players who move to meet those needs and at the same time address the labor and material issues will take over the industry.

A system like the chassis + infill system is inevitable, and it may not even be that far off. When the pressure is great enough and the technology and cost is appropriate some players in the industry will make the move to a better way of providing people with housing. The industry has already started down this path by adopting some modular approaches, all that is needed now is for someone to step back and take a system view. Something like the chassis + infill will be the obvious conclusion.

The chassis + infill approach is a system architecture, which takes advantage of new technology and allows many companies to work together. It allows factory-manufactured components to be easily assembled on-site to create a mass customized, adaptable, high quality, high tech, and high value home. This is made possible by dividing the house into chassis and infill. The chassis provides the structure and services for the building, and the interchangeable infill wall and floor components provide for customization and adaptability.

6.2 Future Work

To make the chassis + infill system a reality there are many aspects that remain to be examined. A few potential infill panels should be developed, prototyped, and placed in real living environments for testing. A prototype of this system or one like it should be built to verify its feasibility. A design tool must be developed that can allow the homeowner to understand and meet their needs without the financial burden of an architect that is currently required. This kind of a tool is currently being pursued at House_n by Reid Williams, Jennifer Beaudin, and Thomas J. McLeish. There is also work to do developing a strong business case for how this product can be brought to market and defining the new network of business relationships that will be required. Finally, a consortia or alliance should be formed between industry and those researching this kind of advancement. By working together, something can be developed that the industry participants could use to revolutionize their business. This is currently being pursued by Changing Places in the form of the OSBA, Open Source Business Alliance.

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Appendices

Appendix A

Functional Requirements

Beam

FR	DP	Analysis	References	Risks	Countermeasures
Carry weight of floor/roof and panels (100 Lbs/ft ²) (L/360 Acceptable deflection)	Pultrusion	find I, E, basic beam bending	mach. Hand	failure, creep, stress concentrations, holes cut for ventilation/plumbing	thicker walls, careful section design
	Steel, Aluminum protrusion	find I, E, basic beam bending	mach. Hand	cost, creep, stress concentrations, holes cut for ventilation/plumbing	thicker walls, careful section design
	natural resin	find I, E, basic beam bending	mach. Hand	failure, creep, holes cut for ventilation/plumbing	reinforce with multi-directional fibers?
	wood	find I, E, basic beam bending	Creative pultrusions	failure, creep, rot, holes cut for ventilation/plumbing	protect, overdesign
provide insulation (R-30 max DOE rec.)	1" aerogel	cabot	Kent	cost	assume mass prod.
	9.5" of Fiberglass	cabot	Kent	too thick	Increase beam size
Carry power (120 V, 20A)	standard wiring in raceways	length req?	Kent, MIT elec	accessability /onsite labor	put wiring on inside under snap on cover
	separate with connectors	# of connectors?	Kent	cost	get standard conn. Assume mass prod.
Carry signal (type of signal) (Banwidth)	standard wiring in raceways	length req?	ken wacks kenn@alum.mit.edu	accessability /onsite labor	put wiring on inside under snap on cover
	separate with connectors	# of connectors?	ken wacks kenn@alum.mit.edu	cost	get standard conn. Assume mass prod.
	centralized, home run	bandwidth	ken wacks kenn@alum.mit.edu	cost/labor	use sparingly/ install when needed
	distributed, network	bandwidth	ken wacks kenn@alum.mit.edu	low bandwidth	distributed network
Provide heating & cooling	centralized, 6"x12" duct	flow	brent griffith Carrier, Titus	difficult to connect, need for mult. purp	separate connectors

	dist. many HVAC units(not in beam)	flow/output	brent griffith, carrier, John Dikeman AD Little	cost, space, aesthetics	assume mass prod. In infill panel
Easily movable (<200 Lbs)	Pultrusion	densityxV=W	Creative pultrusions	need custom mold	glue standard pieces together
	natural resin	densityxV=W		cost	
	wood	densityxV=W	Creative pultrusions	too many nailed connections	glue
minimal cross section	1'x1'6"	solid model	Kent, Tyrone	bulky look	cover with molding, light fixtures, paneling
Can be any length (3ft- [18ft or 60ft?])	uniform structure w/ end caps	solid model	TJ, Tyrone	cost	DFM
	plug into conn. on column	solid model	TJ, Tyrone	difficult onsite labor	standard/simple snap in connections
Must not vibrate excessively	thick pultrusion	freq. Analysis	Joe	cost, weight	stiff, hollow section
	damping material	freq. Analysis	Joe	cost, space	material choice, combine w/ insulation

Column

FR	DP	Analysis	References	Risks	Countermeasures
Carry weight of beams floor/roof and panels (67,500 lbs) (L/360 Acceptable deflection)	Pultrusion	find I, E, compression	mach. Hand	failure, creep, stress concentrations	thicker walls, careful section design
	natural resin	find I, E, compression	mach. Hand	failure, creep	reinforce with multi-directional fibers?
	wood	find I, E, compression	Creative pultrusions	failure, creep, rot	protect, overdesign
provide insulation (20 R -value)	1" aerogel		Kent	cost	assume mass prod.
	9.5" of Fiberglass		Kent	too thick	Increase beam size
Carry power (120 V, 20A)	standard wiring in raceways	length req?	Kent	accessability /onsite labor	put wiring on inside under snap on cover
	separate with connectors	# of connectors?	Kent	cost	get standard conn. Assume mass prod.
Carry signal (type of signal) (???)	standard wiring in raceways	length req?	ken wacks kenn@alum.mit.edu	accessability /onsite labor	put wiring on inside under snap on cover

Bandwidth)	separate with connectors	# of connectors?	ken wacks kenn@alum.mit.edu	cost	get standard conn. Assume mass prod.
	home run	bandwidth	ken wacks kenn@alum.mit.edu	cost/labor	use sparingly/ install when needed
	network	bandwidth	ken wacks kenn@alum.mit.edu	low bandwidth	distributed network
Easily movable (100 Lbs)	Pultrusion	densityxV=W	Creative pultrusions	need custom mold	glue standard pieces together
	natural resin	densityxV=W	?	cost	
	wood	densityxV=W	Creative pultrusions	too many nailed connections	glue
minimal cross section	1'x1' square (thickn. of beam)	solid model	Kent, Tyrone	bulky look	cover with molding, light fixtures, paneling
Can be multiple lengths (8ft or 9ft)	uniform structure w/ end caps	solid model	TJ, Tyrone	cost	DFM
	plug into conn. on column	solid model	TJ, Tyrone	difficult onsite labor	standard/simple snap in connections

Beam to Column or Beam to Beam

FR	DP	Analysis	References	Risks	Countermeasures
Carry weight of beams floor/roof and panels (900 Lbs) (L/360 Acceptable deflection)	Pultrusion	failure mode?	mach. Hand	failure, creep, stress concentrations	thicker walls, careful section design
	natural resin	failure mode?	mach. Hand	failure, creep	reinforce with multi-directional fibers?
	wood	failure mode?	Creative pultrusions	failure, creep, rot	protect, overdesign
Torsional stiffness (TBD Ft-lbs)	brackets	shear? Bending?	Slocum, 80/20, Bosch, Peter Bailey	onsite labor, incorrect attachment	may only be attached one way
	tounge and groove	shear? Bending?	Slocum	cost, strength	bolt/glue
Connect power (120 V, 20A)	standard wiring in raceways	difficulty of setup/removal	Kent	accessability /onsite labor	put wiring on inside under snap on cover
	separate with connectors	# of connectors? How made?	Shri	cost	get standard conn. Assume mass prod.

Connect signal (type of signal)	standard wiring in raceways	length req?	ken wacks, shri kenn@alum.mit.edu	accessability /onsite labor	put wiring on inside under snap on cover
	separate with connectors	# of connectors?	ken wacks, shri kenn@alum.mit.edu	cost	get standard conn. Assume mass prod.
	home run	bandwidth	ken wacks, shri kenn@alum.mit.edu	cost/labor	use sparingly/ install when needed
	network	bandwidth	ken wacks, shri kenn@alum.mit.edu	low bandwidth	distributed network
Connect heating & cooling	6"x12" duct	flow	brett griffith carrier	difficult to connect, need for mult. purp	seperate connectors
	many HVAC units (not in beam)	flow/output	brett griffith carrier	cost, space, aesthetics	assume mass prod. In infill panel
Easily connected	bolts	#, size needed, shear	Creative pultrusions	cost/labor	use minimum number consistant size
	glue	bond strength		non removeable	saw
	snap	yield strength	Creative pultrusions	non removeable, strength	saw, glue
Size should not exceed cross section of beam/column	1'x1'6"	solid model	Kent, Tyrone	bulky look	cover with molding, light fixtures, paneling
multiple types of conn. (Beam-Beam, Column-Beam) (corner, straight, T, X	symetric with caps over unused	solid model	TJ, Tyrone	unnecessary steps/material	simple caps
	multiple types	solid model	TJ, Tyrone	cost, onsite labor must pick	mass prod., smart components

Panel

FR	DP	Analysis	References	Risks	Countermeasures
Provide torsional stiffness (TBD Ft-lbs)	specific structural panel	shear? Bending?	Slocum	torsional panel is removed	warning labels/ non-removable
	all panels are structural	shear? Bending?	Slocum	all panels are removed?, Cost	inexpensive, but strong connections
restrict visibility	opaque structure		Kent	does not allow in to out vis.	sliding panels

	electrochromatic glass	power, cost		too slow, too expensive	use sparingly, mass prod.
	shades	solid model	Kent, Tyrone	space, hard to manually actuate, automatic may break	put in beam, simple design
Aesthetically pleasing	removable finish int/ext	materials	Kent, TJ	cost, difficult to attach	assume mass prod. Snap on?
	mass customization	cost	Kent, TJ	difficult to change	paintable
place to mount decorations (artwork, etc.)	provided mounts	spacing, structure	Kent	aesthetics	hidden
	nailable	materials	Kent	difficult to repair holes	replaceable
Sound barrier (TBD Decibels)	insulation	standards	Kent	cost, space	assume mass prod., high tech
	well sealed	standards	Kent	cost, ventilation?	sealed in factory, auto seals when installed
weather barrier (wind, Rain)	tounge and groove	solid model	Kent, LEED standard	must place/remove in order	separate connectors
	caulking	caulk properties	Kent, glass curtain wall manufacturer	must reapply if moved, ugly	home user may apply, color/texture match
provide insulation (20 R -value)	? " aerogel		Kent	cost	assume mass prod.
	9.5" of Fiberglass		Kent	too thick	Increase beam size
allow ventilation/sunlight	windows	solid model	Kent	prevents panel from perf. other tasks	only part of panel is window
	glass doors	solid model	Kent	no visibility restrict, panel too large	blinds/panels, mutiple panels work together?
allow travel from room to room	door	solid model	Kent	prevents panel from perf. other tasks	only part of panel is door
	opening	solid model	Kent	no sound barrier	active sound masking
Access to power (120 V, 20A)	standard outlet	solid model	Kent	aesthetics	hidden
	track lighting type track	solid model	Shri	safety	switched?/covered?
Access to signal (type of signal)	standard outlets	solid model	ken wacks kenn@alum.mit.edu	aesthetics	hidden
	wireless	bandwidth	ken wacks kenn@alum.mit.edu	cost	Assume mass prod.

Provide heating & cooling	Riser for air/plumbing	flow	brett griffith, carrier, copper association	difficult to connect, need for mult. purp	separate connectors
	HVAC units	flow/output	brett griffith carrier	cost, space, aesthetics	assume mass prod. In infill panel
Easily lifted (<200 Lbs)	Pultrusion	densityxV =W	Creative pultrusions	need many custom molds	glue standard pieces together
	natural resin	densityxV =W		cost	
	wood	densityxV =W	Creative pultrusions	too many nailed connections	glue
managable size	(3' or 4' x 8' or 9')	solid model	Kent, Tyrone	cannot fit large comp. (garage door)	minimum large panels, mult. panels work tog.
contain storage space or appliances	1' - 2' thick	solid model	TJ, Tyrone	changing wall profile	use same thickness on any given wall
	installed appliances (TV)	solid model	TJ, Tyrone	fragile, difficult to upgrade	sep. pieces installed on-site/ by consumer?

Panel to Beam

FR	DP	Analysis	References	Risks	Countermeasures
Provide torsional stiffness (TBD Ft-lbs)	bolted	shear? Bending?	Slocum	difficult on-site labor	minimum bolts
	latched	shear? Bending?	Slocum	too easily removed	warning labels/ non-removable
Connect power (120 V, 20A)	separate connectors	# of connectors? How made?	Shri	onsite labor	simple design
	integrated w/ phys connectors	# of connectors? How made?	Shri	cost, possible bad connection	good design
Connect signal (type of signal)	separate connectors	# of connectors? How made?	Shri	onsite labor	simple design
	integrated w/ phys connectors	# of connectors? How made?	Shri	cost, possible bad connection	good design
Easily connected	bolts	#, size needed, shear	Creative pultrusions	cost/labor	use minimum number consistant size

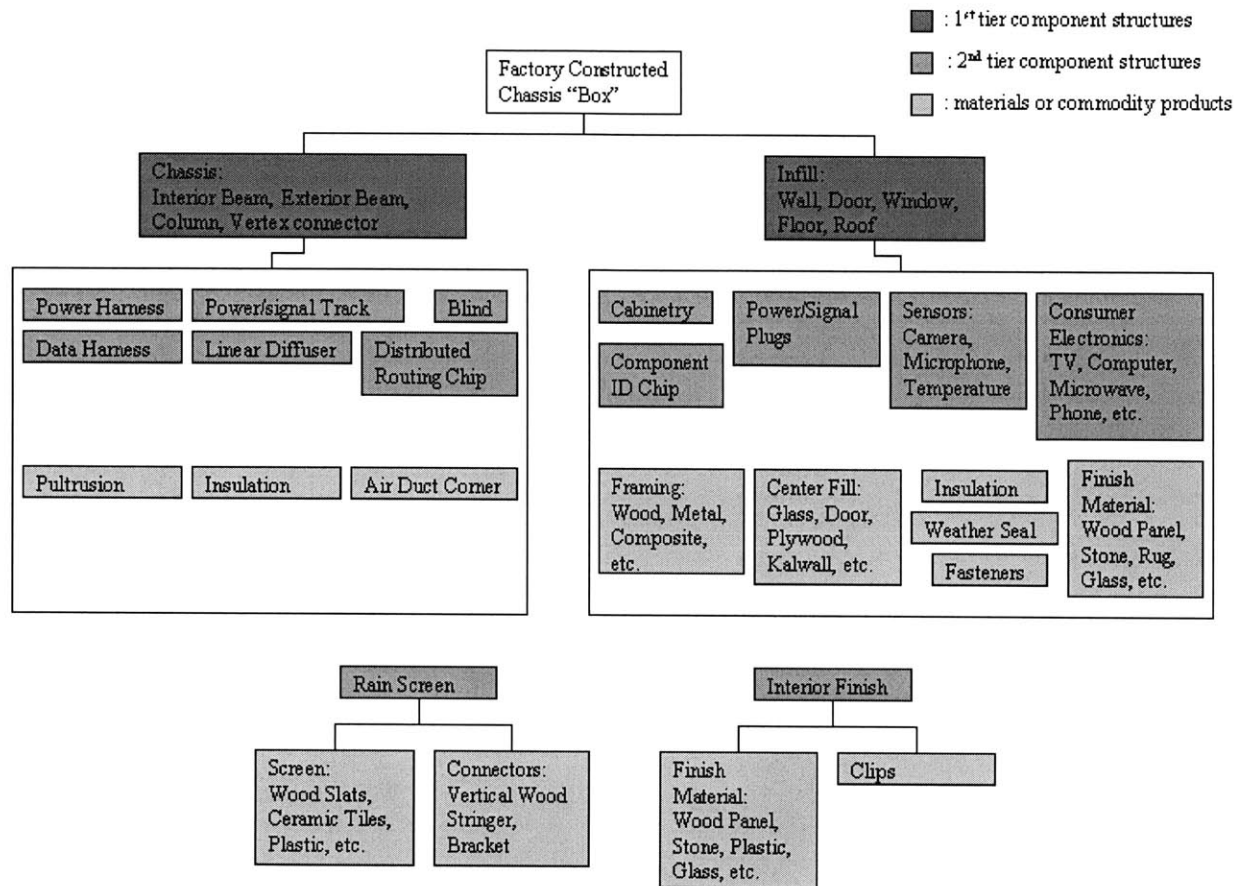
	glue	bond strength		non removeable	saw
	snap	yield strength	Creative pultrusions	non removeable, strength	saw, glue
Connect heating & cooling air, plumbing	Riser for air/plumbing	flow	brett griffith carrier	difficult to connect, need for mult. purp	separate connectors
	HVAC units	flow/output	brett griffith carrier	cost, space, aesthetics	assume mass prod. In infill panel
weather barrier (wind, Rain)	tounge and groove	solid model	Kent	must place/remove in order	separate connectors
	caulking	caulk properties	Kent, glass curtain wall manufacturer	must reapply if moved, ugly	home user may apply, color/texture match
multiple types of conn. (interior, exterior) (2 sides of beam)	symetric beam with caps over unused	solid model	TJ, Tyrone	unnecessary steps/material	simple caps
	multiple types	solid model	TJ, Tyrone	cost, onsite labor must pick	mass prod., smart components

Interior Panel

FR	DP	Analysis	References	Risks	Countermeasures
Withstand 200lbs sidewise force without moving	bolt on	ergonomic analysis	Kent	complicated, difficult to reach/hide	use cheap cover (snap-on?), minimum # of bolts
	friction	$F = \mu * N$	Kent	not strong enough	combine with deadbolt method?
	Clip or deadbolt type attachment	solid model	Kent	complicated, expensive, takes up a lot of space	simple design, minimize moving parts
restrict visibility	opaque structure		Kent	does not allow in to out vis.	sliding panels
	electrochromatic glass	power, cost		too slow, too expensive	use sparingly, mass prod.
	shades	solid model	Kent, Tyrone	space, hard to manually actuate, automatic may break	put in beam, simple design
Aesthetically pleasing	removable finish int/ext	materials	Kent, TJ	cost, difficult to attach	assume mass prod. Snap on?
	mass customization	cost	Kent, TJ	difficult to change	paintable
place to mount decorations (artwork, etc.)	provided mounts	spacing, structure	Kent	aesthetics	hidden
	nailable	materials	Kent	difficult to repair holes	replaceable

Sound barrier (TBD Decibels)	insulation	standards	Kent	cost, space	assume mass prod., high tech
	well sealed	standards	Kent	cost, ventilation?	sealed in factory, auto seals when installed
Easily movable	casters	test	Kent	complicated/expensive	fix casters, use cheap cover (snap-on?)
	dolly	test	Kent	not worth keeping dolly around	use standard dolly, or collapseable dolly
allow travel from room to room	door	solid model	Kent	prevents panel from perf. other tasks	only part of panel is door
	opening	solid model	Kent	no sound barrier	active sound masking
Access to power (120 V, 20A)	standard outlet	solid model	Kent	aesthetics	hidden
	track lighting type track	solid model	Shri	safety	switched?/covered?
Access to signal (type of signal)	standard outlets	solid model	ken wacks kenn@alum.mit.edu	aesthetics	hidden
	wireless	bandwidth	ken wacks kenn@alum.mit.edu	cost	Assume mass prod.
Easily lifted (<200 Lbs)	Pultrusion	densityxV=W	Creative pultrusions	need many custom molds	glue standard pieces together
	natural resin	densityxV=W	?	cost	
	wood	densityxV=W	Creative pultrusions	too many nailed connections	glue
managable size	(3' or 4' x 8' or 9')	solid model	Kent, Tyrone	cannot fit large comp. (garage door)	minimum large panels, mult. panels work tog.
contain storage space or appliances	1' - 2' thick	solid model	TJ, Tyrone	changing wall profile	use same thickness on any given wall
	installed appliances (TV)	solid model	TJ, Tyrone	fragile, difficult to upgrade	sep. pieces installed on-site/by consumer?

Appendix B



Appendix C

System	Name Brands	Functionality	Similarities	Differences	Possible Application
Chassis/Infill	House_n	structure, insulation, Power, network, HVAC	N/A	N/A	N/A
Aluminum framing, glass or opaque infill	Specialist Structures	structure, insulation, (Power, network in clip on raceways)	prefabricated structural members, panels, quickly and easily built on site	non-permanent, non-residential, no integrated HVAC, wiring is in separate conduit	structural attachments, leveling system, order of installation
Aluminum Framing	80/20, Bosch, IPS, MK products	structure	prefabricated structural members, panels	mostly for smaller applications	T-slot structural attachments
Panelized traditional frame Building	ASBS, Bardon	structure, insulation	prefabricated structural panels	requires crane, panels are structural, generally custom made, stick built in a factory	panel construction, transportation and manufacture
Laminated Wood Framing	Metalfit	structure, insulation	prefabricated structural beams and columns, insulated panels	simple construction, no services,	integrated connectors, wood laminate
Structural Insulated Panel	See SIPA, Enercept, Precision Panel	structure, insulation, Power	prefabricated structure, panels, wiring chases	permanent, traditional finish, tongue and groove nailed & caulked construction	insulation system/material
Fabric Skin Building	shelter systems	structure, wind protection, opaque	prefabricated structural elements	does not allow services	combination of compressive and tensile components
Concrete Form	Reward	structure, insulation	prefabricated forms	onsite concrete pouring	foundation system, integration of onsite construction w/ prefab
Inflatable tubing/tent	Aerotube	structure	prefab	not enclosed, does not include services	easily modified walls/ partitions

Appendix D

Criteria	Chassis to Stick Built
\$ of materials	more \$
# of parts	10-100 times less
# of fasteners	100 times less
# of on-site construction steps	100 times less
Weight (dead load)	similar
Hours to build on-site	100 times less
Total hours to build	10 times less
Tolerances	better
Supply chain	more easily managed due to fixed factory location
Max. joist span	18 ft. vs. 6ft for standard
Live load limit	100 lbs/sqft vs. 40-100
Wind load limit	100 lbs/sqft vs. 65
Pest resistance	much better
Mold/rot resistance	much better
Lifespan	Longer
Responsibility	branded components so responsibility lies with manufacturer instead of homeowner
Thermal expansion	good
Moisture driven expansion	none
Thermal conductance	better
Fire resistance	low glass transition (165C)
Network	many attachments, more easily upgraded

Appendix E

Building System Progression

Problem	Timber Frame Method	Prototype Solution (2-year)	Ideal Solution (10-year)
		Chassis components remain constant	
Network physical layer (high bandwidth)	Coaxial and Cat-5 cables, controlling televisions and computers.	Wireless networks for some applications and Cat-6 cable which would require individual physical connection every 3'.	For better consistency, there should only be one network, either wireless or run through the track.
Network physical layer (low bandwidth)	18-24 AWG copper wire, untwisted and unshielded, used for devices such as doorbells, thermostats, security systems, and powered blinds.	Either through the dedicated wire in the Eutrac product, or through the tracks using a powerline carrier.	
Networking system/protocol	Each system in the house has its own wiring and protocol.	TCP/IP, low and high bandwidth use the same protocol for easy bridging.	Embedded, distributed computing and routing system. Provides physical location information to appliances (TJ).
Sensors	None, in most houses.	Sensor packs containing a processor and several sensors, including temperature, humidity, sound, visual, light, and infrared, are mounted in the floor troughs at the perimeter of the room. These detect conditions in the room below the troughs.	Sensors with processors are placed wherever needed, perhaps embedded in appliances. Distributed networks carry their signals throughout the house.
Low-voltage power (DC)	110V AC runs through non-metallic sheath wires to all standard outlets in the house. This current must be converted to DC by transformers in appliances.	Two wires in the track carry a 15V DC circuit. This leaves two wires for a standard 110V AC circuit.	Ideally, only DC power will run through the track in the house. The voltage can be stepped down where needed. All appliances will run on DC power, (almost everything already does), and it will be more efficient to never switch to AC because many types of power generation such as PV cells, and Fuel Cells produce DC
High-voltage power	For appliances requiring higher voltage, such as ovens, dryers, or water heaters, NM cable is run to 220V outlets in the rooms of these appliances.	As in the timber frame method, NM wires carrying 220V will be run through the raceways to appliances requiring high voltage power.	

Power connections (chassis to infill)	Fixed wiring runs from the circuit breaker box to junction boxes and then to devices.	Wiring runs in raceways from the circuit breaker box to each track circuit. Attachments on the panels may be made at any point along the beam draw power from the track.	The power could be transferred through induction (meaning there would be no need for a track attachment), or through the structural connection.
Power generation	None, in most houses.	Photovoltaic panels on the roof or walls can decrease dependence on power companies and provide clean energy.	Photovoltaic panels on the roof or walls could supplement fuel cell power generation, providing power in a clean and efficient manner.
HVAC	Varies; Forced air, hot water, steam, window ACs, resistive electric heating, etc.	Forced Air; Ducts will carry air for heating, cooling, and ventilation from a centralized furnace and air conditioner	Distributed; small efficient HVAC units will be placed throughout the building providing environmental control wherever needed. Water and gas will be supplied through the chassis.
Insulation	Insulation is placed in walls between joists before being covered with facing.	Polyurethane panels placed in beams, columns, and finfill.	Nanogel or aerogel panels placed in beams, columns, and finfill.
Energy-efficient dynamic components	Shutting shades or moving awnings out during sunny days can reduce air conditioning loads, while replacing regular windows with storm windows in winter can reduce heating loads.	By automating certain energy-saving practices, such as shutting shades, moving awnings, and opening and closing windows, the prototype will not be susceptible to homeowners' laziness.	By regulating the color of the walls and roof, energy can be either absorbed or deflected depending on the seasonal conditions. Also, dynamically controlling insulation around a thermal mass can help regulate temperature between daytime and nighttime.
Duct cleaning	Ductwork is assembled from small components attached with duct tape or crimped ends. Most cleaning is done from the end of the duct by hand.	Access panels will provide the ability to either hand-clean the ductwork, or insert a robot to clean the ductwork.	Particle-repellant coating will keep ducts clean and maintenance-free.
Fire/heat protection	The wood frame is often protected by drywall. Wood when on fire does not melt, and will not experience failure until it is significantly charred.	During fire, intumescent paint, which coats the chassis system, will swell and create an insulating barrier for up to four hours, keeping the chassis from failing.	The pultrusion should be built using a resin with a sufficiently high glass distortion temperature to withstand the heat from most fires.

Maximum beam span (LL: 100 lbs/sqft)	6' (From TJM.com) with a 2-1/2" x 8-5/8" beam.	18', using the L/360 deflection ratio.	18'-60'. By increasing wall thickness and material strength, span may be increased as the market demands. Mass customized structural properties.
Sheer strength	The sheer strength of the plywood covering walls in a house is great enough to provide sufficient sheer strength.	One panel in each wall will be permanent, providing sheer strength to that wall. If a riser is placed in the wall, that may serve as a sheer wall.	If moment connections are made at the intersection of beams and columns, the chassis itself will be rigid, and a sheer panel will not be necessary.
Design method	The "average" family is the basis for most houses. This model only satisfies about 7% of the market.	Since this is a single house, it is designed by the House_n group.	Through some medium, customers can input their individual preferences into a design tool which helps them design a house that best fits their needs and desires.

Appendix F

Expert Concerns

Field	Name	Category	Comment
Pultrusion Manufacturer	Jerry Fanucci	Acceptance -	Convincing public to purchase a new kind of house (first use as officer housing on a military base where there are less issues with acceptance and insurance and reconfiguration is desirable)
CM Project Manager	Tony Papantonis	Acceptance -	public must be convinced modular does not mean "cookie-cutter crap"
CM Project Manager	Tony Papantonis	Acceptance -	need some historical data to prove a house can be built with this system and will work over time. At least a couple years.
Cabinet Manufacturer	Peter Humphrey	Acceptance -	"I would like to see one built and a cost vs. advantages analysis"
Developer/Architect	Art Klipfel	Acceptance -	People may not want to think about their house this much. Too many choices and decisions.
Insurance	Todd Wietlispach and Team	Acceptance -	modular is perceived as low quality
Contractor	Nelson Oliveira	Acceptance -	"Pre-fab homes aren't as durable"
Contractor	Nelson Oliveira	Acceptance -	"People think they can't afford things that are out of the ordinary" e.g. a cherry floor instead of oak. "They don't understand costs even when told"
Modular Builder	Ray Cudwadie	Acceptance -	the market isn't ready for versatility like this.
Estimator	Bill Sweeney	Acceptance -	marketing, public stigma against modular
Builder - Multi-Family	John Tocci	Acceptance -	(make initial sale on basic product, flexibility, modularity, not technology. High end apartments.)
Structural Engineer	Andre Chaszar	Acceptance -	(at first focus on performance rather than newness)
Insurance	Todd Wietlispach and Team	Acceptance -	Consumers will have to be convinced this is something they want
Wire Manufacturer	Jim Sheridan	Acceptance -	will have to create consumer awareness
Wire Manufacturer	Jim Sheridan	Acceptance -	At the same time system integrators will have to be educated on the new product and its benefits
MEP Engineer	Dick Topping	Acceptance -	Difficult to make modular systems LOOK high quality. Can't seem futuristic. Must be durable, homey, comfortable.
Builder - Multi-Family	John Tocci	Assembly -	modular systems tend to have problems with pre-applied finishes due to misalignment and gaps between components. (use conventional flooring finishes)
Contractor	Nelson Oliveira	Assembly -	"If you are missing a part you can't make it, you will have to wait"
Pultrusion Manufacturer	Jerry Fanucci	Assembly -	even composite parts may be too heavy to be carried by two people (carbon fiber would be lighter, but more expensive)
CM Project Manager	Tony Papantonis	Assembly/Tolerances -	modular components may not be quite right, must allow for it
Developer/Architect	Art Klipfel	Cash Flow -	Because of the way the money works the building has to be finished all at once before the sale. Waiting to build out interior causes problems.
Developer/Architect	Art Klipfel	Change -	System does not accommodate all scenarios, for example moving a bathroom is difficult, and the type and volume of a building can't be changed, for example a suburban family home cannot become a condo unit and visa versa.
Wire Manufacturer	Jim Sheridan	Change -	the house should allow for a wood stove in the kitchen
MEP Engineer	Dick Topping	Change -	No one does daily change
CM Project Manager	Tony Papantonis	Change -	(solves a big problem which is managing the customer during construction. Customer is always demanding changes as the building goes up, this system makes those changes easier.)
Developer/Architect	Art Klipfel	Change -	it may be more expensive to pay for a fancy rolling infill panel then to just pay someone to tear down and move drywall walls, even if it is done multiple times.

Insurance	Todd Wietlispach and Team	Change/Repair –	if part of the house is damaged can it be easily replaced?
Insurance	Todd Wietlispach and Team	Change/Repair –	generally new components do not match old components in color and look. This could be a problem when moving or replacing infill components.
Modular Builder	Ray Cudwadie	Code -	“Will not be as universal as we like due to code.”
Modular Builder	Ray Cudwadie	Code –	enforcement of code compliance would be very difficult if walls were so easy to move.
Building Inspector	Michael Grover	Code –	home owners can very easily create non-compliance, plug every 12ft, plugs at counter height in kitchen. (could put plugs on top of the beam? Or on every panel?) Could also create two apartments without proper egress or fire rated separation.
Structural Engineer	Andre Chaszar	Code -	Getting a certificate of occupancy for a pultrusion based building
Pultrusion Manufacturer	Jerry Fanucci	Code –	Getting a certificate of occupancy for a pultrusion based building (introduce in the southeast where building codes are more open)
MEP Engineer	Al Marzullo	Code –	building code and fire code issues. Material is biggest code problem, doesn't fit into current types of construction
Developer/Architect	Art Klipfel	Code –	Building must be finished with a bathroom and kitchen to get a C of O
Modular Builder	Ray Cudwadie	Code/Liability –	allowing people to move walls will allow them to create dangerous configurations. For example a bedroom without a window for egress, an improper outlet near a sink, sprinklers, etc. This can be construed as negligence allowing for the code violation. This is a very real concern in our litigious society.
Builder – Multi-Family	John Tocci	Cost –	to be profitable over the long term the difference increase material cost must be close to the savings in labor cost.
MEP Engineer	Dick Topping	Cost –	wiring and piping still requires a lot of on-site labor (protect piping inside armored area then use flexible easy to install tubing)
Cabinet Manufacturer	Peter Humphrey	Cost –	material costs can't be too high (find a way to use more lumber and less steel or pultrusion. Engineered lumber can be very strong and cost effective)
Developer/Architect	Art Klipfel	Cost –	making a flexible building will never be as cheap as building one without flexibility. (Honda strategy include all options rather than offering choice)
Structural Engineer	Craig Barnes	Cost –	need to balance innovation with local constraints, ie. Hurricane zone vs. a calm area. If the system is designed to work in any environment it will be too expensive.
MEP Engineer	Dick Topping	Cost -	The system will require a large amount of venture capital to get started. Big risk.
Builder – Multi-Family	John Tocci	Cost –	The system will require a large amount of venture capital to get started
Structural Engineer	Andre Chaszar	Cost –	There will need to be a large number suppliers of pultrusion for it to be cost effective
Insurance	Todd Wietlispach and Team	Cost –	A modular house should cost the same as a site-built home
Contractor	Nelson Oliveira	Cost –	materials cannot be too expensive
Structural Engineer	Andre Chaszar	Duct Cleaning –	(remove linear diffuser and top of duct, strength problem?)
Wire Manufacturer	Jim Sheridan	Energy –	the house should not require external energy
Wire Manufacturer	Jim Sheridan	Energy –	Should allow for exterior rolling shutters
Developer/Architect	Art Klipfel	Environment –	non renewable, non recyclable, compare to other materials
Structural Engineer	Andre Chaszar	Environment –	non renewable material, petroleum based
Structural Engineer	Andre Chaszar	Environment –	non recyclable material (make connections demountable, dissolvable adhesive?, to allow reuse of chassis components)
Insurance	Todd Wietlispach and Team	Fire -	Structural property loss at 165C and toxic gases are a problem. An electrical fire in a raceway could cause a structural collapse and toxic gases.
Pultrusion Manufacturer	Jerry Fanucci	Fire –	Polyester and vinyl ester emit toxic gases when exposed to fire
MEP Engineer	Al Marzullo	Fire –	must caulk all holes in walls for fire spread resistance

Insurance	Todd Wietlispach and Team	Fire –	Should allow for safety devices such as sprinklers
Contractor	Nelson Oliveira	Fire –	The system must protect inhabitants in a fire
Building Inspector	Michael Grover	Fire –	too many cavities going through building allow fire spread
MEP Engineer	Al Marzullo	Fire –	Structural property loss at 165C (no problem if house is sprinkled)
Building Inspector	Michael Grover	Fire –	loss of structural properties in a fire is a problem. “must come sprinkled” (perhaps could have an advanced fire detection system)
Building Inspector	Michael Grover	Fire –	Intumescent paint doesn’t help with temperature only with directly applied flame.
Wire Manufacturer	Jim Sheridan	Health –	there should not be materials that outgas or cause health problems
MEP Engineer	Dick Topping	HVAC –	Air return??? (in riser)
Wire Manufacturer	Jim Sheridan	HVAC –	The house should be quiet
MEP Engineer	Al Marzullo	HVAC –	condensation will form on cooling duct if not insulated (add insulation inside duct)
Insurance	Todd Wietlispach and Team	Industry –	Builders will not get onboard until there is consumer demand this will cause the system to initially be expensive with few infill choices thus reducing consumer demand. Chicken and egg problem. Builders will fear committing to a standard before it is clear it will be successful. Betamax example.
Wire Manufacturer	Jim Sheridan	Industry –	NAHB will resist this change.
MEP Engineer	Dick Topping	Industry –	building industry is very resistant to change
CM Project Manager	Tony Papantonis	Industry –	new is bad. Hard to get contractors on board. Risky for sub-contractor to spend time learning something that might not work
Structural Engineer	Craig Barnes	Industry –	Political reality is that many parts of the industry will not like this change
Structural Engineer	Craig Barnes	Industry –	There must be a good business plan for getting this system into the market. Otherwise it will fail like so many others.
Pultrusion Manufacturer	Jerry Fanucci	Jobs –	The new method of construction will eliminate a number of trades and jobs (introduce in southeast where there are fewer unions)
Wire Manufacturer	Jim Sheridan	Jobs –	The new method of construction will eliminate a number of trades and jobs (easier to sell to a modular builder than a traditional builder)
Structural Engineer	Andre Chaszar	Jobs –	The new method of construction will eliminate a number of trades and jobs (could actually be a good thing because pool of skilled labor is shrinking)
Building Inspector	Michael Grover	Labor –	Hardest part is assembly of chassis
Estimator	Bill Sweeney	Labor –	“assemblers can’t make changes in the field”
Building Inspector	Michael Grover	Labor -	Customized setup requires specifically trained workers.
Modular Builder	Ray Cudwadie	Labor –	Traditional finished box modular housing requires far less on-site labor.
Building Inspector	Michael Grover	Labor –	Not wood, “how can I build with this?” Manufacturers will have to provide assemblers at least initially.
Contractor	Nelson Oliveira	Labor/Training –	“I will have to spend more time planning, buying and organizing parts, and learn to assemble them.” “hard at first, then easier then the old system.” (should be much faster to learn than traditional, because there are less components and details)
Structural Engineer	Andre Chaszar	Labor/Training –	Contractors will have to be retrained. Resistant to new things.
Pultrusion Manufacturer	Jerry Fanucci	Manufacturing –	very large pultrusion largest machine can only do 1’x10’
Estimator	Bill Sweeney	mass cust –	not enough flexibility, “too modulated, even if it’s just a perception I feel limited”
MEP Engineer	Dick Topping	Network –	installers must be well educated (raceway allows replacement of defects)
Wire Manufacturer	Jim Sheridan	Network –	“Wireless makes home a microwave”
MEP Engineer	Al Marzullo	Nomenclature –	don’t call electrical wire area a “raceway”

MEP Engineer	Al Marzullo	Power –	Track lighting connections only rated to 600W. An iron is 1500W
MEP Engineer	Al Marzullo	Power –	all power connections must be made in a UL listed junction box
Structural Engineer	Craig Barnes	Power –	connections must be field tested for corrosion and compliance to misalignment.
Wire Manufacturer	Jim Sheridan	Power –	code says power should be >2" from data wiring
MEP Engineer	Al Marzullo	Power –	can only fill power "raceway" 40% could be a problem at connector
MEP Engineer	Dick Topping	Power –	connections are a concern. Must be reliable and simple in field
Wire Manufacturer	Jim Sheridan	Power/Network –	wires must not be forced to turn sharp radii
Wire Manufacturer	Jim Sheridan	Power/Network –	will need a telecommunications closet particularly in multifamily, one every two floors.
Building Inspector	Michael Grover	Prototype –	"To sign off on a prototype I would need to see: engineering drawings for everything, energy performance data, and construction liability coverage. There would also need to be an education program for the inspectors and fire department."
Cabinet Manufacturer	Peter Humphrey	Safety –	The house must be safe and provide good security
Insurance	Todd Wietlispach and Team	Safety –	Can the elderly handle infill components.
Building Inspector	Michael Grover	Stairs???	Stairs???
MEP Engineer	Dick Topping	Standards –	historically it has been difficult for industries to agree on standards
Pultrusion Manufacturer	Jerry Fanucci	Strength –	column corners can't take torque (add radius)
Pultrusion Manufacturer	Jerry Fanucci	Strength –	columns do not seem strong enough to take compressive load
Structural Engineer	Craig Barnes	Strength –	the floor must have a diaphragm strength to transfer loads from sheer panel on opposite wall
Structural Engineer	Andre Chaszar	Strength –	point connections do not work well with composites and plastic
Structural Engineer	Andre Chaszar	Strength –	Chassis connector may not be strong enough
Insurance	Todd Wietlispach and Team	Weather –	It is important that the house protect the belongings for insurance
CM Project Manager	Tony Papanonis	Weather –	difficult to keep water out, especially with remove and replace parts

Appendix G

Expert Positive Comments

Field	Name	Category	Comment
Pultrusion Manufacturer	Jerry Fanucci	Acceptance	"Modularity is good for construction"
Builder – Multi-Family	John Tocci	Acceptance	"Might work well for high end apartments in New York"
Builder – Multi-Family	John Tocci	Acceptance	"I would like to control the sales process from beginning to end with a more direct relationship with the customer and I think this system could help me achieve that"
Builder – Multi-Family	John Tocci	Acceptance	"I would be willing to try and implement a system like this in order to differentiate myself from my competitors."
Builder – Multi-Family	John Tocci	Acceptance	"If the cost of components is reasonable I would adopt the system because there is value-added for the customer"
CM Project Manager	Tony Papantonis	Acceptance	"I would reorganize my business to use this system in order to take advantage of the decreased time from start to finish"
CM Project Manager	Tony Papantonis	Acceptance	"I would like to offer this product to my customers. If we got in early the potential is for great profit."
Cabinet Manufacturer	Peter Humphrey	Acceptance	"I could produce infill panels. It would be a new product, but not a big departure. It would compliment what we do now (pre-hung doors, window assembly)."
Cabinet Manufacturer	Peter Humphrey	Acceptance	"I am interested in being an infill manufacturer, more internal panels than external though"
Developer/Ar chitect	Art Klipfel	Acceptance	"Not having to fit out the interior of an apartment until the buyer is present would lower my risk considerably."
Wire Manufacturer	Jim Sheridan	Acceptance	"Installers would reorganize their businesses to take advantage of this system because it offers a new opportunity to generate money."
Modular Builder	Ray Cudwadie	Acceptance	"Great job thinking through market and trades"
Estimator	Bill Sweeney	Acceptance	"Suffolk is doing something similar for dormitory construction"
Estimator	Bill Sweeney	Acceptance	"Already going in this direction - modular."
Estimator	Bill Sweeney	Acceptance	"#1 consumer complaint is home construction"
MEP Engineer	Dick Topping	Adaptability	"More flexibility than conventional housing"
MEP Engineer	Dick Topping	Adaptability	"It would allow families to stay put through change"
MEP Engineer	Dick Topping	Adaptability	"I would use the systems ability to upgrade"
CM Project Manager	Tony Papantonis	Adaptability	"The ability to easily change things would help alleviate one of my biggest problems which is dealing with customer changes demanded in mid construction."
Insurance	Todd Wietlispach and Team	Adaptability	"I would like to be able to change my house. Right now I would like to change my upstairs."
Insurance	Todd Wietlispach and Team	Adaptability	"I had to move four times to accommodate kids."
Insurance	Todd Wietlispach and Team	Adaptability	"I may need to modify my house to accommodate a wheelchair, etc."

Contractor	Nelson Oliveira	Adaptability	"I would like to be able to change spaces from interior to exterior."
Contractor	Nelson Oliveira	Adaptability	"I would use movable walls to make a larger space for parties"
Contractor	Nelson Oliveira	Adaptability	"I would use the system to change the layout of my house to give it a new feel maybe once a year."
Contractor	Nelson Oliveira	Adaptability	"When children are small they may want to share a room, but when they get older it would be nice to be able to divide their room into two. Maybe then they would spend more time at home."
Modular Builder	Ray Cudwadie	Adaptability	"Might be nice for elderly living in a single family home."
Modular Builder	Ray Cudwadie	Adaptability	"Expandability and customization in single family is more attractive than for apartments. Partially because apartments are more problematic with codes and issues."
Wire Manufacturer	Jim Sheridan	Code	"The system would be transparent t building inspectors allowing them to inspect in ½ the time. Plus some inspection could be done right in the factory."
Building Inspector	Michael Grover	Code	"Outgasing in a fire not as much of a concern as structural property loss"
Builder – Multi-Family	John Tocci	Cost	"After the learning curve I expect a 15-20% savings could be achieved due to better quality control and lower labor requirements"
CM Project Manager	Tony Papantonis	Cost	"It is mass-produced so it will be cost effective"
CM Project Manager	Tony Papantonis	Cost	"The new system would allow a large decrease in time spent managing the process"
Insurance	Todd Wietlispach and Team	Cost	"Repair costs could be less with the chassis/infill system because parts can be replaced so easily."
Insurance	Todd Wietlispach and Team	Cost	"The structural system is a small part of insurability"
Insurance	Todd Wietlispach and Team	Cost	"We would most likely charge the same for a house built using the chassis infill system as a traditional house."
Wire Manufacturer	Jim Sheridan	Cost	"The system would allow an experienced professional to install wiring quickly so it works! That alone is worth a lot of money."
Wire Manufacturer	Jim Sheridan	Cost	"Many-many economic plusses."
Wire Manufacturer	Jim Sheridan	Cost	"I think this system will provide affordable housing"
Estimator	Bill Sweeney	Cost	"Using this system I could make a 98% correct budget estimate, because there is less contingency"
Estimator	Bill Sweeney	Cost	"Would save us upwards of 30%"
Estimator	Bill Sweeney	General	"A complete structural, electrical, plumbing, HVAC system for a multi-dwelling complex."
Pultrusion Manufacturer	Jerry Fanucci	General	"I'm sure it could be made to work"
MEP Engineer	Dick Topping	General	"Has tremendous potential!"
CM Project Manager	Tony Papantonis	General	"The system would allow improvements in cost, quality, schedule, and in general allow us to be more competitive"
Developer/Architect	Art Klipfel	General	"More flexibility, technology, and environmental considerations than typical modular building. Allows rooms and lights to be reconfigured."
Contractor	Nelson Oliveira	General	"The chassis/infill system allows remodeling and customization and makes it easy to access wires and data network."
Contractor	Nelson Oliveira	General	"I think the chassis/infill system could be used to create my dream house"
Wire Manufacturer	Jim Sheridan	General	"I think the chassis infill system would give me more bang for my buck providing a quality product in a reasonable amount of time that is customized."

Modular Builder	Ray Cudwadie	General	"This is a forward thinking concept that has merit"
Modular Builder	Ray Cudwadie	General	"Great concept, very imaginative"
Modular Builder	Ray Cudwadie	General	"Is versatile, expandable, and allows more hi-tech materials and integration of technology than anything currently available. We are way away from hi-tech."
Building Inspector	Michael Grover	General	"Comes put together, pre-wired, insulated, quick setup, customized interior"
Estimator	Bill Sweeney	General	"#1 consumer complaint is home construction"
Builder – Multi-Family	John Tocci	Labor	"I like how you have built the specialization into the product rather than the labor. This is needed in an era of declining per capita labor pool"
Structural Engineer	Andre Chaszar	Labor	"The new system may cause a loss of jobs, but that is okay, because there are less and less skilled people available anyway."
Estimator	Bill Sweeney	Labor	"Almost something that has to take place to address problems like unsophisticated workforce"
Builder – Multi-Family	John Tocci	Mass cust	"I like the flexibility and availability of mechanicals distributed throughout the building"
MEP Engineer	Dick Topping	Mass cust	"I think the chassis/infill system could be used to create my dream home"
MEP Engineer	Dick Topping	Mass cust	"I would be willing to invest more time to customize my home"
Wire Manufacturer	Jim Sheridan	Mass cust	"This system would allow homeowners to customize economically."
Wire Manufacturer	Jim Sheridan	Mass cust	"I wouldn't have to look at so many places when shopping for a condo. First I could find the geography I wanted, and then customize the interior instead of compromising between the two."
Modular Builder	Ray Cudwadie	Mass cust	"It combines small modular components to provide versatility."
Estimator	Bill Sweeney	Mass cust	"Ready to suit framework, customization"
Estimator	Bill Sweeney	Mass cust	"Customization is important to the consumer"
MEP Engineer	Dick Topping	Mass cust & adapt	"The flexibility allows customization originally and over time"
Pultrusion Manufacturer	Jerry Fanucci	Quality	"I could produce structural pultrusions to $\pm .005$ inches and pultruded panels to $\pm .01$ inches" (Thermal distortion is a concern)
Builder – Multi-Family	John Tocci	Quality	"I would only have to train one person as an assembler, rather than electrician, plumber, HVAC, etc."
Builder – Multi-Family	John Tocci	Quality	"The ability to cut out the subcontractor and have more power over quality control would help my business a lot"
Builder – Multi-Family	John Tocci	Quality	"Control of labor would allow better quality assurance."
Builder – Multi-Family	John Tocci	Quality	"The system allows a menu-driven assembly and design process"
Builder – Multi-Family	John Tocci	Quality	"2-4% of onsite construction time is rework"
Builder – Multi-Family	John Tocci	Quality	"I estimate the system would cause a shift from 50% labor 50% materials to 20% labor 80% materials"
Structural Engineer	Andre Chaszar	Quality	"Pultrusion chassis offers an alternative to traditional materials like steel, concrete, and wood"
Structural Engineer	Andre Chaszar	Quality	"The chassis also offers the additional advantage of integrating infrastructure services in the beam"
Structural Engineer	Andre Chaszar	Quality	"Current developer construction needs reform. What they do now can be described with the acronym CATNAP (cheapest available technology narrowly avoiding prosecution)"
MEP Engineer	Dick Topping	Quality	"Allows fabrication an a factory and uses advanced materials."

MEP Engineer	Dick Topping	Quality	"Wiring and piping requires a lot on on-site labor and this system would relieve that problem."
CM Project Manager	Tony Papantonis	Quality	"It is made in a controlled environment so it will be high quality"
CM Project Manager	Tony Papantonis	Quality	"15-20% of on-site labor is spent on rework"
CM Project Manager	Tony Papantonis	Quality	"There are <5% of mistakes left incorrect, but there are quality and workmanship issues on finishes and details, caulking may leak, etc."
CM Project Manager	Tony Papantonis	Quality	"Wood can warp badly causing misalignment of walls and cracking of finishes"
Cabinet Manufacturer	Peter Humphrey	Quality	"Pultrusion homes is now providing warranties, recognizing the need for accountability"
Developer/Architect	Art Klipfel	Quality	"Architectural design would be easier because it is systematic, but it would still be flexible enough."
Developer/Architect	Art Klipfel	Quality	"It's like building and designing with a kit of parts. An ordered system approach would help architects immensely. As it is buildings are just too complicated, architects can't keep up and then they screw up."
Contractor	Nelson Oliveira	Quality	"Pultrusion would last longer and provide more value than traditional pre-fab."
Contractor	Nelson Oliveira	Quality	"This system would be much easier to learn than traditional construction because there are less details and less components."
Wire Manufacturer	Jim Sheridan	Quality	"The reduction in labor costs would allow more energy efficient materials, windows, shutters, etc. The home owner would be empowered to help the environment!"
Wire Manufacturer	Jim Sheridan	Quality	"This system solves a huge problem for the cabling industry"
Wire Manufacturer	Jim Sheridan	Quality	"Staples damage cable, wire is bent at too sharp an angle, cables are connected wrong and the wrong cable is often used. The chassis raceways allow no staples, no incorrect bend radius, and bring the wire to a standard connector."
Wire Manufacturer	Jim Sheridan	Quality	"If cable is installed in the factory it would be more repeatable."
Wire Manufacturer	Jim Sheridan	Quality	"There is also less liability when there is less labor, less human error."
Wire Manufacturer	Jim Sheridan	Quality	"Raceways remove the need for excessive connections and help with installation time"
Estimator	Bill Sweeney	Quality	"pros: ease of construction, superior quality control, ease of quality assurance in the field, schedule predictability, make cost more predictable"
Estimator	Bill Sweeney	Quality	"5% of work is rework"
Estimator	Bill Sweeney	Quality	"100 things are left incorrect at an average suburban home construction site."
MEP Engineer	Al Marzullo	Strength	"The material's loss of structural properties at 165C is not a concern if the house is sprinkled and it should be (it's cheap)."
Structural Engineer	Craig Barnes	Strength	"The structural system seems reasonable as long as the floors have diaphragm strength."
Building Inspector	Michael Grover	Strength	"If wind loading is okay seismic strength will be okay."
Pultrusion Manufacturer	Jerry Fanucci	Tech. integration	"Allows a house to be cost effectively designed to include modern features"
MEP Engineer	Dick Topping	Tech. integration	"I would like more technology in my home and think the chassis/infill system would facilitate it"
MEP Engineer	Dick Topping	Tech. integration	"The easily accessible raceways would allow simple replacement of wiring defects"

Appendix H

HVAC Calculations

one riser every 300sqft two ducts per riser
10X15 room = 150sqft

area served by each duct	150 sqft
HVAC requirement	1 cfm/sqft
area of duct	0.30556 sqft
speed of air in duct	490.909 ft/min
noise created y air speed	decibels

width of linear diffuser	1 inch
total approx length of beam	50 feet
% of beam exposed	60%
approximate length of diffuser	30
total diffuser area per duct	2.5 sqft
speed of air through diffuser	60 ft/min

Insulation

3" of polurethane	20 R-value
Nanogel equivalent	0.45 inches

Stength of T-slot

thickness of flange	0.125 inches
number of flanges	2
shear strength	7,000 psi
safety factor	3
shear area per foot	3 inches ²
strength per foot	7000 lbs/ft

diameter of connector	0.75 inch
Strength of connector attachment	437.5 lbs
bearing length of connection	1 inch
Strength of connector attachment (tension and shear)	583.333 lbs

Appendix I

Cost estimation

Component cost estimates				
Chassis elements				
pultrusion cost	\$1.80	per pound		
coulmn weight	100	lbs		
beam weight per foot	8.33	lbs/ft		
column	\$180	per column		
Beam	\$14.99	per foot		
Infill elements				
wall panel	\$500	per panel		
width of wall panel	3	feet		
floor panel	\$10	per sqft		
roof panel	\$20	per sqft		
cost of box of hilti connectors	\$33	box of 25		
cost of one connector	\$1.32			
floor area	2500	sqft		
Dimensions				
length	50	ft		
width	50	ft		
distance between columns	12	ft		
# of columns in length	5			
# of columns in width	5			
# total columns	25			
feet of beam	500	ft		
# of infill panels	167			
# of connectors in house	1936			
cost of columns	\$4,500			
cost of beams	\$7,497			
total chassis cost	\$11,997			
cost of wall panels	\$83,500			
cost of floor panels	\$25,000			
cost of roof panels	\$50,000			
cost of connectors	\$2,555.52			
			Typical house cost	\$25 per sqft
Total materials cost	\$173,053		Total typical materials cost	\$62,500
New estimated ratio of labor to materials	0.25		Typical ratio of labor to materials	2.33
Total labor cost	\$43,263		Total typical labor cost	\$145,833
Total typical cost	\$216,316		Total typical cost	\$208,333