

# MIT Open Source Building Alliance

White Paper

The **MIT Open Source Building Alliance (OSBA)** explores this premise:



*A web of cross-industry relationships, and tools that allow individuals to craft their physical and digital environment – directly connecting manufacturers to customers – will lead to an explosion of creative energy and path to market for innovative products*

## Open Source

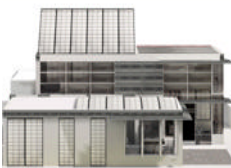
"Open source" allows independently developed modules to work together in a larger system due to mutually agreed principles. It insures integration and interoperability because:



*the system as a whole provides a framework - an architecture - that allows for both independence of structure and integration of function. Modularity encompasses physical components, electronics, software, and services from design through use.*

Linux, for example, has proven that a complex, stable, open source, modular operating system can successfully evolve without the control of a single entity. The PC industry is "open source" in that hundreds of device manufacturers can develop innovative new products that successfully integrate with other independently developed devices (and Dell Computer has become the largest manufacturer of PCs by allowing customers to configure high-performance, high-value modular components that work together in an integrated system). The automobile industry is moving towards integrated modules provided by tier-1 suppliers that are interchangeable across platforms - with the ultimate example GM's proposed AUTOnomy and Hy-wire chassis for ALL platforms that accepts mass-customized modular body components, seating, communication devices, etc. With "open source," manufacturers are free to focus on the quality and performance of their sub-system – designers are free to focus on design and integration.

## Open Source Building



Providing individuals with choice creates competition and incentives for innovation. Mass-customization requires a modular component-based approach, which creates a pathway for new players to enter the \$852 billion/yr construction market (by comparison, the home PC market is approx. \$30 billion per year). This fundamentally alters the rules of the game and the relationships of parties. It leads to huge opportunities for companies who take advantage of this, and risks for those who do not. **Open Source Building** enables the development of new products, services, and technologies that come together to create tailored, agile, responsive, high-performance environments.



Based on well-established principles of modularity - and paralleling recent developments in the automobile, ship building, and electronics industry - **Open Source Building** is a strategy developed by the MIT House\_n research group for the mass-customization of responsive buildings using modular physical/logical components (rather than the labor-intensive, craft-based approach of conventional construction). It separates a building into a chassis (providing structure, power, communication, etc.), and mass-customized modules (for interior fit-out, exterior facades, electronics, communication, etc.). Component design, engineering, and integration are at the system level. This allows building designers to concentrate primarily on the unique programmatic and environmental context of a building, and allows individual occupants to focus on tailoring their environment according to needs and values. In doing so, the additional cost, risk, and coordination errors associated with "one-off," highly engineered complex structures are avoided.



Unlike the failed industrialized building experiments of the 1970s, **Open Source Building** is not limited to standardized, repetitive building elements. It establishes ground rules for connections, but is otherwise unconstrained. New tools for creating environments make this practical: information technologies, CNC fabrication, automated design tools, supply-chain management, almost free computation, low-cost electronics, new materials, mass-customization strategies, and the integration of physical and logical infrastructure.

A transition to **Open Source Building** is inevitable. Countless companies making products for the home are developing web-based design and information tools to establish direct communication with customers; the cabinetmaker Merillat, for example, has an online tool for kitchen design. All of these, however, are disconnected from the design and decision making process for production housing. This changes when a sophisticated web of cross-industry relationships evolve to provide integrated solutions.

### Why is This Transition Necessary?



In the future, homes will contain the most complex activities of any building type. With the aging of the baby boomers and pending crisis in the healthcare industry, homes must become proactive environments for keeping people healthy and autonomous. With the difficulties in building new centralized power plants and expanding the electric grid, homes must become key components of a system of distributed energy production. Homes will increasingly become a center for work, commerce, and learning. It is likely that multifamily housing will become a dominant new housing type in the US as the baby boomers retire.

Market studies indicate that the home buyers of tomorrow – the baby boomer and GenX population - are sophisticated, financially enabled consumers who want choice and tailored solutions in homes that closely reflect their values and needs, accommodate increasingly complex activities and work patterns, adapt over time as family financial and health conditions change, and accommodate rapidly evolving technologies and services in the home.

It is clear that current approaches to housing meet none of these expectations. Our places of living are poorly prepared for this future. Most new homes and apartments are low-grade, low-tech, inflexible, disruptive to upgrade, high maintenance, and ill-designed. Few are tailored to the unique and changing needs of its occupants, and architects/engineers play no significant role in the creation of most places of living.

In addition, the housing industry is fragmented, resistant to change, labor intensive, inefficient, unresponsive, and wary of new processes and technologies. The realities of production housing development make it difficult to assemble the expertise and craft skills to sustain a complex engineered systems approach using conventional labor-intensive construction. The industry is far behind other industries in the adoption of new process and technology innovations. We intend to demonstrate that many of the **OSBA** concepts can be employed immediately, pointing the way to a more viable process for creating high value, sophisticated housing.

### **Open Source Building Alliance**

**OSBA** establishes a pre-competitive forum at MIT for a broad range of industrial stakeholders and academic researchers to develop key elements of an "open source," modular component approach to creating high-value, responsive, mass-customized, "net zero energy" buildings. The goals of **OSBA** are:

1. Develop **Open Source Building** as a model for cross-industry participation in mass-customization of places of living and its related products, technologies, and services.
2. Establish a bridge between MIT/national laboratory research and industry in the area of next-generation building design and technology
3. Exploit existing process/technology transfer opportunities from other industries that relate to building design and technology.
4. Develop the **Open Source Building** model as a pathway for companies outside and inside of the building industry (technology companies, new material manufacturers, etc.) to become key players in this \$852 billion/yr. market (\$412 billion for residential construction and retrofit)
5. Focus on solutions that address multiple problems simultaneously (i.e. a common sensing and networking infrastructure for energy management as well as proactive, preventative healthcare - solutions that scale from commercial to residential buildings)
6. Expose industry and the public to next-generation building design and technology concepts (through publications, broadcast media, exhibitions, etc.)

### **Proposed OSBA Special Interest Areas**

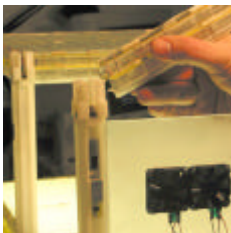
Special interest groups, with members from academia and industry, will be formed to concentrate on aspects of the problem. The precise formation of **OSBA** Special Interest Areas will be defined through discussions with industry team members. The following is a preliminary list:

#### **Special Interest Area 1: Open Source Building System Architecture**



This **OSBA** special interest group will define a cross-industry framework for all other special interest groups. It will set high-level criteria for performance, modularity and interoperability of design systems, services, supply chain management, fabrication strategies, electronic subcomponents, etc.

#### **Special Interest Area 2: Chassis and Infrastructure**



Central to **Open Source Building** is the separation of a building into a chassis that efficiently integrates the essential building services of a building, and mass-customized components (including interior fit-out

and exterior façade elements). Significant work has been completed at MIT on two possible chassis systems: 1) a prefabricated frame and 2) prefabricated volumetric loft modules. Both systems combine structure, ductwork, power, signal, sensing, mechanical attachments, sensing, etc. Both offer the possibility of significantly increasing quality and functionality while dramatically reducing field labor and eliminating site construction waste.

In year one, this special interest group will study both concepts, but will target volumetric loft modules for field-testing. Volumetric “modular” construction is the fastest growing segment of the housing market, but its potential is limited by a narrow range of design possibilities, its failure to take advantage of modern manufacturing technologies, and the labor intensive operations required to connect modules at the site. This research will employ volumetric modular construction for what it is most suited for - structural shells that can be rapidly assembled to create flexible, open “loft” space with integrated infrastructure. It makes possible a super-insulated, ultra-tight shell. Year one chassis component types to be investigated include:

- a. Modular platform over parking (sized to the car module)
- b. Volumetric modules (with insulation, weather seal, exterior doors and windows, interior loft floor/wall/ceiling finishes)
- c. Interface to HVAC appliances with associated vents/intakes/piping and ductwork
- d. Power communication, water, gas, waste infrastructure
- e. Low field-labor connections between adjacent loft modules

### **Special Interest Area 3: Integrated Interior Infill Modules (I<sup>3</sup>) and Related Technologies**



The objective of this special interest group is to conceptualize and assess the viability of a new integrated interior infill (I<sup>3</sup>) system combined with prefabricated modular shells and web-based automated design/decision making tools, to create an agile and efficient methodology for mass customized multifamily housing. This group will investigate the range of customization possible, including conventional layouts, open loft live/work environments, and dynamically transformable multi-use arrangements.

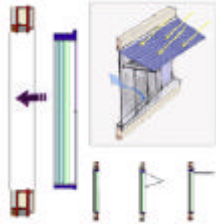
In year one, this special interest group will study the possibilities for cabinetry-like interior components. The millwork industry employs sophisticated, automated computerized numeric control (CNC) technologies capable of highly efficient “batch quantities of one,” but most millwork companies limit their production to kitchen and bath cabinets installed into conventional construction. This research will extend the application of automated cabinetry fabrication to create concepts for a new integrated interior infill (I<sup>3</sup>) system that will replace conventional interior framing, drywall, and finish elements. Standards for connections will be outlined that, if adopted by industry, would allow for many companies to innovate with the production of specialized I<sup>3</sup> components.

Year one research will include:

- a. Use of existing cabinetry fabrication technologies to create partitions, reconfigurable dividers, storage/organizing units, special purpose components for work, education, and entertainment, etc.
- b. Subcomponents for power, communication, and lighting systems with next generation environmental sensing and HVAC.
- c. The use of high performance, low maintenance, lightweight materials for interior components such as advanced polymers, composites, fabrics, and special-purpose metals
- d. Low field-labor connections (physical, power, signal, piping, etc.) between technology components and the infill components they are installed in, between adjacent infill components, and between infill components and the modular shell. Particular attention will be paid to the use of the I<sup>3</sup> system to allow for the quick and seamless connection at the marriage line as modules are erected, and for the efficient and non-disruptive

reconfiguration/upgrade of components. As the I<sup>3</sup> components arrive at the site, they will be installed in the modules, much as an interior automotive component is installed in an automobile chassis. Physical, power, and communication connections will be straight forward, based on Design for Assembly principles.

#### Special Interest Area 4: Integrated Exterior Finish Components



Just as I<sup>3</sup> components will allow interiors to be tailored to the needs of its occupants and rapidly installed with little field labor, exterior component strategies will be developed to tailor the exterior finishes, detailing, and technologies according to the community and environmental context and energy production requirements. Borrowing from high performance building envelope technologies extensively used in new commercial and institutional buildings (particularly in Germany), strategies for mass-customized exterior components will be developed.

Year one exterior component types to be investigated:

- Rainscreen panels – strategy for incorporating multiple materials and detailing
- Photo-voltaics integrated into exterior panels
- Shading devices, active and passive

#### Special Interest Area 5: Distributed Energy Technologies, Energy Management/Control Systems, HVAC Appliance, and Hybrid Lighting



HVAC systems typically generate the majority of complaints building occupants and by building owners. This special interest group will develop concepts for an integrated approach to mechanical systems, including a distributed HVAC “appliance.” It will investigate related component-integrated distributed energy systems. Year one research will map out performance and dimensional requirements for distributed energy systems and integrated HVAC appliances:

- HVAC appliance concepts with optional add-on components that bring together domestic hot water, heating and cooling, air quality sensing, air filtration, heat exchange, humidification, kitchen and bathroom exhaust fans, distributed control (networked with other such units in the apartment/house), wireless remote control, grill assembly to the exterior for the various vents and intakes (including clothes dryer vent) - or single rated riser enclosure to roof, fuel cell, sealed combustion gas fireplace option.
- Distributed energy systems, include component-integrated PVs, micro-turbines, fuel cells, etc.
- Integrated building control systems and networked appliances
- Hybrid Lighting



Note: The viability of creating a "one-off," highly engineered "net zero energy" building has been proven and is no longer an interesting problem. **Open Source Building** strategies may lead to thousands of net zero buildings that are tailored to the needs, values, and budgets of their occupants by integrating energy producing/control systems into building components that can be installed with little field labor.

## Special Interest Area 6: User Configuration Tools (and Related B2B Tools)

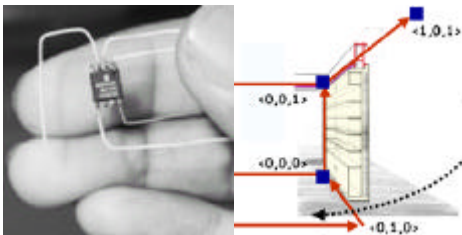


Central to **Open Source Building** are web-based, consumer design/configuration tools that provide individuals with the means to make informed decisions design and the products and services they incorporate into their places of living. This approach will allow new and ever-expanding webs of business-to-business connections that make up a mass-customization network - from component manufacturers to real estate agents. Year one research will focus on developing user-tools for parametrically defined  $I^3$  components:

- The development of concepts for a preference engine for the integrated interior infill (I3) system that collects information on family size, budget, aesthetic values, range of activities, etc.
- The development of concepts for a design engine that proposes design solutions that respond to the profile developed via the preference engine, and provides tools for the refinement of the design
- The development of concepts for linking the results of the design engine to automated CNC fabrication
- Digital customer profiling for use by design/configuration tools
- Information and help systems for configuration tools
- Guidelines for B2B connections to user configuration tools.

Note: Participating MIT researchers are leaders in the development of sophisticated design and customization tools that are accessible to non-experts through the encoding of design knowledge as rules and the use of computational algorithms (shape grammars) to tailor solutions. Linking this to 1 through 5 will create a complete customer-to-fabrication integrated system.

## Special Interest Area 7: Embedded/distributed IP (Internet Protocol)



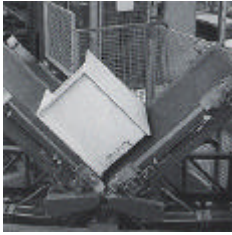
A recent meeting at MIT of industry leaders (Intel, Motorola, Lightolier, Johnson Controls, Steelcase, Sun Microsystems, United Technologies, etc.) agreed that embedded/distributed internet protocols (IP) at the level of the light bulb was probably inevitable. This will largely decouple the building design process from configuration of many subsystems (lighting, HVAC control, etc.) -

fundamentally altering how buildings are designed and conceived.

- Distributed control
- Addressable devices (lighting, HVAC control, etc.)
- Fine-grained sensing

Note: Industry is already moving in this direction. Lightolier, for example, has decoupled the circuiting from switching by making addressable lights and switches that communicate via powerline carrier. This research will be in collaboration with MIT's new Center for Bits and Atoms directed by Neil Gershenfeld.

## Special Interest Area 8: Fabrication/Assembly Methodology

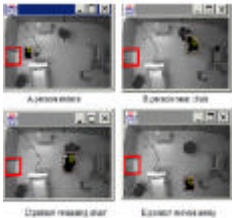


The realization of **Open Source Building** will require a coupling of automated design tools to highly efficient fabrication, delivery, and installation of modular components. Industry in general, and a few sectors of the building industry are moving in this direction. The millwork industry, for example, is moving towards "lights out" factories using robotics and CNC milling machines, with little production penalty for the manufacture of unique items over identical items. First year research will focus on:

- Linking I<sup>3</sup> components and related user configuration tools to millwork fabrication
- Using new materials, etc. to extend cabinetry fabrication to integrated wall systems.
- Just in time logistics

Note: GrifnerHaus (an Austrian single family home manufacturer) uses CNC factory automation to produce fully finished building panels for high quality, high performance, affordable, customized houses.

## Special Interest Area 9: Responsive Environments

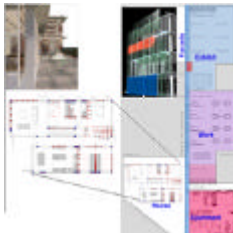


Participating MIT researchers have funding from NSF and the Robert Wood Johnson Foundation to develop systems that encourage health behaviors in the home (eating, diet, and exercise). Research indicates that the same techniques could affect energy-related behavior - perhaps significantly. With improvements in the performance of building envelopes and associated components, a focus on energy-related behavior will become an increasingly important research topic. This special interest group will focus on:

- Just-in-time health and energy related information and advice to encourage responsible related behavior (delivering the right message at the right time at the right place in the context of energy-related behavior)
- Dynamic adjustment of environments (lighting, space conditioning, etc.) in response to occupant activity
- Dynamic adjustment environments in response to environmental conditions (wind, sun, temperature, etc)

Note: Embedded/Distributed IP will greatly facilitate the low-cost implementation of the necessary infrastructure for responsive environments.

## Laboratory Testing and Evaluation: the MIT Place Lab



Consortium researchers are developing a "Place Laboratory" adjacent to the MIT Museum. This modular, highly flexible house-scale facility will initially focus on issues related to the single-family house. The Place Lab will have two complementary purposes:

Testing of Open Source Technologies, Materials, and Infrastructure

The Place Lab will explore the integration of new design and fabrication strategies, sensing, embedded IP, construction methodologies, and materials. The house-scale facility will be constructed with an integrated pultrusion "chassis" assembly that provides structure, insulation, sensor arrays, lighting, signal and power cable raceways, and ductwork —with "mass customized" infill components rapidly connecting to the chassis. It is designed to test the limits of new systems and materials in the context of their everyday use.

## Testing with People

The sensor infrastructure of the Place Lab will allow for scientific studies of people and the relationship to their environment and its technology. Researchers will have the capability to qualitatively and quantitatively collect data about people and how they react to new technologies. The Place Lab will be operated as a shared research facility. Proposals will be accepted from sponsors and the MIT community to engage in research that takes advantage of this unique facility. Complimenting this effort is the development of a “Portable Place Lab” —tools that can be easily employed in existing homes, workplaces, and urban environments. They may incorporate device use logging, identity recognition, position recognition, activity recognition, computer vision and time lapse photography, etc., as well as traditional, manual fieldwork techniques.

## A “Straw Man” Test Case

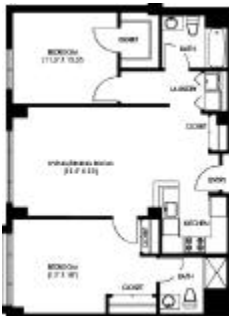


Working with the developers (Oaktree), a new market-rate, conventionally built development project in Cambridge has been selected to reconsider according to OSBA concepts. Located near the Alewife T-station, Cambridge Park Place was designed to appeal to young, urban professionals. It provides concierge, landscaped courtyard, high-speed internet access, state-of-the-art fitness center, etc.



The program - multi-story housing erected over covered parking - is typical of medium density housing designed for urban infill sites that are increasingly popular for the baby boomer generation.

The carefully conceived design reveals the basic design rules required for a modular approach: the sixty-foot width of the building is designed to efficiently reflect the sixty-foot width required for parking below. Twenty-six foot column bays (accommodating three cars) matches the twenty-six foot bearing walls of the apartments above (rooms average thirteen feet).



As is the case with essentially all market rate housing projects, the building was not designed to accommodate customization of apartments or change over time. It offers a limited number of standard, generic one and two-bedroom layouts.

## An Alternate Approach

The building has been schematically redesigned to accommodate OSBA principals. Outlined below, these concepts will be presented in greater detail at the October 15<sup>th</sup>, 2002 workshop.

The first step is to separate components of the building into “chassis” and “infill.” The chassis, in this case, consists of mass produced, volumetric modules designed so that two modules fit precisely over the parking column grid of thirteen foot by sixty feet.



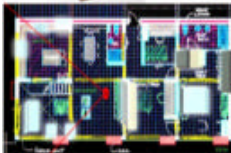
This is approximately the maximum size object that can be efficiently carried over the highway (thirteen foot, nine inches wide by sixty-four feet long). Creating open loft spaces, they stack to provide – in one efficient, highly insulated assembly – structure, ductwork, power, signal, plumbing connections, mechanical attachments for infill, HVAC (or its infrastructure), floor finishes, and ceiling finish.



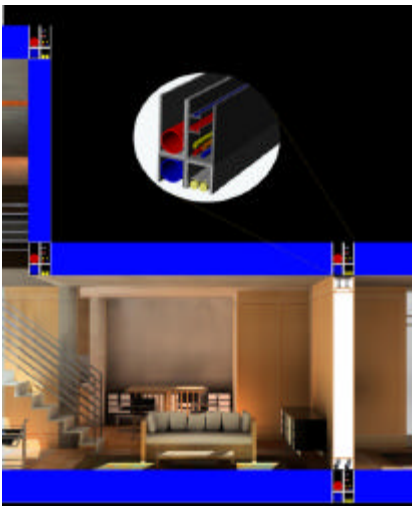
A conventional plan, volumetric modules, and alternative component-based interior (House\_n study).



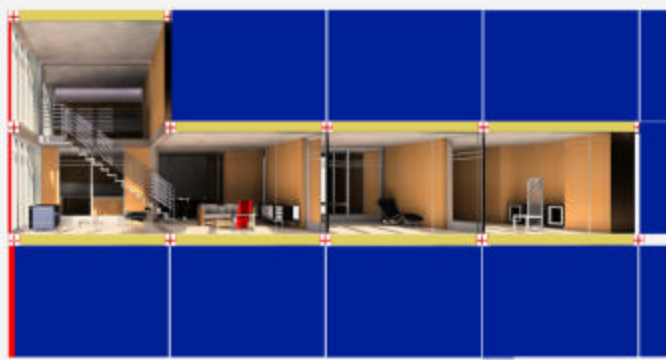
Rule-based design tools, created according to the branded product offering of the **developer/integrator**, allow condominium buyers to engage in a process of exploration of their values, activities, and needs - allowing them to make informed decisions about planning, materials, light, services and technologies. This tool is linked to a web of manufacturers and service providers.



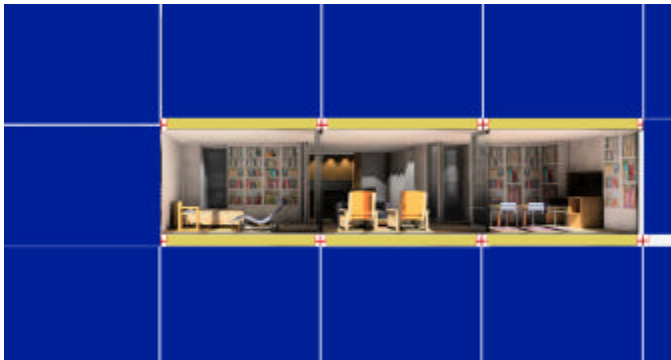
The output of this design tool allows the manufacturers to coordinate the manufacture of integrated components and their "just-in-time" delivery for rapid installation in the apartment interior. Technology and material companies have a path to market as "**Tier-2**" suppliers of components and subcomponents.



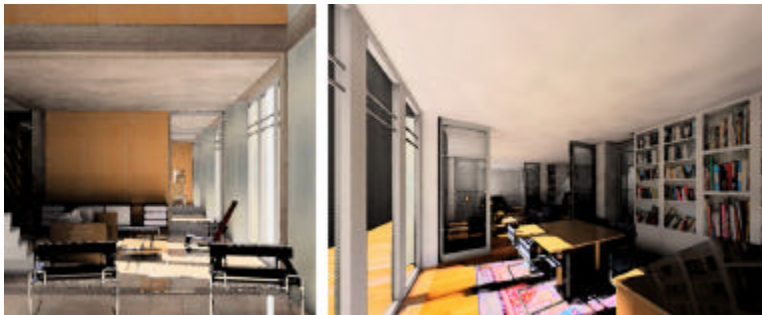
A detail of the modular chassis with integrated services (House\_n study).



A section through a portion of the redesigned building showing a 5-bay mass customized apartment with loft. (House\_n study).



A section through a portion of the redesigned building showing a 3-bay mass customized apartment (House\_n study).



Two apartment solutions, using similar components with alternative finishes and detail (House\_n study).

Rather than a conventionally installed façade, exterior "rain screen" façade panels with integrated solar technologies, shading devices, and HVAC penetrations are rapidly installed with minimal field labor. Each 13 foot module has an independent HVAC appliance with optional add-on components that bring together domestic hot water, heating and cooling, air quality sensing, air filtration, heat exchange, humidification, kitchen and bathroom exhaust fans, distributed control (networked with other such units in the apartment/house), wireless remote control, grill assembly to the exterior for the various vents and intakes (including clothes dryer vent) - or single rated riser enclosure to roof, and sealed combustion gas fireplace option.

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### Appendix A: Related Current Work

MIT House\_n researchers Thomas McLeish (Masters candidate, MIT Media Lab) and Tyson Lawrence (Masters candidate, MIT Department of Mechanical Engineering) are developing concepts for creating single-family houses from an integrated “chassis” that can be rapidly and precisely installed with minimal field labor. In one integrated assembly, pultrusion glass fiber composite beams and columns provide structure, insulation, sensor arrays, lighting, signal and power cable raceways, and ductwork.



Fig. 1. House\_n chassis system: axonometric, scale model with embedded networking, and full scale study model (House\_n study).

The chassis provides the necessary physical, power, and signal connections for mass customized infill components to be quickly installed, replaced and upgraded without disruption. Infill components may include integrated wall/floor assemblies, specialty millwork with transformable elements, display systems, networked appliances and devices, etc. Based on the House\_n chassis/infill system, an architectural scale model is being constructed to develop and test distributed network concepts. In this project, each building component has embedded computational technology that allows newly-introduced devices to announce their presence on the network, and to take on functionality according to their location in the structure and their physical relationship to other components. This investigation is assuming changes that could occur in the industry within ten to fifteen years.



Fig. 2. The floor plan of a conventional builders house has been duplicated using interior cabinet-like components (House\_n study).



Fig. 3. Prototype plan with chassis/infill components (House\_n study).

The MIT House\_n research group has a number of efforts underway to develop automated, web-based design tools called "preference engines" and "design engines." A preference engine engages the user in a dialogue to uncover needs, preferences, and values and the tradeoffs they are prepared to make. The system would, ideally, approximate the dialog that a good architect may have with a client at the beginning of the design process. A Design Engine can be thought of as computation system that makes use of a set of rules encoded into a shape grammar that defines the architectural strategy of the designer. House\_n researcher Lawrence Sass (Ph.D. thesis, MIT Department of Architecture, 2000) systematically extracted these rules from Palladio's text and the construction practices of the time to develop the basis for their codification into a shape grammar and Palladian design engine. This project extended the work of George Stiny (Professor, MIT Department of Architecture) and William J. Mitchell (Dean, MIT School of Architecture and Planning), who demonstrated that the design rules of Andrea Palladio can be inferred by analyzing other plans in the Renaissance publication, The Four Books of Architecture. House\_n researcher Jose Pinto Duarte (Ph.D. thesis, MIT Department of Architecture, 2000) explicitly encoded the design rules of the Portuguese architect Alvaro Siza for a mass housing project at Malagueira into a shape grammar and computer-based design engine that allows users to generate unique house designs.

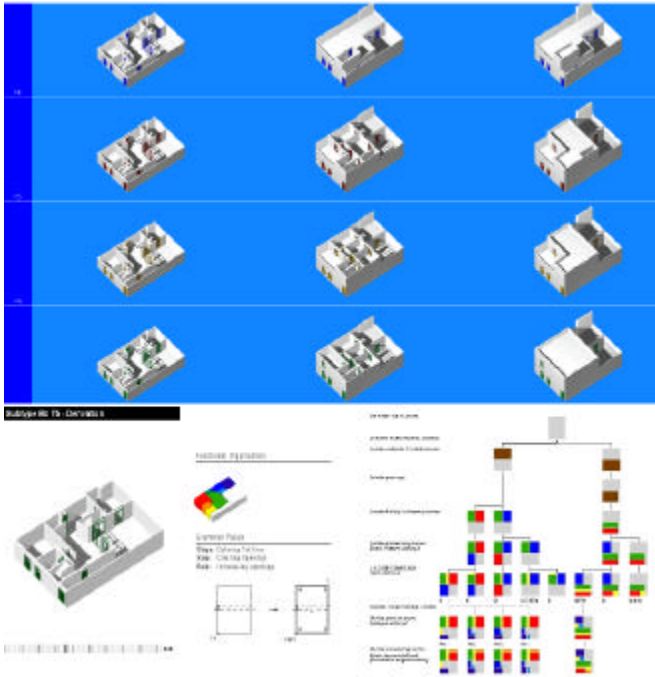


Fig. 4. Jose Duarte, Customizing Mass Housing: a Discursive Grammar for Siza’s Malagueira Houses. Ph. D. dissertation, Massachusetts Institute of Technology.

Making use Duarte's work, House\_n researcher Xioayi Ma (Masters thesis, MIT Department of Architecture, 2002), has developed a web-based Universal Design Engine and decision-making tool for new kitchens (funded by AARP Andrus foundation). With separate funding provided under this proposal, an additional Masters candidate will apply and extend relevant ongoing work to the integrated interior infill ( $I^3$ ) system.

## Appendix B: Historical Background

There have been many proposals to reinvent the process of design and construction for housing over the past 80 years. Few have had any lasting effect on how homes are designed and built. Recent research in academia and developments in industry point the way towards a new and viable approach to the customization of multi-family housing. The brief history below is to put this research proposal in the context of past efforts.

### Le Corbusier and Walter Gropius - 1920s thru 1940s

Le Corbusier, the most influential architect of the twentieth Century, wrote in 1923, *“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.”* This challenge was met in the 1940s by Walter Gropius, founder of the Bauhaus, with the development of a factory based, mass-production system to manufacture highly customizable homes – the Packaged House. Gropius 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.”* The effort failed spectacularly. A factory was built to produce 10,000 panelized houses per year. They soon found that it was impossible to actually offer personal choice with their system. Customized solutions took far too much time to develop, and custom manufacturing was a logistical nightmare in 1945. The company eventually settled on a few standard models, which looked cheaper than conventional alternatives while being more expensive and less flexible. Less than 200 had been manufactured by the time the company closed its doors. Other post-war industrialized housing efforts met a similar fate for similar reasons.

### Habrakan and Open Building, MIT Department of Architecture, 1970s to Present

John Habrakan, Chair of the MIT Department of Architecture from 1975-1981, developed a far more sophisticated approach to mass housing thirty years later. He addressed the problems of industrialized housing at the time: relentless monotony, lack of occupant participation in the design process, and the failure of the industry to benefit from industrialization. He formulated a radical alternative: the division of mass housing production into two parts: "support" and "infill." Support is the communal part of the building that contains the structure, services, etc.; and infill is the private part of the building that can be fitted to the needs of the occupant and changed over time. Habrakan's influential book of 1974 presented the concepts developed at the MIT Laboratory for Architecture and Planning. This approach, which has come to be called Open Building, is popular today in the Netherlands, Japan, and Finland. Its adoption has been limited, however, by the use of proprietary, stand-alone systems rather than open source systems.

### **Mass Customization Trends in Other Industries - 1990s to Present**

The automobile industry reveals three trends: 1) the standardization of the chassis, engine components, sensing, wiring harnesses, etc. across an entire product line, 2) the use of "tier-2" suppliers who replace thousands of assembly line parts with integrated component assemblies, and 3) the mass customization of body parts, finishes, accessories, and other elements that customers want tailored. Both Ford and BMW, responding to market pressures, have announced plans to move towards "batch quantities of one." The use of integrated modules has resulted in 30% reduction in design and labor costs and a 16% reduction in materials cost - while improving quality and accommodating customization and flexibility of production.

### **Designer Tools for Non-Experts, Industry Efforts - 1980s to Present**

In the 1970s, companies needing customized semiconductors contracted with a chip manufacturer to design, prototype, and test custom circuitry. In the 1980s, companies such as LSI Logic Corporation began to offer toolkits for non-experts to design their own custom chips using extensive libraries of pre-tested circuit modules. Today, this \$15 billion industry provides tools for customers to become the designer, fabricator, and programmers of custom chips, called field programmable gate arrays (FPGAs). The automobile industry, moving in this direction, envisions show rooms where the consumer would "design" their car with the desired features, test-drive it using VR, finalize details, arrange the financing, and then transmit the order to the factory. Similar trends can be seen in the PC industry (where Dell provides online customization tools), and the appliance industry (where Electrolux allows individuals "design" a personalized refrigerator).

This trend can be seen in the millwork industry. In the early 1990's, the Portuguese cabinetry company, Barros & Barros, developed software that asked users about their needs, such as types and quantities of apparel they want to store. The software knew the rules of good cabinet design, developed a customized solution, and generated a drawing that was used for fabrication. Similarly, Ikea and Home Depot now offer customized kitchen design services to create unique combinations of standardized cabinetry components – with a large selection of finishes, door types, and hardware. Merilatt, one of the largest cabinetry manufacturers in the U.S., has developed "Organomics," an online cabinetry design tool for lay customers to analyze their needs and explore design options for the kitchen, garage, home office, and bathroom.

### **Automated Cabinetry Fabrication Trends - Current.**

Cabinetry fabrication is perhaps the most sophisticated home-related industry. The trend is towards "lights-out" production by taking advantage of information technology and automated CNC (computerized numeric control) production equipment. As equipment costs decline, even small shops are becoming automated, allowing both high-production and "batch quantities of one." As wood-based fiber products become scarce, the industry is making use of a wide variety of alternative sheet materials. The trade publication, Wood and Wood Products predicts that "a trend for the year 2002 may be mass customization . . . every customer has some special needs. To satisfy them and maintain a competitive edge, the only way to do this is to customize products." This publication also predicts, "almost every piece of kitchen cabinetry and other furnishings in the home will have electronics integrated into them."

### **Modular Housing Trends - Current**

Although the US housing industry has not yet made any serious attempt to address the increasing demand for customized form, materials, and technologies in housing, there has been significant attempts to address the shortage of skilled construction labor - identified by more than 80 percent of US contractors as the most significant challenge facing the housing industry over the next five years. The construction of a new conventionally built home in the US typically consists of 80% field labor and 20% material costs - an extraordinarily high labor component compared to other industries. These shortages have contributed to a general decrease in quality and increase in price of both single and multi-family housing.

One increasingly popular, partial solution to this problem is modular construction, which transfers many field operations to the more controlled environment of a factory. Modular homebuilders now produce about 7% of the single family and low-rise multi-family homes built in the U.S. In 2001 their 12% growth made them the fastest growing segment of the housing market. Modular homebuilders use 3-dimensional sections or modules that are typically 95% finished when they leave the factory. After transport to the construction site, modules are lifted by crane and assembled on a permanent foundation. The resulting home meets conventional code and zoning requirements and is typically indistinguishable from nearby conventional site-built housing. While growing, the modular industry has yet to realize its potential due to design and production limitations.