Open source building — reinventing places of living

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In this paper, we argue that new technologies and strategies for design can enable a more responsive model for creating places of living. We describe work by the House_n Research group at MIT to develop a conceptual framework for Open Source Building, and to prototype and test both alternative construction methodologies and new design tools that support it. We believe that this approach could transform how homes are created over the next 10-15 years, and create new pathways into this $322 billion per year market for companies producing materials, products, and services for the home [1].

1. Introduction — architecture, technology, and the problem of housing

1.1 Introduction

With dark and crowded tenements filling cities, the great architects of the early 20th century focused on reinventing housing. They imagined that their new tools — electricity, steel, concrete, plate glass, mass production, and fresh ideas about design — could be used to transform society for the better. 'The problem of our epoch is the problem of the house,' wrote Le Corbusier in 1927 [2] and Walter Gropius, founder of the Bauhaus, hoped that industrialised construction processes could 'meet the public's desire for individuality and offer the client the pleasure of personal choice' [3].

Though not their intention, the result was relentless monotony and even more impersonal mass housing. This has continued into our time with suburban sprawl and banal urban apartment buildings.

Today, those interested in a new home have two distinct options:

- purchase a standard, generic house produced by a speculative developer (the choice of almost everyone), or
- engage an architect to produce a tailored design, with the associated time, expense and risk (the choice of a tiny minority).

Currently, architects have no meaningful involvement with most of the housing produced in the USA, and unlike the early 20th century, few architects today are interested in addressing societal problems via architecture. In this paper, we advocate a third way. We propose a new model for industry called 'Open Source Building'.

Opens Source Building takes advantage of the new tools of our epoch — inexpensive computation, almost-free electronics, the Internet, wireless communication, high-performance materials, and new design, fabrication, and supply-chain technologies. With these new tools, we may finally have the opportunity to make excellent design ubiquitous — while simultaneously addressing looming societal problems. Industry may be able to combine much of the quality and responsiveness of a 'one-off' architect-designed house, with even greater efficiencies than speculative mass housing. Open Source Building brings together aspects of open building as developed by John Habrakan [4], with open source strategies, as found in the software and electronics industries.

Building on trends that are evident in other industries (see section 4), we advocate the replacement of generic speculative housing development with an open source building model where:

- developers become integrators and alliance builders, offering tailored solutions to individuals,
- architects design design-engines to efficiently create thousands of unique environments,
- manufacturers agree on interface standards and become tier-one suppliers of components, producing systems that share common sensing and communications infrastructure,

- builders become installers and assemblers,
- customers (home-buyers) become 'designers' at the centre of the process by receiving personalised information about design, products, and services at the point of decision [5].

In this paper, we outline the work of the House_n Research Group to formulate an integrated and agile strategy for creating highly responsive environments for people, and describe prototypical, proof-of-concept systems we have designed and built to support Open Source Building.

1.2 Scenario (housing industry in 2015)

The following scenario provides a high-level, integrated view of a design and construction process that it may be possible to achieve over the next 10—15 years given current trends in the housing industry, innovations in other industries, and emerging technologies for the home [6].

Scenario part 1 — developers as integrators

Residential developers now specialise in the process of acquisition, financing, and an increasingly complex public approval processes. They form business relationships with competing 'builder-integrators,' who manage the process of delivering individually tailored homes.

Competing head-to-head in a manner comparable to automobile and consumer electronics manufacturers, these integrators have evolved an efficient process of offering a wide range of features, quality, and performance. The most successful find particular market niches where they excel. Mirroring the trend towards 'Tier-1' suppliers in other industries, home building has evolved from field-labour processes organised by trade (subcontractors), to integrated 'solutions' provided by outsourcing partners.

Scenario part 2 — design, configuration and industry standards

Multifamily buildings are the first to adopt 'open source building' strategies. With a lengthy approval process, buildings must be designed long before an apartment buyer enters the process. To decrease risk and increase sale prices, developers now separate the building into two components: an open loft base building 'chassis' that efficiently integrates the essential services of a building, and customised 'infill,' configured by the user at the point of sale, fabricated to order and quickly connected to the chassis.

Each integrator licenses computational design engines from architect/programmers that are used by a customer to create a unique but formally coherent result. Some use a 'home configurator' with a constrained set of options on the Dell model. For the more adventurous, a design engine can be selected that is mainly constrained by code and structural requirements. Others specialise in face-to-face interaction with a para-architect to lead customers through the complex decision-making process related to space planning, finishes, appliances, lighting, future options, etc. As options are explored, tailored information is presented — often directly from manufacturers — to help the 'designer' make informed decisions about cost, performance, aesthetics, life-cycle cost, durability, etc.

Regardless of the design and configuration strategy, all integrators capture the final design using computational tools that insert and manipulate industry-provided descriptions of each component — from bathroom fixtures to kitchen cabinets to HVAC equipment. Although there are a wide variety of proprietary systems, components all connect according to industry established standards. Power, data, water, gas, and floor/wall connections are largely interoperable among manufacturers. Companies that formerly produced commodity wood fibre building materials, now produce high-value building components including exterior wall, floor, roof, and interior infill systems. Companies that formerly produced pipe and wire, or proprietary fixtures or systems, now produce interoperable components for electrical, plumbing, HVAC systems — comparable to interchangeable devices in the PC industry. Technology companies discover new markets, becoming subcomponent suppliers to building component manufacturers, as the number of processors and sensors in the home exceeds that of the automobile.

the chassis infill approach has been developed to allow every home to be unique

Scenario part 3 — fabrication and installation

When a design is complete and the buyer transaction executed, a description of each system is transmitted to the integrator's assembly factory. The integrator receives just-in-time deliveries of the required components from manufacturers and distributors, taking advantage of supply chain management tools similar to those developed in the automotive industry. With standardised connections, and tighter dimensional tolerances, the fit-out takes no more than 10 days. Although the systems of the home are functionally integrated, they are also carefully disentangled so that each can be changed during design or use without affecting the performance of the larger system. Most devices and systems have IP addresses and communicate wirelessly or by powerline carrier, allowing, for example, lighting control to be made and changed during the occupancy of the home.

2. New ways of building — chassis, infill, and integrated technologies

The following section describes work by the House_n Group and the Open Source Building Alliance to separate a structure into a 'chassis' (the standardised bones and utilities of a building) and 'infill' (elements that are customised by the individual and connect in standard ways to the chassis). This is an alternative to site-based mass production commonly used by merchant builders, where crews move from site to site, repeating operations. The chassis/infill approach has been developed to allow every home to be unique, and to efficiently accommodate new technologies and change over time (Fig 1).

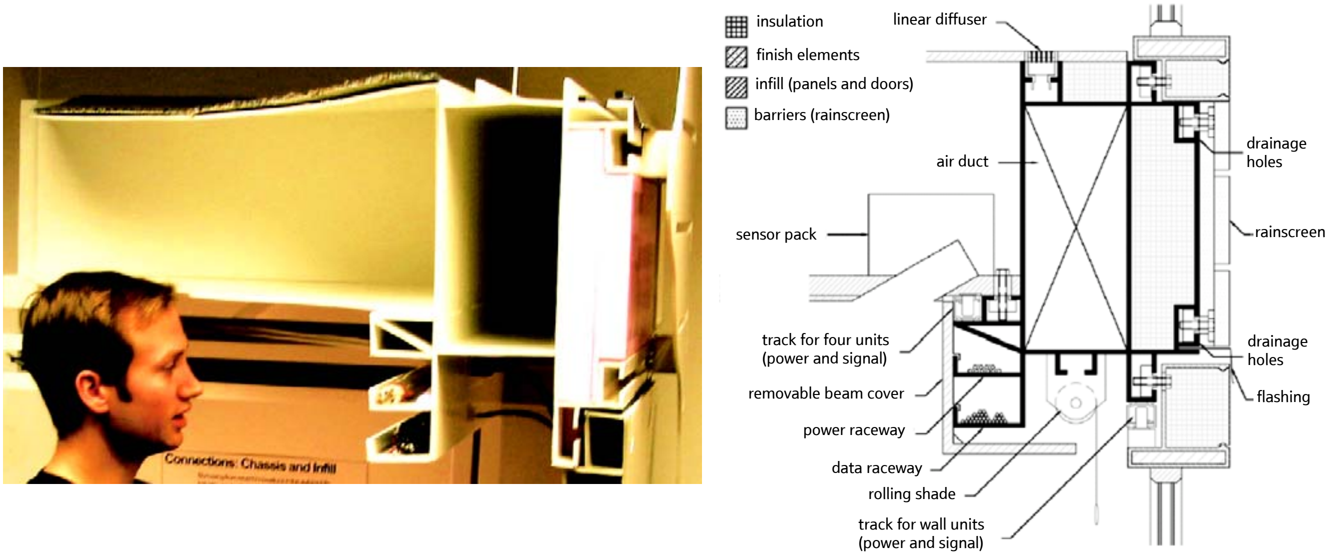

Fig 1 House_n pultrusion chassis — full-scale model (left) and detail drawing (right) of a prefabricated pultrusion chassis showing beams, column, connectors, raceway for power and data, attachments for exterior wall and floor, housing for equipment, exterior insulation, and linear diffuser [7].

2.1 Chassis prototypes

House_n researchers have developed several chassis concepts. Tyson Lawrence developed an integrated post and beam pultrusion chassis for single-family houses that could be rapidly and precisely installed with minimal field labour [7]. In one integrated assembly, the chassis provides structure, insulation, sensor arrays, signal and power cable raceways, and ductwork. The chassis contains the necessary physical, power, and signal connections for mass customised infill components to be quickly installed, replaced, and upgraded without disruption. Full-scale mock-ups of key pultrusion components were built, and proposals for standardised mechanical, power, and data connections details were developed.

Based on the House_n pultrusion chassis, T J McLeish constructed an architectural scale model to develop and test distributed network concepts (Fig 2). Network infrastructures in buildings are complex and difficult to install, maintain, and expand. In the future, networks should be self-configuring, self-maintaining, easily adaptable and expandable. They should require no complex programming, not rely on a central computer, and promote error-proof construction. In this project, each schematic 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.

A second chassis design was developed for mid-rise, urban-infill multifamily condominium projects. Open loft apartments are created by stacking mass-produced, volumetric, steel and concrete modules of dimensions that are optimised to be efficiently transported down highways (Fig 3). Each is complete with structure, ductwork, power, signal, plumbing connections, mechanical attachments for infill, HVAC systems, floor finishes, and ceiling finishes. At the point of sale, demising walls are added to create the size of unit required, and the buyer then engages in a design process to define the interior design, systems, and services.

Fig 2 House_n pultrusion chassis and communication — 1/12th scale model of a post and beam chassis to study embedded computational technology that allows newly introduced devices to announce their presence on the network [8].

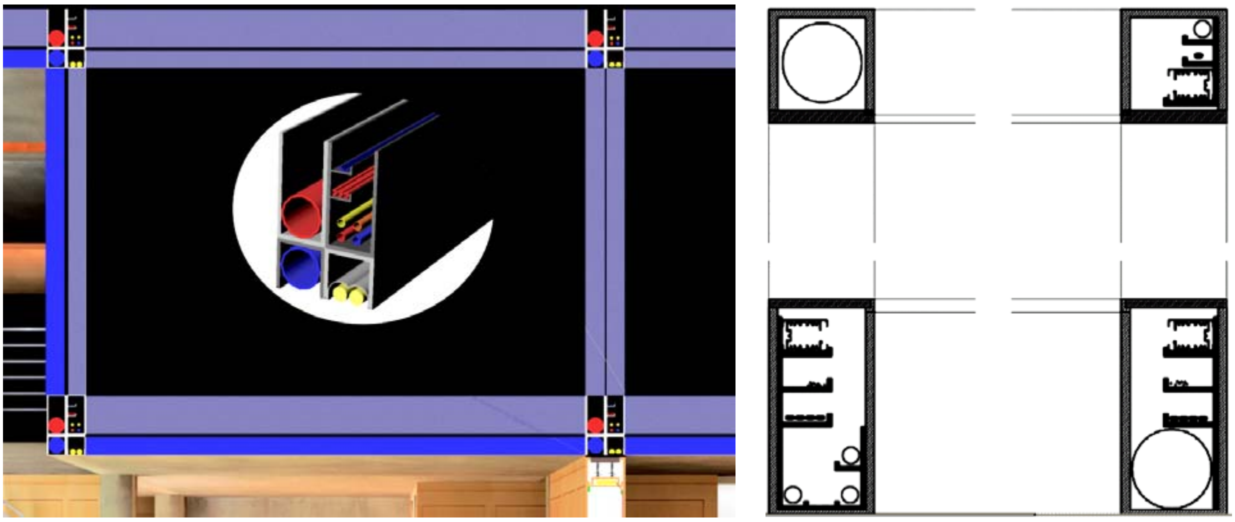

Fig 3 Volumetric chassis. Left: Section showing module intersections. Each module is optimised for efficient highway transportation at 13ft 6 in wide by 10 ft high. Right: Ceiling and roof beams of a module, with utilities installed in the factory. In this diagram, the top left beam of the chassis unit holds a duct to carry air from the HVAC unit to the interior space. In the lower left beam, hot and cold water, and gas are run to the HVAC unit. This 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 [6—8].

2.2 *Integrated interior infill*

In our model of apartment interior design, multiple manufacturers compete to offer a wide variety of options. The millwork industry, with its sophisticated, automated computerised numeric control (CNC) technologies capable of highly efficient 'batch quantities of one,' can play an important role in efficiently and affordably creating customised interiors. We have extended the application of automated cabinetry fabrication to create concepts for an integrated interior infill (I3) system that replace conventional interior framing, drywall, and finish elements. The components integrate power, communication, and lighting systems with environmental sensing and HVAC systems. Component types will include reconfigurable dividers, storage/organising units, and special purpose components for work, education, and entertainment (Fig 4). Standards for connections will be outlined that, if adopted by industry, would allow for many companies to innovate with the production of specialised I3 components.

2.3 *PlaceLab as an Open Source Building prototype*

A variation of the infill system described above has been used at the PlaceLab. The chassis/infill strategy was used to create

Fig 4 House_n volumetric chassis/infill building section showing loft modules and two possible apartment infill solutions. Upper apartment is a five-bay unit with wood-veneer cabinetry. Lower apartment shows a three-bay 'Ikea-like' fit-out [6].

an apartment-scale research environment to study the interactions of people with new technologies. The PlaceLab[1] interior consists largely of prefabricated cabinetry that houses sensing, communications media, lighting and control systems (Figs 5 and 6). If developed into a commercial, customisable interior fit-out system, complex technologies could be pre-installed in prefabricated interior components in homes — minimising problematic field labour, and allowing for non-disruptive upgrade and changes.

[1] PlaceLab is a joint initiative between the MIT House_n Research group and TIAX LLC.

The upper section of each cabinetry infill element contains a micro-controller that connects to the apartment networks and the local one-wire sensor bus (Fig 7). Located in raceways behind hinged panels at the cabinet top, bottom, and sides are a variety of sensors and communication devices (Fig 8), including:

Fig 5 Perspective views of the two possible apartment infill designs shown in Fig 4. Right: scale study model of the building exterior [6, 8].

Fig 6 PlaceLab interior, showing I3 fit-out. Each of the 22 interior components contains a micro-controller, sensor bus, and a variety of state change sensors, environmental sensors, and communications devices.

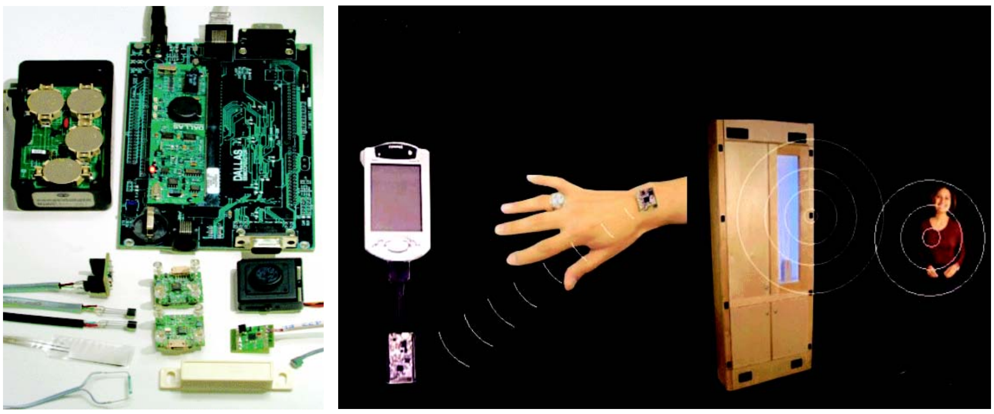

Fig 7 'Tini' micro-controller and one-wire sensors installed in each PlaceLab infill component, and wireless, wearable House_n MITes (MIT environmental sensors) communicating accelerometer, location, and identity data to receivers located in either PlaceLab I3 components or wearable PDAs [9].

Fig 8 PlaceLab interior testing one aspect of Open Source Building — I3 components with sensing and addressable lighting infrastructure. Shown are hinged, accessible sensor bus raceways. All cabinets use the same embedded connections and technologies, simplifying installation and increasing flexibility. The facility contains hundreds of modular sensors.

- sensor network — each of the interior components contains a micro controller and network of 10 to 30 sensors, to which new sensors can be rapidly added as required,
- environmental sensing — each interior component can accept an array of environmental sensors, including CO, CO_2, temperature, and humidity,
- state sensors — small, wired and wireless sensors are located on the objects that people touch and use, including cabinet doors and drawers, controls, furniture, passage doors, windows, kitchen containers, etc, in order to detect on-off, open-closed, and object movement events,
- location beacons — radio frequency devices will permit the identity and approximate position detection of people within the PlaceLab (in development),
- audio sensing — nearly invisible microphones are installed in each interior component to capture audio,
- audio communication — stereo speakers are installed in each interior component, allowing audio to be directed as required,
- addressable lighting — the intensity and colour temperature of light in each major PlaceLab space will be dynamically controlled, allowing light to be used as a communications tool or to adjust the ambient qualities of each room.

While the technologies installed in PlaceLab components are principally for laboratory purposes, commercial versions may be useful for future home-based applications. Homes that can automatically determine what occupants are doing, using sensors built directly into the environment, would enable a new class of innovative, home-based service for proactive and preventive healthcare applications — as well as learning environments, security systems, lighting control, HVAC control, energy management, personal communication, and more effective appliance and device interfaces. Simple switch sensors like those built into the PlaceLab interior infill can be used by computer algorithms for automatically recognising activities in the home [9]. Such a sensing system presents an alternative to the more typical activity recognition devices, such as cameras and microphones, which are often perceived as invasive by today's homeowners. We envision a future where individuals could tailor their physical and computational environment according to their needs and values via customised I3 components, each with pre-installed, tailored technologies.

3. New ways of designing — tools for non-expert designers

MIT recently celebrated the opening of Frank O Gehry's largest project to date: the Ray and Maria Stata Center for Computer, Information, and Intelligence Sciences. The complex forms of the building were made possible by the use of new computational design, fabrication, and co-ordination tools. If the processes that created the Stata Center are among the most sophisticated of the profession, at the opposite end of the spectrum is housing. Most new homes are poor quality generic commodities, created with processes little changed since post-war Levittown (Fig 9).

While the new design and fabrication tools deployed by the Gehry team are useful for singular buildings like the Stata Center, they are not directly applicable to housing. We argue that next generation computational tools that place the individual (customer) in the centre of the design process, if mated with a more rational approach to construction and fabrication, can enable a democratisation of excellent design and technology in housing. These new processes must scale to a mass market.

In our model of design, experts create systems that capture their design knowledge and values. They are used to guide non-expert designers through complex design and decision-making problems — without requiring that one think like an expert. This is an extension of a 'customers-as-innovators' approach advocated by Stefan Thomke and Eric von Hippel, who write:

> 'With the customers-as-innovators approach, a supplier provides customers with tools so that they can design and develop the application-specific part of a product on their own. This shifts the location of the supplier-customer interface, and the trial-and-error iterations necessary for product development are now carried out by the customer only. The result is greatly increased speed and effectiveness'. [10]

Fig 9 Left: MIT Stata Center by architect Frank O Gehry. Centre: Levittown — early suburban mass-housing development. Right: late 20th century generic, speculative, merchant-builder suburban housing built on the Levittown model. [Photos: Larson, Scherschel]

The customisation of homes is, in many ways, more challenging than the mass-customisation of individual products since the users of the system have a wide range of age, interests, skills, and cognitive ability. In addition, the resulting home is a complex mix of many products, some standard and some customised, with less tangible elements such as light, form, and materials. It requires a design interface that provides individuals with the means to effectively make informed decisions without becoming overwhelmed by the process. This involves much more than simply offering choice since, as Joe Pine writes:

> 'Customers do not want choice. They want what they want (and generally now).' [11]

Our approach to design decision making for non-expert designers involves four integrated components.

- Preference engine

  This takes people through a series of exercises or games to uncover needs, preferences, values, and reasonable trade-offs — what might be called the architectural program. The preference engine builds a user profile that includes family size, budget, aesthetic values, and range of activities.

- Design engine

  The architectural program generated by the preference engine is used to create a starting point design that the 'designer' (i.e. the future homeowner) then refines. We envision many design engines, each capturing the unique values of a particular designer.

- Design iteration interface

  Using one of many possible design iteration interfaces, customers can experiment with design alternatives, and evaluate a complex mix of attributes including form, finishes, light, cost, appliances, performance, durability, technologies, and services. Through this interface, participating manufacturers can provide tailored information directly to the customer at the point of decision about the design, systems, appliances, and services for their tailored place of living. Once the design is set, data can be sent directly to manufacturers such as millwork fabricators who have pre-negotiated specifications and prices. For customised millwork and wall systems, data may go directly to the production line with little or no increased cost over mass production manufacturing. This new model may create a path to market for companies not presently players in this industry.

- Computational critics

  While iteratively exploring a design solution, most non-expert designers will require feedback from experts related to best practices, building codes, and design integrity. Computational critics can provide feedback to the user as incremental changes are made to the design.

The following sections describe current work to develop a prototypical preference engine, design engine, design iteration interface, and computational critics.

3.1 Preference engine — understanding needs and values

The process we have developed begins by drawing on the expertise and personal experiences of each homeowner. At its most basic, the 'preference engine' asks carefully tailored questions such as: How many people will live in your home? or Do you like to cook? House_n researcher Jennifer Beaudin has explored a series of potentially more powerful approaches to understanding the needs and values of the homeowner [12]. She conceives the pre-design stage as an iterative learning process of defining perspectives, uncovering needs, expressing plans for the future, and making personal connections. Beaudin worked with a series of volunteers to test the use of story telling, scenario building, image sorting, and other design exercises (Fig 10 left). One strategy made use of technology to encourage families to reflect on their actual behaviours and needs, rather than revert to stereotyped responses, when making decisions about their new home [13]. Experience-sampling technology on a PDA was used to periodically ask questions about current activities in the home [13]. Simple sensors on cabinetry, fixtures, and appliances were also used to automatically collect data about inhabitants' activity patterns (Fig 10 right). The result could be distilled to generate an architectural program used to begin the design process.

	1. Questionnaires basic	1. Question slips	2. Image sorting basic	2. Image sorting resorting	2. Image sorting tours	3. Reflection	4. Sketching	5. Storytelling	6. Scenario building	7. Wish lists	8. Photographic inquiry	9. Field exercise	10. Design your own
Arlene			tried	tried		recommended		applied	recommended	recommended			
Emma	tried		tried	tried	tried					recommended		recommended	
Gwen	tried	tried	tried	tried	tried	applied	tried		applied				
Kristen	tried		applied			applied			tried		recommended		
Patricia	tried		tried			recommended	recommended		recommended	recommended			
Tom and Barbara	tried	tried	tried	tried	tried				applied	recommended			
Zach	applied	tried	tried	tried	tried	recommended	tried	applied	recommended	tried	recommended	recommended	

= tried = recommended or would have tried = applied some aspect

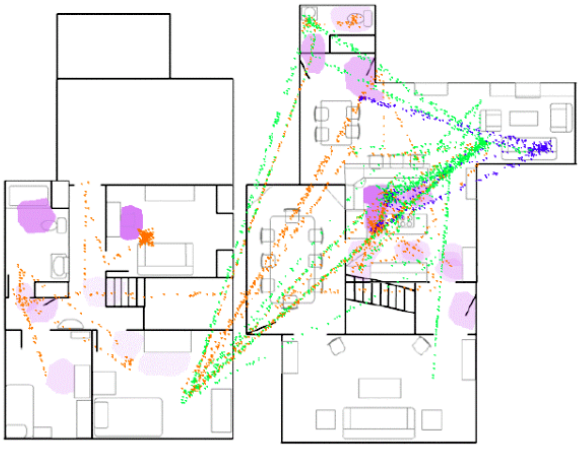

Fig 10 Left: the results of a pre-design exercise study showing which strategies were found to be more effective for an individual; participants are shown at left, pre-design exercises at the top. Right: a family's movements, as recorded by the position-tracking, and actions, as recorded by the open-close sensors, for two hours on a Thursday evening. The mother's path is orange, the father's path is blue, and the daughter's path is green. Approximations of where the actor stands when an open-close sensor is activated are indicated in purple. Showing such data on a consumer's behaviour in their own home may have an impact on how they design future spaces, helping them focus on important design considerations that could have an impact on everyday behaviour [12].

3.2 Design engine

Computational design systems have been used for architectural design in prior work. For example, Duarte created a computational design system based on the work of the architect Alvaro Siza [14].

In the 1970s, Siza developed a system aimed at increasing user participation in the design of mass housing at Malagueira. Devising implicit design rules, Siza used those rules to generate over 35 different layouts, ranging from one to five-bedroom houses — in an effort to incorporate the users' desire for a customised house into the design process. Duarte's design engine explicitly encodes Siza's design rules into a shape grammar.

Building on Duarte's work, House_n researcher Xiaoyi Ma, developed a computational system for kitchen design [15]. Ma created an exhaustive database of design typologies for kitchen room shapes, functional arrangements, appliance configurations, etc, as well as the parametric rules for their configuration (Fig 11 left). She also developed user typologies that included family profiles, eating styles, cooking patterns, physical disabilities, etc. While a good architect can synthesise complex information to generate a solution that addresses multiple problems simultaneously, non-expert designers often find this difficult to do.

Working with criteria established by an individual's interaction with a preference engine, and factoring in architectural context constraints and universal design guidelines, Ma developed a design algorithm that searches for an initial best-fit layout type and adjusts the dimensions parametrically (Fig 12 right). This is used as a 'starting point' design. Acknowledging that no design algorithm can have a sufficiently rich description of an individual's needs and values, she then leads the user through a series of steps to refine the design by exploring additional issues related to function, appliance specification, universal design attributes, and aesthetics.

3.3 Design iteration interface

While Ma's design tool was conceived as a Web-based interface, McLeish constructed a tool to rapidly explore condominium design variations for a multifamily loft building chassis and interior infill as described above. A digital table is used to present three simultaneous representations [16]:

- conceptual — a 1 inch = 1 ft diagrammatic plan view showing relationships and information,
- tangible — an intuitive means of manipulating architectural infill components by physically moving scale objects placed on the 2D diagrammatic plan,
- perceptual — a perspective view, continuously updated as the physical objects are moved, to reveal how the form, light, and materials would be perceived.

Because manipulating the plan via a mouse would be difficult for most users, physical models of each infill component type, a limited selection of furniture, and a human figure to set views, were created. Maintaining synchronicity between the physical objects and the projected plan representations requires that each object be precisely identified and located in 2D space on the table (Fig 12). To do this, each model has an embedded visual LED tag, seen through the surface of the translucent table by a camera and recognised by a computer vision system (Fig 13). As the designer moves the tagged objects on the table, both the plan view projected on the table and the perspective view projected on the wall beyond are updated in real time.

Interacting with McLeish's interface begins with a 'preference engine' that gathers basic information by asking questions (Fig 14 left). Using this information, a design engine generates a starting point apartment plan made up of I3 components (Fig 14 right). Depending on the strategy of the integrator, these may be large aggregations, such as an entire kitchen, or smaller elements, such as individual kitchen cabinets and appliances, for a wider range of possibilities. The designer

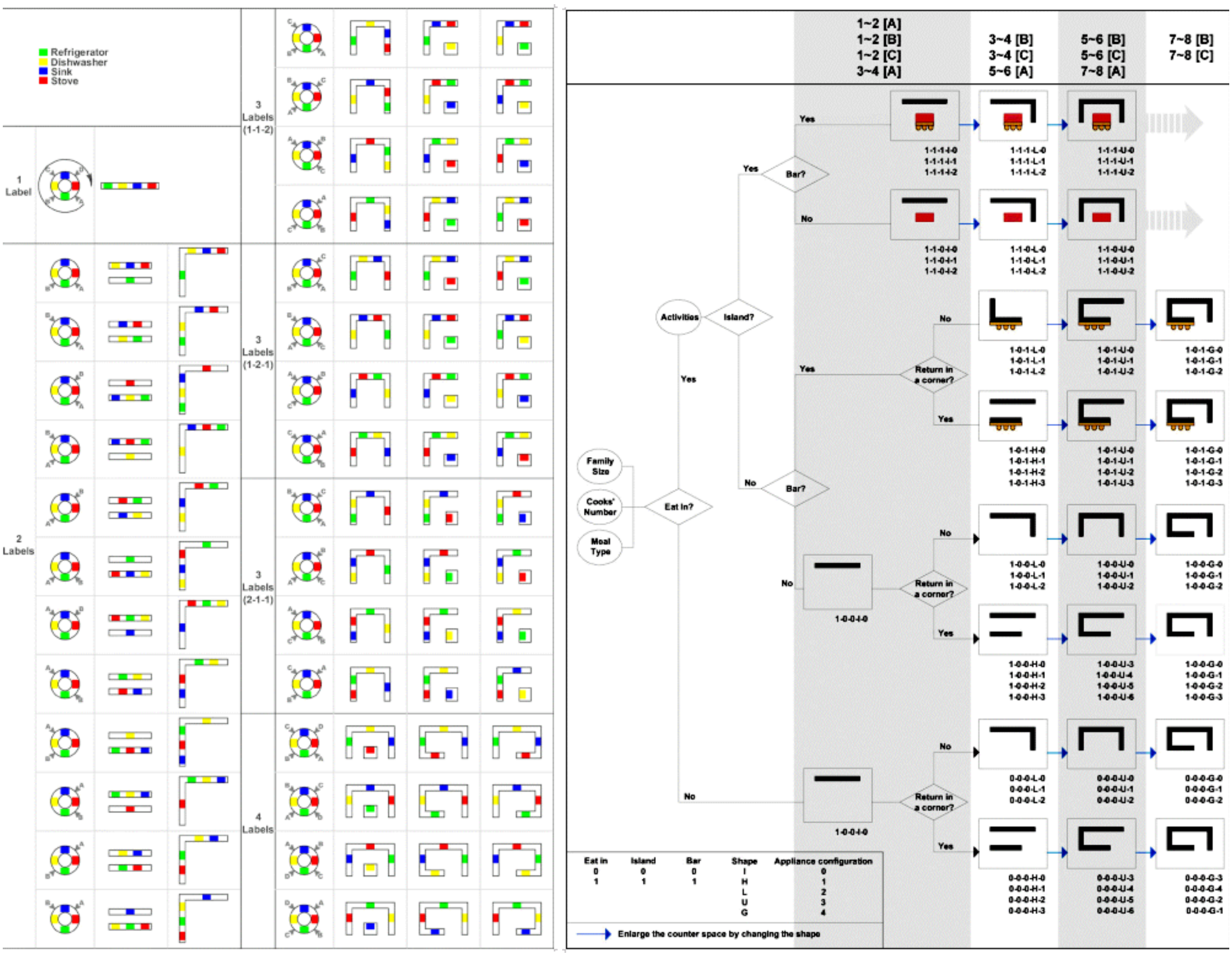

Fig 11 Left: diagrammatic kitchen types and their transformations. Right: a decision-tree example for the parametric design of kitchens [15].

places physical objects representing I3 components on the table, registered with the 2-D plan (Fig 15 left). As the designer rearranges or replaces these physical components with others (Fig 15 right), both the plan representation and a perspectival rendering showing form, light and materials is updated in real time. In the process, the designer may receive updated information on initial cost, life-cycle cost, performance, options, etc. Manufacturers and service

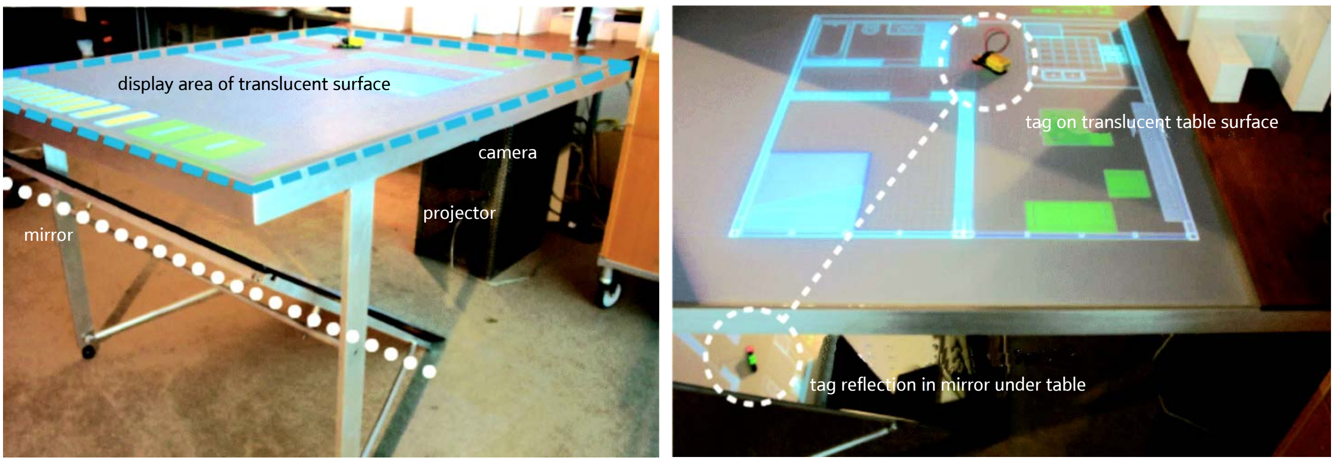

Fig 12 Digital table [16], with a design iteration interface [8]. A video projector below projects an edge-to-edge image, reflected off an angled mirror. A camera below can be used for computer vision tracking of objects with unique LED patterns above.

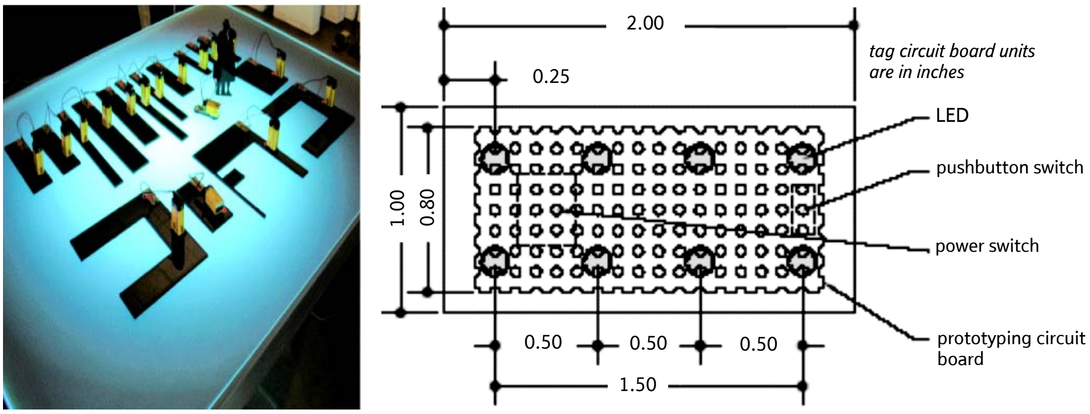

Fig 13 Left: optically tagged object bases before the model covers are applied. Right: LEDs at base of each object that provide a unique pattern for computer vision recognition of identity, location, and orientation [8].

providers — strategic partners of the integrator — have the ability to provide tailored information when decisions are being made about a particular aspect of the design.

3.4 Computational critics

As the designer considers alternatives, 'computational critics' that encode some of a particular architect's expertise can be used to provide instant feedback. Since face-to-face interaction between a skilled architect and client is typically not feasible for housing developments, we envision a system where architects provide software 'plug-ins' that non-expert designers can use to get real-time feedback as they make changes to their designs. While code requirements can be rule-based, capturing the more subjective values of a designer may require a more open-ended approach. House_n researcher Reid Williams implemented a prototype of a computational critic system that runs with the design iteration interface described above [17]. Experts train critics by simply rating a large set of example floor plan designs constructed with standard infill components. The algorithm then creates a critic for each architect by encoding the biases used by the architect as he or she makes decisions. Unlike previous critic systems, the architectural perspectives are learned by example, not by tedious and costly manual rule creation.

The designer simply selects a desired architectural critic. As the user moves an infill component, a rating of that move according to the currently selected computer critic is displayed on the table. Ratings are 'acceptable,' 'unacceptable,' or 'unrated.' For 'unacceptable' changes, the critic displays a

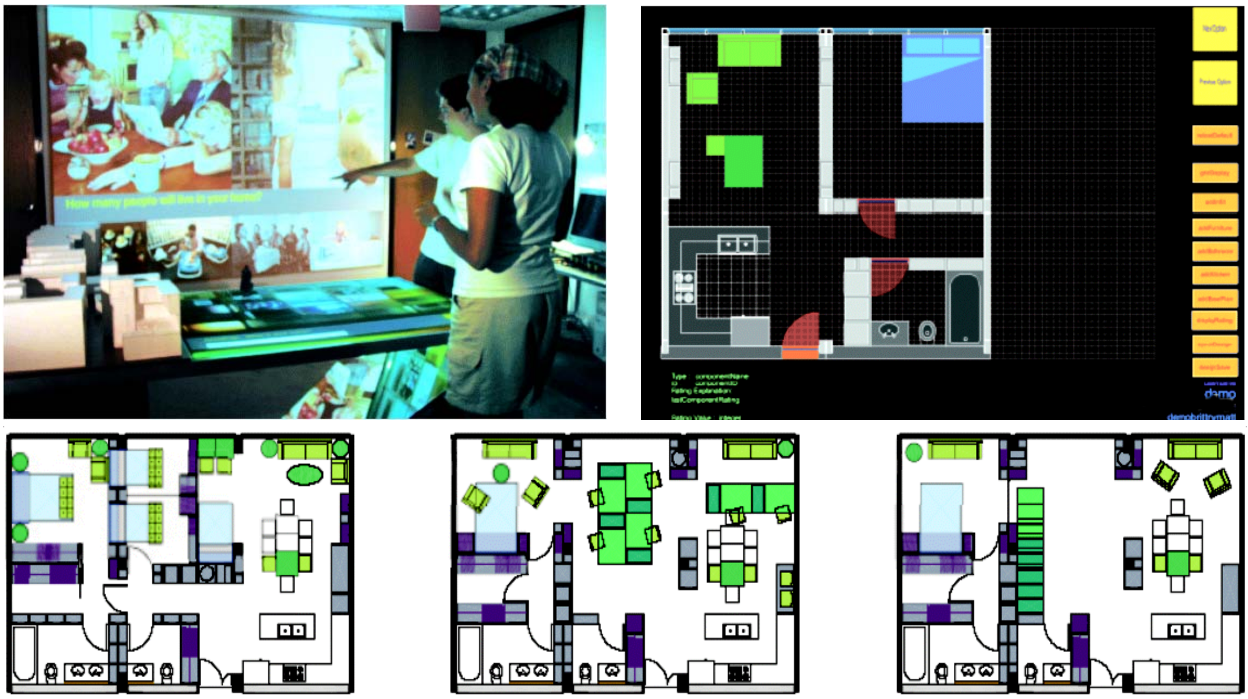

Fig 14 Upper left: the 'preference engine' in the process of collecting basic information about needs, values, and activities — in this case asking: 'How many people will live in your home.' Upper right: a suggested design requesting the designer to register an optically tagged phicon on the schematic plan projected on the table. Below: apartment plan variations generated during a design session, using 13 infill components within a loft apartment chassis [8].

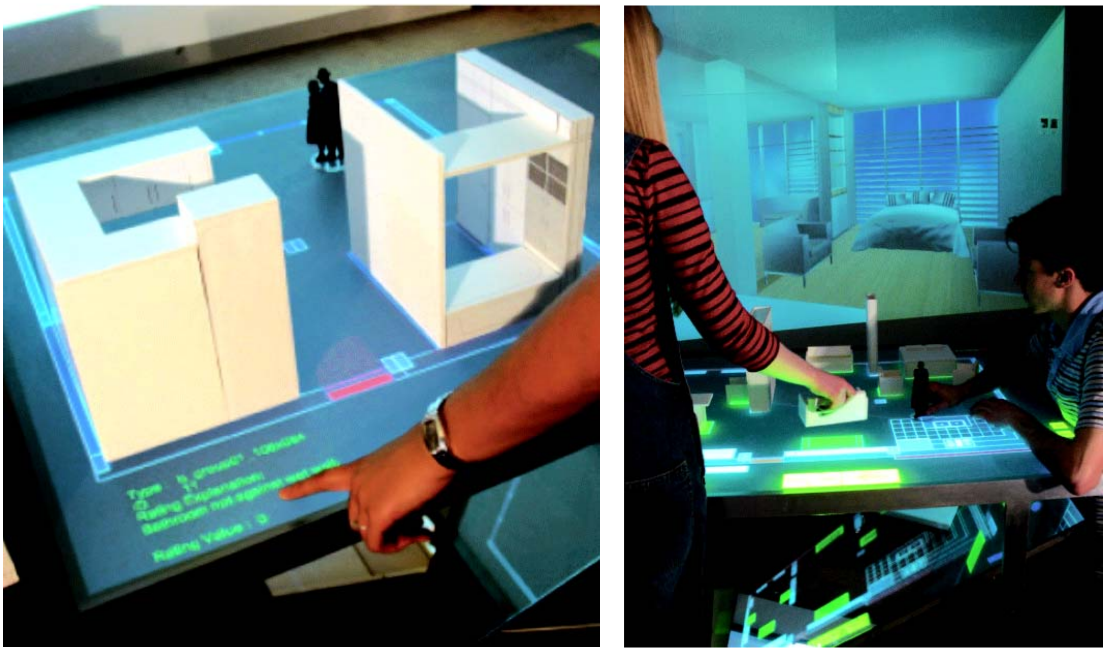

Fig 15 Left: view from above of digital table showing plan, information display, tagged physical components and continuously updated feedback about design. Right: digital table in use with 3 types of interface: (1) conceptual representation (2-D diagrammatic plan view that shows relationships and information), (2) tangible representation (3-D objects registered with the plan view, used to study design alternatives and relationships), and (3) perceptual representation (for the visualisation form, light, and materials) [8].

brief explanation that provides a hint of how the problem might be corrected. Critics can be trained with specific biases and then used together. For instance, one critic may be trained to judge appropriate relationships between a kitchen and dining room based on spatial layout, but another may be trained to evaluate the same design based upon a criterion such as privacy. The privacy critic may report that two rooms are not private with respect to each other because there is a straight path or direct line of sight between the kitchen and dining room table, whereas the spatial layout critic may find the design acceptable (see Fig 16).

To date we have constructed a prototype version of the critic system. Although it learns only relatively simple rules about spatial layout for a small set of infill components, it does so without requiring any knowledge expertise from the experts or any architectural expertise from the novice users. The critics use a decision-tree algorithm in order to learn a particular perspective when given a large, labelled set of floor plans from a particular designer [17]. Although critics attempt to offer some guidance by reporting how the decision-tree algorithm determined that a design is unacceptable, sometimes the rules the computer learns from the expert examples are difficult for a person to interpret. However, the algorithm runs in real-time on the table interface. Therefore, even if the algorithm does not provide the user with a helpful hint, the user can simply experiment with the interface to find a solution that is acceptable for the selected critic. Or (as people sometimes do with actual architects) the user can simply ignore the critic's advice altogether. Although currently implemented to address relatively simple plan relationships, this approach could be extended to more complex three-dimensional form issues.

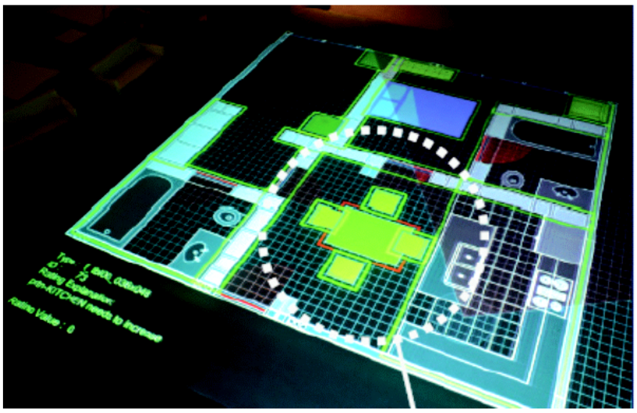

Fig 16 Plan view of a proposed design, showing how a computational critic evaluates the relationship of the dining area and the kitchen with respect to access and privacy [17].

4. Convergence of opportunities and next steps

4.1 Changing places of living

Powerful societal forces are at work that may trigger a fundamental change in how we design, build, and integrate technologies into places of living:

- the nature of work is changing, with up to 1/3 of the workforce working out of the home in some companies,
- a looming crisis in healthcare, caused by baby boomer demographics, will require a transition to home-based preventative medicine,

- energy shortages, brought on by an inability to expand the grid and build new centralised plants, will motivate home-based renewable production and advanced conservation methods,
- technology companies developing products and services for home-based health care, work, commerce, play, energy conservation, and communication require a sophisticated, agile, upgradable infrastructure in the home,
- affordable sensing and computation will find its way into nearly everything man-made, including building components,
- building material companies are looking to migrate from low-margin commodities to high-value systems,
- a shortage of skilled construction labour, identified by 80% of contractors as their most serious problem, will force a transition to automated fabrication processes (a site-built new home in the US consists of up to 80% field labour and 20% material costs),
- Web-based customer configuration tools, supply chain management innovation, and automated fabrication processes are changing how products are marketed, designed, and fabricated,
- a return to urban life and escalating property values place a premium on multi-use, compact, flexible, high-quality living space,
- baby boomers and GenX homebuyers, with unprecedented assets, demand environments and products that directly reflect their unique values and needs.

The expectations of the baby boomers may be the most important factor in changing the industry. Speaking at a National Association of Home Builders conference in 2002, William Novelli, Executive Director and CEO of AARP said the following about baby boomers and housing:

> 'They love choice: set up the smorgasbord and let them help themselves. They will. They want information — and the more sources the better because they are not afraid to make decisions — but only on their own clock and in their own terms.' [18]

Providing tailored solutions in housing is a radical departure from the 'one size fits all' model of merchant builder speculative housing development.

4.2 Recent trends in industry — modularity + Open Source + customisation

New technologies have not only transformed products, but they have dramatically altered the ways in which products are designed, manufactured, and marketed. Many companies are now bringing together three concepts:

- principles of modularity (where interface between systems are standardised),
- a form of open source (where designers and engineers at many different locations and organisations share knowledge and details and agree on common design rules),
- customisation (where products are tailored for the specific needs and values of an individual).

Dell, for example, has become an integrator who forms business relationships with a network of strategic partners and suppliers, and offers consumers a Web-based configuration and decision-making tool for customisation, and builds 'batch quantities of one' computers tailored for individual customers from largely standardised chassis and modular add-on components.

In the automobile industry, these developments are evident with:

- the standardisation of the chassis, engine components, sensing, wiring harnesses, etc, across product lines,
- the use of 'tier-1' suppliers who replace thousands of assembly line parts with integrated component assemblies,
- ubiquitous 'car configurators' for the customer to 'build your own car'.

Both Ford and BMW, responding to market pressures, have developed plans to move towards 'batch quantities of one.' GM's well-publicised HyWire concept car is conceived as a standard chassis to be common across their entire product line, with highly customised 'infill' (the body parts, finishes, electronics, etc). Commercial aircraft production and cruise ship manufacturing use similar strategies. No comparable approach, however, can be found in the design and construction of buildings.

4.3 Open Source Building Alliance

There is a tremendous potential for new products and services as we reinvent the process of design, fabrication, and the integration of new technologies into the home, but there are barriers to innovation that must be overcome.

> the goal of OSBA is to trigger an explosion of creative activity

The research that is needed to tap this potential is fragmented and out-of-context. Computer scientists attend pervasive computing conferences to present visions of life in the home in the future, but rarely does an architect attend. Architects gather to debate the latest design ideologies without including those who actually make the systems and materials they will use. Dozens of industry groups meet to discuss new manufacturing processes or home networking standards without including those who actually design and build buildings. Health researchers propose visions of the smart medical home of the future, but without careful study of how the behaviour and non-medical needs of their patients will change when they leave the hospital and return to the home.

Devices are prototyped for the home without evaluating their use in the complex mix of everyday activities.

We propose that industry and academic researchers come together to create a high-level 'systems architecture' that allows for integrated research leading to industry agreement on design principles (resulting in industry standards). To this end, we have formed the Open Source Building Alliance (OSBA). The goal of OSBA is to trigger an explosion of creative activity resulting in high-performance, cost-effective environments by:

- standardising approaches to a building 'chasis' and the interfaces between elements,
- developing an agile methodology for unlimited variations of the elements that people see, touch, and interact with or 'infull'.

This will involve industry agreement on standards related to data, electronics, software, and physical component connections, etc. We believe that this could lead to the democratisation of good design and engineering. It may also provide the integration and economies of scale necessary for new materials, technologies, and services that address the great societal needs of our time, from preventative medicine to distributed energy production.

References

1 USA Census Bureau, Construction Expenditures Branch (2003) — http://www.census.gov/const/c30_curr.txt

2 Le Corbusier C-E J: 'Towards a new architecture', original edition (1927).

3 Gilbert H: 'The packaged house: dream and reality', Technion-Israel Institute of Technology (1981).

4 Habraken N J: 'Variations, the systematic design of supports', in Boekholt J T, Thyssen A P and Dinjens P J M: 'MIT Laboratory for Architecture and Planning', distributed by The MIT Press, Cambridge, USA and London (1976).

5 Kent L: 'The home of the future', Architecture and Urbanism, A+U 361 (October 2000).

6 Larson K, Tapia M A and Duarte J P: 'A new epoch: automated design tools for the mass customisation of housing', Architecture and Urbanism, A+U 366 (March 2001).

7 Lawrence T: 'Chassis + infill: a consumer-driven, Open Source Building approach for adaptable, mass customised housing', MS Thesis, Mechanical Engineering, Massachusetts Institute of Technology (September 2003).

8 McLeish T J: 'A platform for consumer driven participative design of open (source) buildings', MS Thesis, Media Arts and Sciences, Massachusetts Institute of Technology (September 2003).

9 Munguia E T, Intille S S and Larson K: 'Activity recognition in the home setting using simple and ubiquitous sensors', in Ferscha A and Mattern F (Eds): 'Proceedings of PERVASIVE 2004', Berlin Heidelberg, Springer-Verlag, LNCS 3001, pp 158—175 (2004).

10 Thomke S and von Hippel E: 'Customers as innovators: a new way to create value' Harvard Business Review, 80 No 4, pp 74—81 (April 2002).

11 Pine J: 'Markets of One', Harvard Business School Press (1997).

12 Beaudin J S: 'From personal experience to design: externalising the homeowner's needs assessment process', MS Thesis, Media Arts and Sciences, Massachusetts Institute of Technology (September 2003).

13 Intille S S, Rondoni J, Kukla C, Anacona I and Bao L: 'A context-aware experience sampling tool', Proceedings of the Conference on Human Factors and Computing Systems: Extended Abstracts, ACM Press (2003).

14 Duarte J: 'Customising mass housing: a discursive grammar for Siza's Malagueira houses', PhD dissertation, Massachusetts Institute of Technology (2001).

15 Xiaoyi M: 'A Web-based user-oriented tool for universal kitchen design', Department of Architecture, Cambridge, Massachusetts Institute of Technology (2002).

16 Stigge B: 'Informed home energy behaviour: developing a tool for homeowners to monitor, plan, and learn about energy conservation', Masters Thesis, Department of Architecture, Massachusetts Institute of Technology (June 2001).

17 Williams R E: 'Training architectural computational critics by example', MEng Thesis, Electrical Engineering and Computer Science, Massachusetts Institute of Technology (2003).

18 Novelli W D: 'Helping aging boomers to age in place', Lecture Presented at 2002 Seniors Housing Symposium, National Association of Home Builders, Orlando, FL (May 2002).

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