

Digital Design for Disassembly

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INTRODUCTION

The building sector is now widely known to be one of the biggest energy consumers, carbon emitters, and creators of waste. Some architectural agendas for sustainability focus on *energy efficiency* of buildings that minimize their energy intake during their lifetime – through the use of more efficient mechanical systems or more insulative wall systems. The focus on efficiency is but one aspect or system of the building assembly, when compared to the effectiveness of the whole, which often leads to ad-hoc ecology and results in the all too familiar “law of unintended consequences” (Merton, 1936). As soon as adhesive is used to connect two materials, a piece of trash is created. If designers treat material as energy, and want to use energy responsibly, they can prolong the lifetime of building material by designing for disassembly. By changing the nature of the physical relationship between materials, buildings can be reconfigured and repurposed all the while keeping materials out of a landfill.

The concept of *design for disassembly* is a recognizable goal of industrial design and manufacturing, but for Architecture it remains a novel approach. A classic example is Kieran Timberlake’s Loblolly House, which employed material assemblies “that are detailed for on-site assembly as well as future disassembly and redeployment” (Flat, Inc, 2008). The use of nearly ubiquitous digital manufacturing tools helps designers create highly functional, precise and effective methods of connection which afford a building to be taken apart and reused or reassembled into alternative configurations or for alternative uses.

This book will survey alternative energy strategies made available through joinery using digital manufacturing and design methods, and will evaluate these strategies in their ability to create disassemblable materials which therefore use less energy – or minimize the entropy of energy over the life-cycle of the material.

– THE ENERGY PROBLEM

It is widely known that the building and construction industries account for a large portion of global energy use. According to a publication by the International Energy Agency in 2013, “buildings are the largest energy-consuming sector in the world, and account for over one-third of total final energy consumption and an equally important source of carbon dioxide (CO₂) emissions” (International Energy Agency, 2013). More specifically, the United States Green Building Council reported that the building sector accounts for 38% of all CO₂ emissions in the United States, as well as 73% of electricity consumption in the United States (U.S. Green Building Council, 2015). Further, they report that buildings use 40% of raw materials globally (three billion tons annually) (U.S. Green Building Council, 2015). This extreme energy use and environmental impact of the building sector are problematic in a world of limited resources. The issue necessitates a look at the current design, construction and operating methods that are prevalent in the building industry in order to evaluate the distribution of energy use, to speculate on new approaches and methodologies, and to mitigate the negative environmental impacts within the sector. In 2012, the American Institute of Architects Code of Ethics was amended to include an obligation to the environment, which calls for environmental responsibility and advocating of sustainable practices (AIA Office of the General Counsel, 2012). In extension, designers have a responsibility to understand the environmental impacts of the profession, as well as the potential impact of their own work.

Energy use in the built environment has been extensively researched in a variety of disciplines, including, but not limited to, architecture, engineering, urban planning, environmental science and infrastructure. The variety of approaches serves as evidence to the complexity and vacillation of the issue. The different research approaches vary in terms of the scales of analysis, mainly focusing on the urban scale and the building scale (Anderson, 2015). Assessment of energy use within the building scale can be summarized into several research areas: architectural design, construction, materials, operational systems and structural systems (Anderson, 2015).

So how is energy used in the building sector? Over the life of a building, the majority (over 95%) of the energy use is attributed to the embodied energy and the operational energy of the building. Embodied energy, or energy, is the total

energy needed to procure, manufacture, transport and install materials through the construction of a building. Operational energy includes all energy needed to use a building over its life span – heating, cooling, electricity, water, etc. The most commonly accepted scientific methodology for analyzing the environmental performance of buildings is the life-cycle assessment method (LCA) (Anderson, 2015). The LCA method is often used to assess both the embodied energy use and operational energy use in buildings.

One example of this type of assessment is a study by the National Trust of Historic Preservation, which aimed to understand the environmental impacts of new construction versus retrofitting buildings. The life-cycle assessment compared new construction projects and retrofit projects in a number of ways; computing the life-cycle impacts of buildings, determining which stages of a building's life contributes most significantly to its energy use, and assessing influences of building typology, geography, performance, and life span. They claimed that “building reuse almost always yields fewer environmental impacts than new construction when comparing buildings of similar size and functionality” (Preservation Green Lab of the National Trust for Historic Preservation, 2011). A key finding in the research shows that new, energy efficient buildings can take decades to overcome the negative impact of carbon emitted during the construction process. Many assumptions were made in this study, but it is important to note that no retrofit is the same. There are a wide number of variables and circumstances that might make a building upgrade more or less extensive. Retrofitting existing buildings often involves demolition of existing materials, as well as increased embodied energy use through modification and construction of the building, in return for improved operational energy performance (if it is the goal of the retrofit). In order to compare the retrofit to new construction, the building would have comparable dimensions, life-span (75 years), shape, orientation, and construction to the older, existing building. The study, while said to “provide the most comprehensive analysis to date of the potential environmental impact reductions associated with building reuse,” failed to address, in a comprehensive manner, the research areas associated with the building scale (architectural design, materials, construction, operational systems and structural systems) (Preservation Green Lab of the National Trust for Historic Preservation, 2011).

In order to combat the energy issues in a way that recognizes the different areas of research, we must define a new approach that decreases the need for renovation (and new construction) by prolonging the life-cycle of buildings. Computational methods and digital fabrication techniques are changing the way that buildings are conceived, materials are used, and assemblies are constructed... Emerging technologies allow buildings to anticipate a future adaptation or disassembly. “Approximately 61% of all construction projects are retrofit projects” (U.S. Green Building Council, 2015). By making buildings more adjustable and easy to maintain or dismantle, buildings can serve multiple uses over their lifetime and substantially decrease energy use attributed to demolition and renovation. “One billion square feet of buildings are demolished and replaced with new construction each year” (Preservation Green Lab of the National Trust for Historic Preservation, 2011). Once two materials are glued or adhered together, the material energy becomes bound, dissipated, and the likelihood of energy feedback is null. Designing for disassembly would decrease the amount of material waste sent to landfills, and would increase the number of recyclable and reusable material assemblies.

AN ENERGY DISCOURSE IN ARCHITECTURE

Energy Hierarchy

Over time, many architects and authors have theorized about energy strategies in the built environment. Kiel Moe, registered Architect and professor at Harvard's GSD, discusses his methodology for evaluating energy use in his book, *Convergence: An Architectural Agenda for Energy*. He believes architecture relies on the understanding that all matter is captured energy. His ideas on *convergence* are based on “the thermodynamic premise that architecture should maximize its ecological and architectural power.” Rather than focusing on making buildings “less bad” by singularly focusing on the performance or efficiency of specific materials, he calls on designers to think of the building as an ecosystem within an energy hierarchy. Thermodynamic principles state that within a system, energy is neither created nor destroyed, but it changes from one form into another. A designer's goal should be to better understand the energy hierarchy, how systems within architecture fall into this hierarchy, and how different forms of energy can be used as inputs and outputs of these assemblies (Moe, 2013).

Moe goes on to talk about energy, entropy, and exergy, from a material perspective. The embodied energy within a material, combined with its captured bio-geophysical factors, is its *energy*, or energy memory. For Moe, a building with high energy content is not bad thing, as the building has a greater capacity for energy feedback. Quality of the feedback is a key design concern, in order to maximize the capacity for energy to do work, or its *exergy*. In any system, some

energy will become bound dissipated energy, or *entropy*. A successful ecological architecture would have high energy, high-quality exergy, and low entropy. This maximum power design decreases overall energy use through a series of nested hierarchies that “maximize the intake, use and feedback of useful energy.” This methodology anticipates, rather than reacts, to the energy issue in architecture (Moe, 2013).

Extending on Moe’s energy approach, *design for disassembly* is anticipatory, while retrofits are reactive, in nature. Disassembly increases the capacity for feedback within the architecture, and therefore increases its exergy. Similarly, assemblages can be taken apart and reused, lowering the entropy of the building. Combining this technique with best practices of reducing material waste, using local and recycled materials, and increasing the lifetime of materials, architects can design buildings that anticipate the way that energy will be used. Further, this approach can address all research areas (materials, construction, design, operation and structure) as ecologies within the building that can feed into each other.

Material Logic

Writer and philosopher, Manuel de Landa has written extensively on topics which provide insight to architects on methods of scientific discourse. His theories on materials and energy can be discussed in the same vein as those of Moe. He warns against a singular method of thinking when approaching a material philosophy. “To a materialist, a typology can become an obstacle to think about the processes that produced the items it classifies and it can hide the sources of variation that give the world its expressivity” (Curti, 2010). In his essay in *Verb; Philosophies of Design- The Case of Modeling Software*, he distinguishes between two theories of design. One design strategy begins with a concept for the form, which is imposed onto materials. The other design philosophy treats the materials as active participants in the genesis of form. De Landa favors the latter methodology, one that is more in tune with a holistic energy-conscious design strategy. He classifies materials based on their behavior and the characterization of their phase transitions. In the creation of a logic or family tree of material behavior, one can better understand the intricate properties of that material, and how those materials might work within a larger infrastructure or hierarchy of energy. To de Landa, buildings are assemblies of heterogeneous materials, which can be critiqued in relation to their particular or general characteristics (De Landa, 2002).

With increased computational technologies, de Landa believes this family tree logic can use genetic algorithms to iterate different combinations (evolutions) of materials into assemblies. A relational or topological understanding of the different materials is key to the combining of materials into larger ecosystems. This “breeding” of material assemblies begins with the designer specifying the evaluation criteria for an assembly (or building). Then the computer simulates different combinations until it finds the best design option (De Landa, 2002).

These digital tools can be scaled up to address the operational and embodied energy distribution for whole buildings. The interrogation of the relationship between the building and the material components is important to any energy-conscious design strategy. Digital *design for disassembly* is a methodology that acknowledges the energy hierarchies that Moe and de Landa discuss: at the scale of the material, the assembly, and the building.

As more highly performative materials become available, *design for disassembly* could permit the replacement of individual elements in an assembly, and further decrease operational energy use in a building. Elements which can function with multiple uses (i.e. wall and roof), or with multiple criteria (i.e. structure and skin) have the promise of further minimizing operational energy use.

Ecological Functionalism

Juhani Pallasmaa, established architect and theorist, writes in his article, *From metaphorical to eco-logical Functionalism*, that architecture needs to re-evaluate Functionalism through the lens of ecological awareness (Pallasmaa, 1993). He calls for an eco-logical architecture which implies conceptualizing the building more as a *process* (topological) than a final product (typological). Pallasmaa’s ideas about architecture are returning to the heroic ideas of Functionalism from Modernism, but pushing these ideas forward as *real*, operative Functionalism that focusing on adapting to “systems of nature in terms of both matter and energy” (De Landa, 2002). His call for an Eco-logical Functionalism are relevant in the discourse on the energy agenda for architecture, particularly as computation allows for the experimentation of techniques for new concepts of living. Pallasmaa notes the continual appropriation in art and architecture, implying that buildings needs to be approached from a different view. This aligns with de Landa’s warning of the obstacle of typology.

“Do more with less”

Pallasmaa speaks of the paradoxical task of architecture is to “become more primitive and more refined at the same time” (Pallasmaa, 1993). One can apply this idea to *design for disassembly*, in that the physical connections and joinery of the building assemblies need to be able to connect in simple or “primitive” ways – and this is made possible through the precision and mobility of digital fabrication. The process becomes more refined in terms of using the computation to adapt and respond to systems of nature by focusing on the energy hierarchies of the building. Pallasmaa references Buckminster Fuller in his writings as being ahead of his time. Fuller’s Dymaxion House pushed this idea to “do more with less” and we can continue to adapt this model and push the idea further (Buckminster Fuller Institute, 2015). While the Dymaxion House aimed to create low-cost housing through developing manufacturing methods, *design for disassembly* takes these ideas and uses the digital realm to confront the energy issue in architecture. Instead of focusing on low monetary cost, computation allows us to focus on low resource and energy costs. Fuller looked beyond the generic housing typologies to display the function and efficiency of the house, and likewise, we should look beyond the typical building construction method (The Museum of Modern Art, 2015).

Interactive Machine

Another architect whose ideas were ahead of his time was Cedric Price. His ideas were supported by Fuller, but many of Price’s projects were unrealized. One project in particular stands out with relationship to *design for disassembly*. The project focused on manipulation of the architecture and an interaction between the user and the building. The *Fun Palace*, as it was called, was to be a “socially interactive machine” in collaboration with avant-garde theater producer Joan Littlewood. The theater project was meant to engage the passive subjects of the audiences in the 1960s in England. The design comprised of a grid and “structural matrix with overhead cranes to allow assembly of prefabricated modules... Pivoting escalators and moveable wall panels would permit endless variation and flexibility”. Price realized the value in variation from the perspective of the performance and social interaction with the user, but unfortunately, the project was never realized. The kinetic and interactive goals of Price’s architecture can combine with our social and environmental goals of *design for disassembly* to make this type of project become a reality with the digital tools at hand (Matthews, 2005).

CASE STUDIES

The concept of *design for disassembly* is a familiar goal of industrial design, but for Architecture it remains largely unexplored. In other disciplines, the idea has developed for a number of reasons, including the ease of replacement of parts in complex assemblies or the ability to flat-pack products for shipping, etc. Digital fabrication allows us to expound upon these ideas in order to confront energy issues in the built environment. The following case studies will survey projects of various scales, collecting strategies for digital design and manufacturing methods for architecture. The evaluation of these case studies will include a critique on the choice of materials, the design of construction, and the design of the joinery.

The choice of materials and their assembly methods are crucial to the critique of their ability to change or perform over time. Does the project use recycled materials? Are hazardous materials used? Can the material be reused? The design of the construction or assembly method is an element which is often left unaddressed. Does the construction use modular components? Is the construction simple or complicated? Is serviceability a concern? Is the assembly stable during construction or disassembly? Finally, the design of the joinery or connections is key to designing for disassembly. Are adhesives used to join materials? How easily can the parts be separated? Is the joinery easy to locate, access, and dismantle? How many joints are there, and what tools are needed to disassemble the system? This evaluation will allow us to anticipate the ability to use digital methods to create disassemblable constructions that will minimize entropy over the life-cycle of the building.

Loblolly House | Kieran Timberlake | 2006



Loblolly House by Kieran Timberlake (Kieran Timberlake, 2015)

Kieran Timberlake's Loblolly House employs material assemblies "that are detailed for on-site assembly as well as future disassembly and redeployment" (Flat, Inc, 2008). This 2,200 square foot private residence was assembled on-site in Taylors Island, Maryland in only six weeks. This project framed much of the work that Kieran Timberlake has continued to do as they have grown. More recently they have released a software plugin for Autodesk Revit called *Tally*, which creates a scoring rubric for the material choices of a design specified in the model (Kieran Timberlake, 2015).

Materials: Many of the materials of the house were off-the-shelf components and easily assembled materials. This includes anodized aluminum, cedar rain-screen components, oriented strand board and laminated veneer lumber. These materials were easy to acquire, as they are all mass-produced and extremely common. The fact that there were no specialty or lavish materials used in the project, and that materials could be locally acquired, lends to a lower embodied energy use.

Construction: Building information modeling allowed the building to be designed and assembled virtually, making the coordination of construction seamless. The Loblolly House was made up of a series of prefabricated components which Kieran Timberlake called Elements; the scaffold, the cartridge, the block and the equipment. The use of parametric modeling afforded the designer to make precise decisions, which made the prefabrication possible. Digital coordination with the different consultants made the process more efficient, from design to fabrication to assembly. The model also assisted in the façade patterning, and helped the designers keep in mind multiple constraints for the elements, such as how each element was going to be shipped or erected on site.

Joinery: Kieran Timberlake facilitated the assembly of these elements by including electrical and plumbing conduits within the cartridges, which make up the floors and ceilings. Each cartridge is made up of plywood sheathing, electric receptacles, radiant heating coils, engineered lumber ribs, and microduct air supplies. The scaffolding, in which the cartridges are inserted, are made of anodized aluminum structural components for easy assembly; each of the components are drilled and cut to size to make a linear procedure of assembly. The blocks and fixtures, since prefabricated, only need to be connected to the utilities once put in place. The number of joints is minimal, and the joints are easily accessible, once the building needs to be disassembled (Kieran Timberlake, 2015).

LYF Shoes | DesignBox | 2014



LYF Shoes components by DesignBox (Lyf Shoes, 2015)

LYF shoes, created by Aly Khalifa of DesignBox, were envisioned with the *design for disassembly* methodology in mind. Shoes like buildings, have long required permanent adhesives in their construction. LYF shoes were designed first to remove these adhesives from the design, under the premise that these adhesives are not only unhealthy for workers putting them together, but also that they prevent shoes from ever being recycled. By combining digital manufacturing processes with an understanding of how components can be assembled, they have created a shoe design which never has to end up in the landfill. The company is also attempting to engage with its customers through social awareness. Each shoe has a small chip embedded in the heel which creates a profile of the user's walking habits. This information will add to a large database of the shoe's durability and improve the design based on the way in which they are used. This chip is only accessed when a shoe is brought back to the store, increasing the likelihood that they would be returned to be recycled (Khalifa, 2014).

Materials: The materials in LYF shoes are 100% recyclable. The sole, heel lock, and performance plate of the shoe is certified compostable material, while the insole material is made from recycled wine bottle corks. The upper fabric portion of the shoe is made from locally sourced natural fibers.

Construction: The shoes are a modular assembly of components that are made separately. The sole, heel lock, and performance plate components are manufactured per each customer's size and specifications. The graphics on the upper portion of the shoe can be designed by the user, or they can choose from shared graphics from other designers. The fabric portion is digitally printed and laser cut per the size specifications. Manufacturing can be done locally, in the store, and on demand using textile printing, 3D printers, and laser cutters. By moving the manufacturing process to the customer, this dramatically decreases the embodied energy put into the shipping and storage of the product (LYF Story, 2015).

Joinery: Once all of the components are made, the shoe can be assembled in 90 seconds (Khalifa, 2014). Each of the components of the shoe snap into place to hold the assembly together without adhesives. Each shoe can then be disassembled into its various components to replace worn elements or to change styles. The information gathered by the microchip can help inform new shapes of the replacement components so that some parts (materials, energy) can feedback and be easily reused (LYF Story, 2015).

PEG Chair | Paul Loebach & Makers Anonymous | 2014



Disassembled PEG Chair by Paul Loebach and Makers Anonymous (Loebach, PEG Chair, 2015)

This chair assembly was formulated around the acronym PEG meaning, “Parts Excluding Glue.” The prototype was shown at NYC Design Week 2014, and was designed to deal with the challenge of shipping furniture compactly – allowing more chairs to be shipped at a time, which saves on the embodied energy use (Loebach, 2015).

Material: The PEG Chair is made completely of solid blocks of birch wood. Birch wood is common and exhibits good machining properties. It sands to a smooth surface and is easy to work with. It is also

one of the cheaper woods on the market, making it extremely accessible.

Construction: The chair is made up of eight different components, including the legs, seat, cross bracing, and chair back. The chair was digitally designed in 3D modeling software. This allowed the use of a CNC (computer numerically-controlled) router machine to do most of the work while fabricating the components. Loebach’s process also focused on ensuring that the integration of technology did not mean that one has to sacrifice craft. However, the CNC router did have a negative effect on the efficiency of the wood regarding the waste of the blocks. Because of the nesting of the objects and the dimensional limitations of the CNC router, it seems as if roughly 50% of the birch wood went to waste. Designing a way to reuse the scraps would eliminate the entropy of the materials needed for construction (Designboom, 2014).

Joinery: The joints of the PEG chair are a series of pegs. The chair does not rely on fasteners such as screws or glue. The piece of furniture relies solely on friction connections. Each component slides into each other and once in place, the constant expansion and contraction of the wood helps stabilize and make the chair rigid. The joints of the PEG chair were roughly cut by the CNC router but later on finished by hand. The simple joinery allows the complex geometry to be assembled and disassembled with ease (Designboom, 2014).

Breaking the Mold – Variable Vacuum Forming | HouMinn Practice | 2014



HouMinn’s final installation of the “VarVac Wall” (Architect Magazine, 2015)

A slightly less intuitive way of focusing on reducing material waste and increasing energy feedback is to focus on the minimizing of material used in the production of building components. Often the largest monetary and material cost for creating shaped panels is the formwork or panel molds. HouMinn Practice has created installations that focus on reusable formwork. In order to create a large number of panels that have a large variety of shapes, HouMinn was able to create

adjustable formwork, which achieved the formal variety of this acoustic wall without tremendous material waste (Core77, 2015).

Material: The wall is comprised of polystyrene sheets that are heated and vacuum-formed to create different surface variations. Polystyrene is mass-produced and, like most thermoplastics, can be recycled. The wall framing elements are plywood strips, which connect the panels to the acoustic fabric material. The formwork for the creation of the panels is comprised of a plywood frame with metal cables pulled across the opening.

Construction: The variation in the shapes of the panels was designed using Grasshopper and Rhinoceros (3D scripting and modeling software) in order to map the areas that required more or less sound absorption. Once the entire wall was mapped, the pattern was broken up into panels. The process only required one plywood formwork frame. Cables were drawn across the frame at different angles according to the pattern. The polystyrene sheets were heated and vacuum-formed over the cables to create the undulating variations. Where the panel depth exceeded six inches, the polystyrene was sliced with a rotary blade on a CNC router. This created further variation by introducing openings in the panels. The panels are thin and lightweight, so assembling rows that tilt up and anchor to the wall was simple.

Joinery: The construction of the wall was straightforward, by assembling the lightweight panels in a vertical row with metal strips and screws, then tilting the row to the wall and using plywood strips and screws to anchor the assembly to the acoustical fabric and wall. The use of common tools to mechanically fasten the panels to the framing, and the accessibility of those joints make it simple to disassemble. Though it may be difficult to find another use for the panels, they could be recycled after use. The joinery of the formwork is also interesting: a series of fasteners were spaced along each side of the plywood form opening, and cables could be adjusted to create different diagonals across the opening, to be pulled tight, or to slump loose. The reuse of the same materials to create multiple panels created a continual feedback loop (Core77, 2015).

Fountain | Greg Lynn | 2008



“Fountain” by Greg Lynn Form (Greg Lynn Form, 2015)

Greg Lynn’s *Fountain* is part of a series of pieces in his Toy Furniture project that reuses plastic toys. The toys are laser-scanned and arranged digitally, then physically manipulated using robotics to make functional and sculptural forms (Greg Lynn Form, 2015).

Material: Lynn chose to recycle objects for their positive value. According to Lynn, at one point plastics were the way of the future. They are lightweight and high-performing as well as great substitutes for metals and fired masonry. Plastics are also very low-energy to produce and easy to transport. Children grow out of toys quickly, making them an unnecessary addition to landfills.

Construction: The pieces of furniture relied heavily on the scanning technology available. Before assembly, each toy was 3D scanned and digitized into a computer-modeling program.

After moving the components around to achieve the desired forms, every single intersection was defined as a cutting path, using Boolean operations. A robotic arm with a spindle blade uses the precision of the scan and model to make surgical slices to the different toys. Every step of the project was made possible with the use of the digital tools.

Joinery: The different toys are then welded together by a tool used to repair car fenders. The different elements have been fused together to create one form. One disadvantage to this method is the choice to weld, because the assembly becomes permanent and cannot be disassembled for a future re-use. Instead the plastic will most likely be melted down and recycled in a different fashion (arcspace, 2015).

Tent Pile Pavilion | Formlessfinder | 2013



Formlessfinder's Tent Pile Pavilion at Design Miami/ 2013 (Medina, 2014)

This structure, the entry pavilion for Design Miami/ 2013, uses a sand pile to support a custom-milled aluminum cantilevered roof. The sand pile acts as a thermal cooling mass, making the pavilion a comfortable refuge for over 50,000 visitors each year (Caula, 2013).

Material: The project was located in Miami where sand is sometimes problematic for building - sand beneath buildings often needs to be removed for construction. The loose sand is used to an advantage as a structural element while also being a zero-waste material. The pavilion is essentially made of three elements: the aluminum roof, the wooden retaining wall, and lastly the pile of sand.

Construction: The aluminum roof is lightweight and connected with rivets using common tools. The roof element sets on top of the retaining wall, which slices the pavilion in half to keep the sand to one side and provide an entrance to the fair. The four corners of the roof element are temporarily supported as the sand is put into place. The pile of sand is placed with heavy construction equipment, creating a 500-ton pyramid.

Joinery: Because of the use of sand, the pavilion for Design Miami/ becomes almost a joint-less structure. Once the retaining and roof elements are assembled and set into place, the weight of the loose sand is used to stabilize the structure and no further joinery is required. The pavilion does require heavy machinery to move the sand, but there is no need for excavation. So the zero-waste material becomes countered by the amount of energy it takes to transport the 500 tons into place (Medina, 2014).

LOOKING FORWARD

These various case studies help to articulate an understanding of the goals for *design for disassembly* and represent methodologies that can be implemented going forward. At the scale of the building, this design idea needs to be implemented in a way that takes into account the energy hierarchies and energy needs of architecture throughout its life and death.

Using recycled and locally-sourced materials is a starting point for how to approach material choices in design, but computational tools can allow for higher energy content and provide feedback to the user throughout the life-cycle of the design. The key is to try and simultaneously design assemblies that have low embodied energy, but are durable and flexible in their use and reuse. Whether that is through a novel use of materials that are not generally used in construction, like in Formlessfinder's Tent Pile, or in the seemingly infinite variation of a mold, like in HouMinn's

VarVac Wall forms, architecture can use this methodology to create nested hierarchies of energy and prolong the life-cycle of building materials.

The design of the construction is very important in the implementation of *design for disassembly*. The way that the assemblies are put together and taken apart is vital in the realization of this idea. Computational tools, complex and parametric modeling software and digital fabrication techniques, are allowing designers to physically manifest geometries that humans could not conventionally make by hand. Robotics, like in the creation of Greg Lynn's Toy Furniture, can assist in the making of the individual elements and assemblies in less time, and with fewer errors, etc. Modeling softwares will continue to develop, while they assist in the visualization of the elements and assemblies - like in Paul Loebach's PEG chair - and allow for iteration and evolution of design ideas before they are created in the physical realm - saving time, material, and resources. The amount of information that can be shared, sourced, and scanned is changing the way that the construction industry operates, and allows for procurement and discipline coordination to save time and energy. Understanding the entire construction process before a single element is built - this can completely change the way a building is created.

The success of *design for disassembly* also relies on the ability for the elements of the design to come apart simply and quickly. The joinery should be designed in advance in order to anticipate future use or future mobility. The joinery needs to be easily accessible and should not require complex tools or equipment to disassemble. Using off-the-shelf components is one way to approach the issue of joinery, like in HouMinn's VarVac Wall, where the adjustable formwork used simple fasteners, and the construction used plywood strips and bolts. Often designing in this way makes for simple physical connections between material components, and generally saves time, money and energy in the construction as well. For example, Kieran Timberlake's Loblolly House was constructed in 6 weeks once all the elements were prefabricated. Similarly, the design of LYF Shoes by Designbox let the assembly snap together in less than 90 seconds. This methodology can confront the energy issue by focusing more on the process - process of design, of construction, and of assembly - than focusing on just the product.

With the aid of computational tools, we can increase the number of ways to reuse and prolong the life-cycle of materials. Greg Lynn's Fountain Toy Furniture project relies heavily on the digital to repurpose old toys into sculptural forms. The increased computational technologies provide us with more ways to adapt the use of existing materials. These computational strategies can also be used to calculate novel structural systems such as Formlessfinder's Tent Pile, or to visualize an assembly or process before anything has been physically created, such as in Kieran Timberlake's Loblolly House.

Each of these projects begins to formulate a methodology of material selection and assembly principles that could be employed moving forward as we move beyond the short-sighted design methodologies of the past. As we gain more control and accuracy over our manufacturing methods we can create products for the built environment which consider both the environmental impact and quality of the space for today and tomorrow.

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IMAGE SOURCES

Figure 1: <http://www.kierantimberlake.com/pages/view/20/loblolly-house/parent:3>Figure

Figure 2: <http://lyfshoes.com/your-fit/>

Figure 3: <http://paulloebach.com/peg/>

Figure 4: http://www.architectmagazine.com/awards/r-d-awards/award-breaking-the-mold_o

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Figure 6: http://ad009cdnb.archdaily.net/wp-content/uploads/2013/12/52b1a65ce8e44ede33000133_formlessfinder-s-tent-pile-a-hit-at-design-miami-15_jamesharris-530x376.jpg