Designing Buildings for Disassembly: Stimulating a Change in the Designer's Role

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Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING
AT THE
MASSACHUSSETS INSTITUTE OF TECHNOLOGY

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Abstract:

Today's industrial infrastructure in the building field results in specific types of problems with current design strategies.

Here, the potential of Design for Disassembly (DfD) is explored as a solution for a new type of architecture that allows for both recyclability of material and space. Particular attention is given to the benefits that result from this new way of designing while beginning the process of an industrial re-evolution. Indeed, if environmental and health impacts are the most obvious benefits, indirect effects such as questioning the boundary between the designer and the user should not be neglected.

In addition, projects built with DfD methods are being analyzed. The studies range from houses that can expand in the longitudinal plan to houses that can be entirely customized. To further explore DfD methods, experiments based on digital fabrication technologies such as CNC, Water Jet Cutting and rapid prototyping are considered.

Finally, conclusions as to how Design for Disassembly can stimulate a change in the designer's role in the building field, and recommendations on how to encourage the implementation of such an innovative and responsible design method are proposed.

Thesis Supervisor: Jerome Joseph Connor
Title: Professor of Civil and Environmental Engineering

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Chapter 1: Introduction

1.1. Today's industrial infrastructure

Today's industrial infrastructure is the result of the industrial revolution. Therefore, to understand the industry problems and challenges we are facing today and in particular in the building field it is necessary to understand the values and philosophy that have driven the industrial revolution system.

1.1.1 The industrial revolution

a. Monstrous Hybrid

Economic growth was certainly the main driving component of the industrial economy and continues in today's economy. We will use the T model of Ford to illustrate the key principles of the industrial values. Indeed, the design of the T car model of Ford embodies the general goal of the first industrialists: 'to make a product that was desirable, affordable, and operable by anyone, just about anywhere that lasted a certain amount of time (until it was time to buy a new one); and that can be produced cheaply and quickly' [1].

The affordability was therefore the core goal of the design. The design was all thought for that unique purpose. To achieve such a goal Ford factory was using mass production methods to drastically reduce the cost of the final design. The revolution led to manufacturing methods that consisted in assigning the worker a repetitive task. Each worker focuses on one task and repeats it as a machine. It is as if all the workers were a piece of the giant construction machine. Along these lines, technical developments centered 'on increasing power, accuracy, economy, system, continuity, speed to use the Ford manufacturing checklist for mass production'.

It is interesting to see that in Ford design, the design of early industrialists were exclusive of the larger system. Indeed, they were not considering their design or product as part of a whole cycle. Their focus was mainly on the delivery phase that represented their final goal. Indeed once the product is delivered and bought by the client the mission was considered to be achieved without thinking of the future of the object. However, if they did not consider the environment of the product or its life cycle, designers did share some global assumption about the world. It is in this same period of time that the Western view saw nature as a dangerous element that the Human had to dominate by technology. 'Indeed, Humans perceived natural forces as hostile, so they attack back to exert control.' They saw technology as a win over nature.

As described in 'Cradle-to-Cradle' book, we can qualify the resulting industrial infrastructure that we have today as a linear system. The idea is mainly to focus on bringing the product to the customer as fast and as cheap as possible without considering 'much else.' This could also be compared to a cradle to grave model where everything is about the production of the product. Once it is made, the use phase is barely considered and the product will be thrown away so that the customer buys a new one. This model that is still dominating in our current industry is often orchestrated by the "law of consumption'. According to Guy and Ciarimboli more than 90 percent of the materials extracted to make durable goods in the United States become waste almost immediately [2].

In particular, we are dealing with products that are the results of a combination of both technical and biological materials. This results in 'monstrous hybrid' products where none of the components can be separated for reuse or recycling.

Nevertheless, besides the fact that the 'after delivery life' of the product was not taken into consideration, the awareness of the connection between sanitation and public health started during the late nineteenth century. This raise of awareness resulted in an increase for more sophisticated sewage treatment [2].

b. One size fits all

One of the main beliefs of the industrial revolution and of most of the current industrial system is the fact that the ideal product is a universal product; a product that anyone can use and that fits everyone. Again, the core principle of mass production and the fact that the product should reach the maximum amount of people results in the most universal product as possible. A parallel can be established with the Modernists in architecture notably with the doctrine of le Corbusier at this same period of time where a modern architecture was considered universal. Back in the French colonization of the North African countries, for example, there was a dictatorial architecture by the French who claimed that they developed with the modernist movement 'a machine for living (in)'.

The problem with that was that this type of system would not consider any cultural difference. Quite ironically, by not considering the other culture and making a " universal" product, architecture and building, the design remained a creation of a unique culture that is the Western culture. Indeed, the resulted design can't be universal or imposed to every culture if it is the result or the expression of one unique culture: the western culture.
Post-modern architecture movements are starting to recognize that this vision of universal architecture was dictatorial. It was a vision imposed to external populations that didn't live the same way and it was ignoring their cultural difference and way of living.

Furthermore, the manufacturing system that is our heritage today and that is facing difficulties is the result of this same western culture. I like the comparison of the system that is made in the Cradle-to-Cradle book. Indeed, they say that in the Western society people have graves and so do products. Very often we are in a scheme where it is cheaper to buy a new product rather than trying to replace a part or repair the original item. ". In fact, many products are designed with " built- in obsolescence", to last only for a certain period of time, to allow and encourage the customer to get rid of the thing and buy a new model."

"What would have happened, we sometimes wonder, if the Industrial Revolution had taken place in societies where people believed not in a cradle to grave life cycle but in reincarnation?"[1].

1.1.2 Mutations of society and technology

Today the world is going through major crises and severe changes from an economic point of view as well as political, social, technological and environmental. Often interrelated, these in depth transformations lead us to redefine our current values and way of functioning, questioning our previous way of thinking, our "system" (all) over (again).

On the other hand, design has always transcribed ways of living and materialized the great changes in our societies from both technological and political ideology perspectives. Therefore, given the severe transformations that mark our societies, we can address the question: Is there a new type of architecture that will emerge from these crises and severe mutations? In particular, is Design for Disassembly the future of architecture and will it meet the new needs and expectations of our societies and future generations?

First of all, the environmental crisis that we know has pushed us to rethink our system in addressing consumption, waste, and pollution issues. Because buildings are responsible for 60% of CO2 emission it is certainly interesting to rethink our way of constructing buildings. Thinking and designing buildings for disassembly (DfD) increases recyclability and reuse of building components in allowing separation of the different layers of construction and materials [4] [2].

In the meantime, the current high-tech revolution makes us enter in a new technological area. In the same way as the industrial revolution of the 19th century, revolutionary technology will transform our way of inhabiting as well as constructing buildings. For instance, electricity producer technologies such as photovoltaic have been developed and are starting to modify the way we conceive buildings in the very first stage of the design. This type of integration addresses the relationship between architecture and technology in general. How can we integrate mechanical (heating, cooling) technologies and structural design and make them part of the design of the building itself? In this respect, Beaubourg, in Paris, is in my point of view a pioneering building in terms of mechanical and structural integrations as part of the design itself.

Because of coordination purposes in the disassembly process, DfD requires an interdisciplinary approach in the design stage, pushing for mechanical, structural and other technology integration in the building conception. Thus, a closer collaboration between the different fields of construction, including architects, mechanical engineers and structural engineers that all participate in the building design is needed.

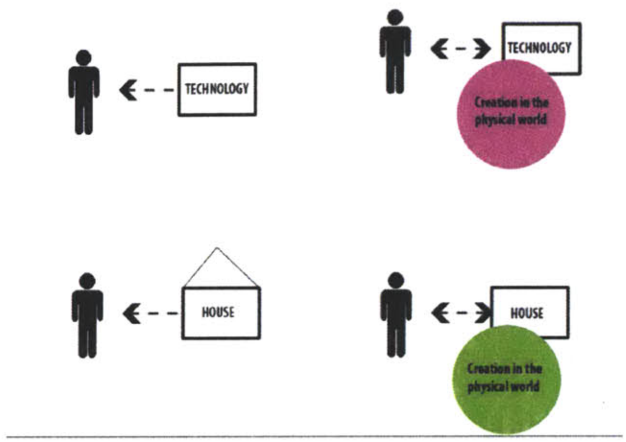


Figure 1: Mutation in human/technology relationship

In addition, these past decades there have been a lot of societal mutations. A major one is the change in family structure itself. Indeed, there is more and more need for adaptation. The scheme of the parental family has become, especially in urban sub-urban areas, a minority and an important proportion of families are recomposed and very often subjected to change in terms of number and ways of living.

Thus, conceiving buildings and housing to be able to meet this increasing need for flexibility and adaptability is necessary. We need to design buildings that allow replacement of elements and ease space adaptation either for extension or reduction, which DfD does.

Furthermore, we have witnessed these past years of a lot of change in the political world. Indeed, with the tendency of Europe to become more liberal, the election of the first black American president in the United States and the recent movements of revolutions in the Arab countries, the notion of individual right has never been more crucial. This political shift is a call for more democracy and human rights, toward the expression of the individual, toward information flows and decent ways of living.

In response to this new political context it is interesting to see in which measure architecture can contribute to satisfy these aspirations by democratizing the construction process. DfD translates this by allowing the inhabitant to participate in the design process, and therefore express himself as an individual that has particular needs by using mass customization techniques for example. In addition, the habitant can participate in the construction process as well, allowing him to get precise information and data on the house he acquired such as the type of material used, their toxicity rate, their price or their environmental impact [11] [3].

Finally, a revolutionary architecture shouldn't be more driven by one issue over the others. Indeed, the environmental, technological, social, politic and economic crises are all interdependent. The economic crisis that stroke in 2007 and still last today has been a real drama and is considered by many economists to be the worst financial crisis since the Great Depression of the 1930's. It has been vital to rethink the ways of being more cost effective in such a situation knowing that buildings represent more than 60% of the material flow in the US [2][6].

Therefore, by increasing recyclability and reuse, by gaining efficiency in the construction process, by encouraging tight collaboration between architects and engineers and thus technology design integration, by allowing space flexibility, by democratizing architecture in individual expression of the inhabitant and managing data information, DfD architecture could drastically decrease the construction cost and thus provide suitable architecture answers to the major mutations of our transforming world.

1.1.3 Resulting industrial system in the building construction field:

Problems in current design [2]

It is the mutation in our society that pushes us to reconsider the way we make things and in particular construct building. Indeed, oneself can ask the question what has changed and what does it imply for the construction field. The system that we had and that we still continue to use doesn't meet the need of our new society where recycling and end of life of products is becoming a requirement.

Furthermore, the study done by the US Geological Survey, which estimated that 60% of all materials flow (excluding food and fuel) in the US economy is consumed by the construction industry (Wagner 2002) highlight the importance of a real change in the construction field[2].

In addition, it is interesting to see, that 92% of the waste produced annually by the US in the construction industry are the results of renovation and demolitions. Indeed, the US EPA also specifically mentions that only 8% of waste is produced from new construction.

Thus, there is a real problem in construction waste and especially with the demolition end of phase and the renovation phase. The construction field is still heavily carrying the heritage of the industrial revolution where the product was thought and designed for delivery only and where no parameters about use life and end of life were shaping the final design. As seen previously, it is precisely the fact that buildings are a 'monstrous hybrid' product that prevents any improvement in both the use life of the product for reuse and its end of life for recycling. Therefore it is makes it difficult to reuse or recycle in a cost effective manner [2] [1] [6].

The roots reasons for those difficulties are part of the design and manufacturing process. First, as already mentioned, the main reason is the increased use of composites and engineering products that are difficult to recycle because of their chemical complexity. The second reason is the cost of labor to deconstruct the building. Indeed, the connection techniques used such as adhesives play an important role in the difficulties of disassembling components and "undo" the construction or assembly. In the same way, parts coating and encapsulation of elements constitute an obstacle as well [1] [11].

Brad Guy and Nicholas Ciarimboli, the authors of ' DfD in the built environment' makes an interesting point concerning the highly speculative nature of much buildings, whereby there is not a long-term ownership, and therefore adaptation, renovation and demolition costs are owned by the original owner [2].

Chapter 2: Re-Evolution & DfD

2.1 Beginning the process of an industrial re-evolution in the building field: How can Design for Disassembly for buildings make a change?

The industry is starting to adopt DfD methods notably in the car industries to optimize the end of life and adaptability of the product while limiting waste. However, few buildings in the building industry allow disassembly and high level of adaptability through time and space.

2.1.1 What is DfD?

a). Introducing new design criteria:

Design for Disassembly (DfD) is a design method that introduces new design criteria. One of the most important notions of DfD is the vision of a building as composed of different layers having different lifetimes.

According to Stewart Brand in his book "How building's learn", we can capture the essence of a building construction by understanding its different layers. For him, a building is composed of different layers that are described as the "6S": Site, structure, skin, service, space plan and stuff [2] [4].

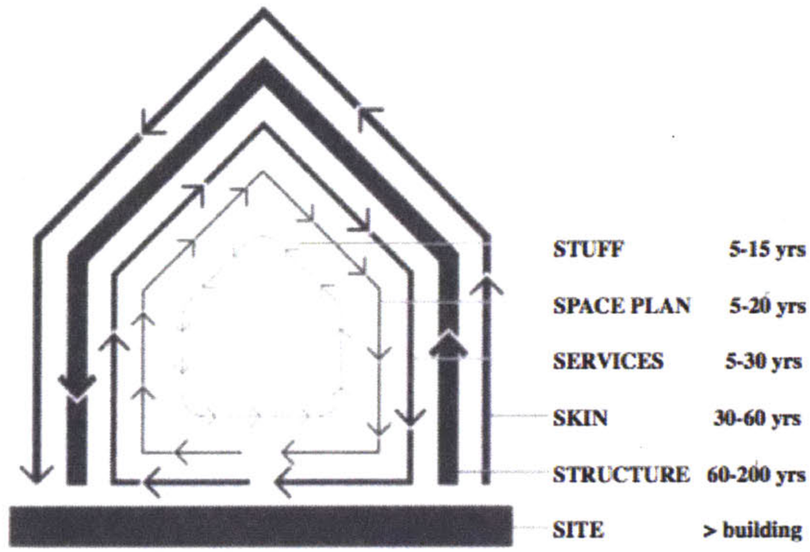


Figure 2:Building layers, The Six S, by Stewart Brand [2]

The site constitutes the first general layer. It is the environment where the building is located. Usually, from the geographic position and type of site where the building is being constructed we can deduce the expected life of the building.

The most important layer is certainly the structure; it is a core layer and essentially the more permanent of the other layers. It is constituted by structural elements such as foundations and load-bearing elements. It can last 30 to 300 years although many buildings don't live that long for other reasons.

The building envelope, consisting of frame, exterior finishes and glazings, are considered part of the Skin layer. They can change for repair or esthetic reasons approximately every 25 years.

Just after the Skin layer, there is the layer of Services that contains all the mechanical elements. It could be compared to the blood of the buildings. It feeds the buildings with water, electricity, air conditioning, etc. It is also called the HVAC system and will generally need to be replaced every 7 to 15 years.

The space plan comes afterward and gathers the separation wall that will organize the space but also interior finishes. It has quite a variable time but is definitely becoming more temporary then the structure or even the serviceability layer.

Finally, what the author qualified of the Stuff layer is everything that is not part of the building and can be removed. In French we would differentiate the building from this specific layer by using antonym for their qualifications: "immobilier": meaning building, something that doesn't move as opposed to "mobilier", for furniture meaning something that is moveable. Thus, as confirmed by the etymologic root the Stuff layer is most exposed to change in space and time and can change daily to monthly.

To conclude, the fundamental difference between each layer is its lifetime. Therefore, each of these layers is important to differentiate from one another because it implies different design considerations. Furthermore, one major point to consider is the fact these different categories of layers are in "constant friction"[21].

Differentiating the different layers of construction is a powerful way of optimizing the recycling potential of the building. To understand in which measures the recycling potential of building can be improved it is important to try defining it first: the recycling potential represents the embodied energy and natural resources, used in a building that could through recycling, be made usable after demolition. For a building, it is often called Rpot and can be calculated as:[6] [21]

$$R_{pot} = \sum_{i=1}^{n} I_{pw\,i} \cdot Lt_i - E_{rec.proc\,i} \qquad (6.1)$$

where

n	is the number of materials.
i	material number.
I_{pw}	is the environmental impact due to production of the material *for which the recycled product will be a substitute.*
Lt	is the remaining lifetime of the recycled material as a percentage of the predicted lifetime of the material for which the recycled material will be a substitute.
$E_{rec.proc}$	is the energy use in all recycling processes, i.e. additional energy use in demolition needed to make future recycling or reuse possible, the energy use in all upgrading or recycling processes as well as transport from the site which it is supposed to be delivered from

Also, the more detailed the calculation of the building, the more precise the result will be concerning the recycling potential. The question of what to include precisely in the assessment is "one of time versus precision". It is still difficult to define, in a general manner, which parts will contribute to the total result in the most significant way [19][21].

Furthermore, a building's total energy use during its lifetime, Etot, is generally calculated as:

$$E_{tot} = E_{material} + E_{transport\ to\ site} + E_{erection} + E_{renovation} + E_{operation} + E_{demolition}$$

where

E_{tot}	is a building's total energy use during its lifetime
$E_{material}$	is the embodied energy of included materials
$E_{transport\ to\ site}$	is the energy need for transports of all building materials to the building site
$E_{erection}$	is the energy need on the building site
$E_{renovation}$	is the embodied energy of substitute materials
$E_{operation}$	is the energy need for heating, ventilation, electricity for pumps and fans and household electricity
$E_{demolition}$	is the energy need for demolition/deconstruction of the building

b). Design process and methods

A design that integrates new criteria in the building design such as the separation between layers and LCA considerations results in a new design called Design for Disassembly. Therefore we can say that DfD is a new type of design, a new vision of constructing buildings in considering both the relations between its different components and layers and their individual lifetime for optimizing the overall lifetime and adaptability of the building itself. Taking new criteria into account in the building design will result in a modification of the traditional design process and methods.

The traditional architectural design methods contain five stages. First, there is the Pre-Design that consists of a study of feasibility of the project but also a market analysis, a site analysis etc. Then, there is the Concept Design that defines what the building is going to look like and relates the building to its specific environment and location. The Schematic Design is the following step and it consist in defining the dimensions and selecting a suitable structural system while making sure that it satisfies the buildings code. The forth step is the Design Development and is a more precise phase that tends to give final decisions and estimations on building dimensions and cost analysis. Finally, the last step can be called Construction Documents. It is the development of final permit drawings and specifications ready for construction and delivery [4] [2].

The Design for Disassembly methods is very different because it includes this extra phase that is deconstruction by disassembly. As explained by Stewart Brand, a building designed to be adaptable and disassembled-able is "scenario- buffered"(Brand 1984). He compares the design phase and process to a DNA code of the building that contains all the information needed for the building construction but by default for its deconstruction as well. Thinking about the deconstruction plan can allow optimizing this phase [5] [17] .

First, in order to have a successful deconstruction plan there is a crucial need for visual transparency. In fact, even the best DfD will not be realized if the building constructors, operators and deconstructors do not understand the process of the building dismantlement. The deconstruction plan tells a story with its different steps that should be simple so that it could be read as easily as possible. Information about material properties and connections are parts of the story. Therefore, this flow of data needs to be organized and classified.

2.1.2 DfD Principles and benefits [2]

The 10 key Principles for DfD are enumerated in the 'DfD in our built environment ' guide as follows. [2]

The first principle refers to materials and methods for deconstruction as seen previously.

The second principle relies on selecting material using the precautionary principle. Indeed, in a process where everything is labeled it is easier to collect information and then make more responsible choices in avoiding toxic materials or materials that are harmful to the environment. It also encourages the selection of materials that tend to a have greater recycling potential.

The third principle concerns the connection. DfD claims that connections should be accessible visually, physically, and ergonomically to increase efficiency and avoid heavy equipment intervention.

The fourth principle of DfD relates to reducing or eliminating chemical connections that are not removable. This results in avoiding binders, sealers and glues on or in materials. Not only they make the materials difficult to separate and recycle but are very often made of toxic chemicals that are a threat for human health and the environment.

The fifth principle is linked to the previous one and suggest as an alternative to use screwed, bolted and nailed connections.

The sixth principle concerns the separation of layers of the building such as mechanical, electrical, plumbing systems, etc. It makes it easier to reuse components once again for repair, reuse or recycling.

The following principle is certainly once of the most interesting because it considers the worker as a key element. Indeed the worker is taken into consideration into the design process where components are scaled for human use to ease the process of construction and decreases the labor intensity.

The eighth principle consists in designing for simplicity of structure and form. It is very subjective because complexity can lead to design challenges and innovations. By encouraging standardization for economic purposes, DfD does not fully participate in an innovative way in an evolution in the construction field.

One of the last principles of DfD is the one of interchangeability that relies on modularity but should not rely on standardization.
Finally, last but not least, the principle of safe deconstruction is established by decreasing worker's risk conditions.[2]

2.2 What Designing Buildings for Disassembly implies us to rethink about?

Besides the fact that DfD has direct primary goals and effects on the construction efficiency and on the environment, it also has crucial indirect effects that are often neglected. Indeed, it is interesting to see in which manner Design for Disassembly can fundamentally change the way we design buildings by redefining the role of the designers and the users of our contemporary society.

2.2.1 Role of the building designer:

First, the process of Designing for Disassembly requires a lot of organization and planning in the design phase itself. In order to smooth the process and manage the complex interaction between all the different types of construction participants, there is a real need for an early and upstream work. This is notably why an intense collaboration between all the different designers, such as architects and engineers, is a key requirement for this type of design.

Figure 3: Numbering of Corn, by artist Damien Ortega [23]

In this photography of the artist Damian Ortega the numbers on each seed of the corncob express the scale of the components related to the object. Indeed, the picture is meant to illustrate this concept of organization related to decomposition with all those numbers written on the multiple corns that all together compose the corncob. If they all look the same, the numbers reveals that they are all specific, reminding us once again of the organizational aspect required in a decomposition-oriented design strategy. The number and order is important because it reveals the position and the size of the corn. *De facto*, if we want to be able to disassemble everything we need to know which corn goes where and so on.

a). Building designers, the Architect and the Engineer:

In order to reach this organizational and planning goal of assembly, disassembly and re-assembly of the building there is a need for an intense collaboration between the different designers of the different types of components or layers. For instance, the skin of the product and its mechanical parts of the product have to be thought and designed in cohesion so that they interact with each other in harmony and in a way that is suitable for disassembly.

This collaboration between the different types of designers is becoming more and more needed and is modifying the way we design things and will change the way we make buildings. The gap between the designers such as architects and engineers is starting to get filled. Each of the designers has to learn more, to be more aware of the work of the other in order to do a better and smarter design. This type of design is smarter because it is global and local at the same time; the components are thought separately but not only. Indeed, they are thought to work together as well. There is then a collective intelligence that has a global vision of the product and thus a better understanding of it.

For instance, for a building design, the architect is not anymore just an artist because he has to understand the rest of the building, its structure, and the mechanical part in order to design something suitable for disassembly. The engineer is not anymore only executing what the architect is requesting for esthetic or unknown reasons but he can understand the essence of the design and provides his technical knowledge in the design stage itself. That also allows avoiding a redesign or even a make up during the construction phase for a mistake that could have been done in the first step of design stage. Indeed, there is more verification and this tends to result to more intelligent design to optimize the efficiency and cost of the construction process.

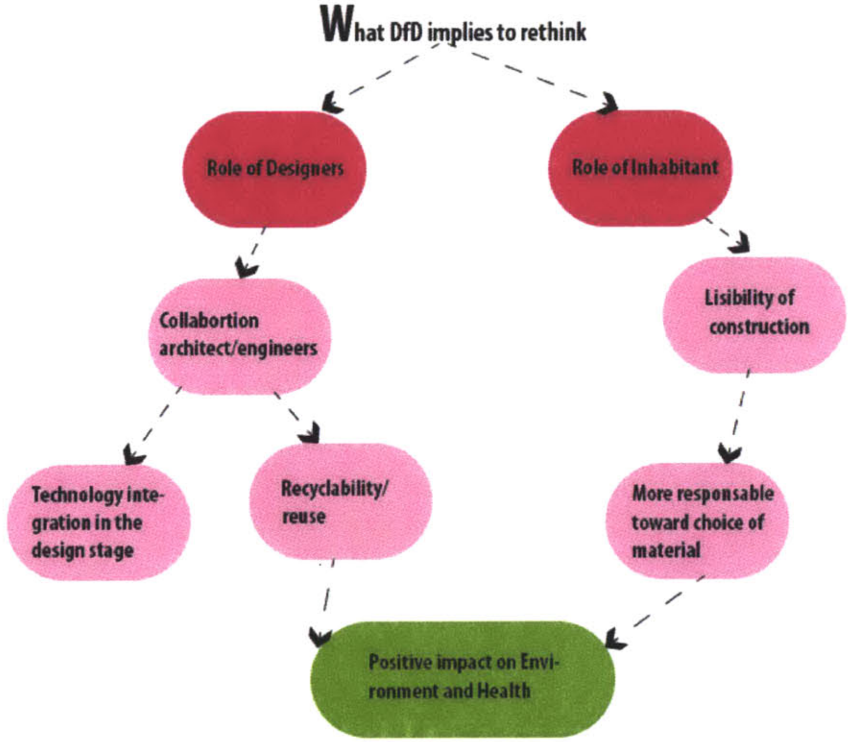


Figure 4:What DfD implies us to rethink about

This idea is reinforced by the fact that among the famous successful building designers, we count a great number of them that are Architects-Engineers or Engineers-Architects. We can see this as the expression of this increasing and crucial need for an understanding and mastering of the design system articulation; leading to a smart and successful design. Also, we can cite Paul Andreu, Marc Mimram or Ricciotti as examples of renowned architects-Engineers. As an example, the architecture of Santiago Calatrava that is shaped by his engineering vision of efficiency creates a very innovative and unique architecture where structure and architecture have the same unique voice. His work is indeed very representative of a bipolar understanding of the construction world. Jacques Ferrier who is a French architect-engineer DPLG, who graduated from Centrale Paris, is a real visionary and relates his vision of what he thinks is the architecture of the future in his book: "Architecture = durable". He comments and criticizes 30 selected and pioneers recent constructions of the past decade. One of the projects that can be retained and especially distinguished itself among the others is the project of the Agency Beckman N'Tepe. This agency is composed of a team of young low cost housing designers in Paris which are working on making buildings sustainable by introducing innovative time and space design. For them, sustainability goes along with adaptability [22].

Furthermore, there already exist countries where the role of the contemporary architect is difficult to differentiate from the one of the engineer and where the architect is necessarily an engineer. "Architectural engineering" is specifically famous in Japan where the term "architecture" and "building engineering" are used synonymously. Brazil, Germany, Austria and a few Arabic countries constitute the very rare countries where the architect receives an engineering degree at the end of his architecture study.

b). Intensifying collaboration between the building designers:

Design for disassembly makes us rethink the relationship and interaction between the different layers that constitute a building. Moreover, redefining and rethinking the boundaries between architecture and structure or architecture mechanical components of the building, enables not only to question the way we use to build but also the relationship between the designers: the architect, structural and mechanical engineers.

As previously mentioned, a very good example of building that resulted in an intense collaboration between architects and engineers and its results in terms of architecture innovation is the George Pompidou Center, which is also the Museum of Contemporary Art of Paris. In this building the structure is the architecture and the architecture is the structure. There is no distinction between function and space.

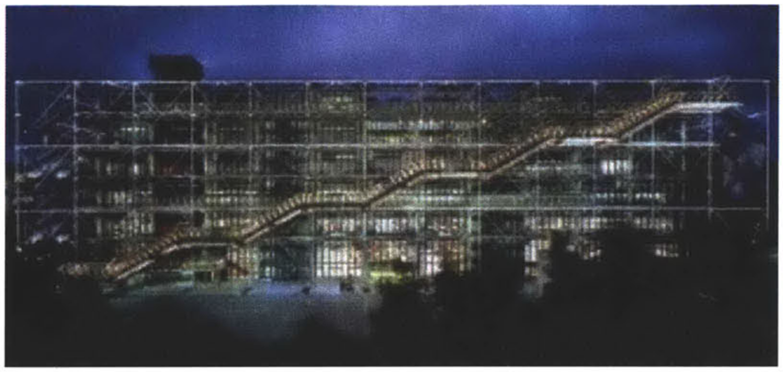


Figure 5:George Pompidou Center, Paris [24]

The Center for Contemporary Art in Paris also called Beaubourg or Pomidou Center is the symbol of this fusion between art and science in the construction field.

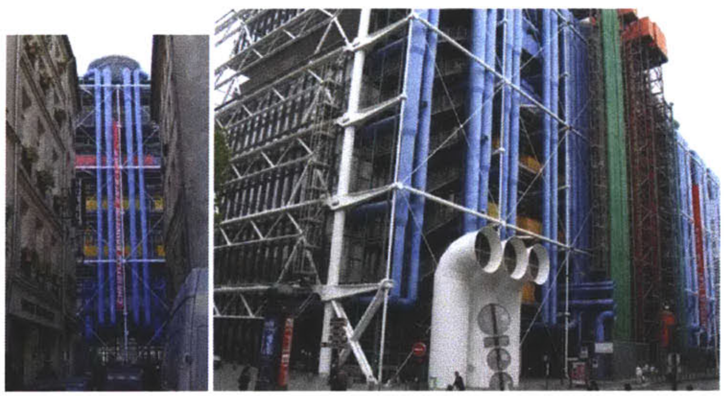


Figure 6: George Pompidou Center-Fluids, Paris [25]

There is an interesting paradox, in the fact that working on separating the different types of building layers and making them visible individually lead to an intense collaboration between architects and engineers: Renzo Piano, Richard Rogers and Peter Rice.

This collaboration between engineers and architects can be pushed further when there is no distinction between the technology and the design. This is only possible in a process of "integration". The technology is integrated in the design and the designer is playing the role of the architect and the engineer as well. The innovative project of Professor Sheila Kennedy is a perfect example of this resulting phenomenon.

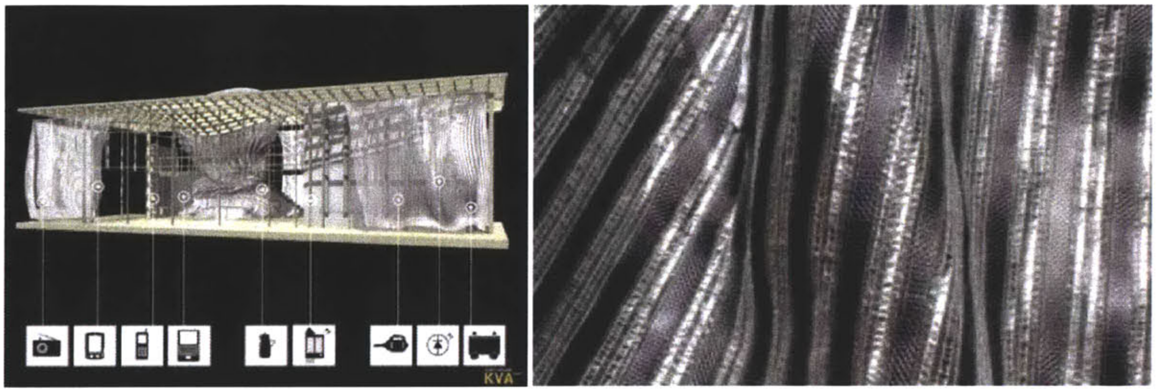


Figure 7: Soft House, Professor Sheila Kennedy [26][27]

Here, the photovoltaic materials are integrated in the curtain of the soft house project and producing electricity. The material and architecture melt with the technology.

2.2.2 role/right of the inhabitant:

a). Readability in the construction process:

Designing buildings with future Disassembly in mind requires a drastic increase in the readability of the object both in its construction and deconstruction. Reaching a level of design for disassembly requires a very methodic and precise procedure.

The work of the artist Damien Ortega illustrates here the dynamic of the mind that is behind the critical design and manufacturing process of such a design.
His work on the decomposition of the object into its different elements and components reveals the soul of the object and makes a complex object understandable to the public. There is a real educational work that is interesting in those pieces of art.

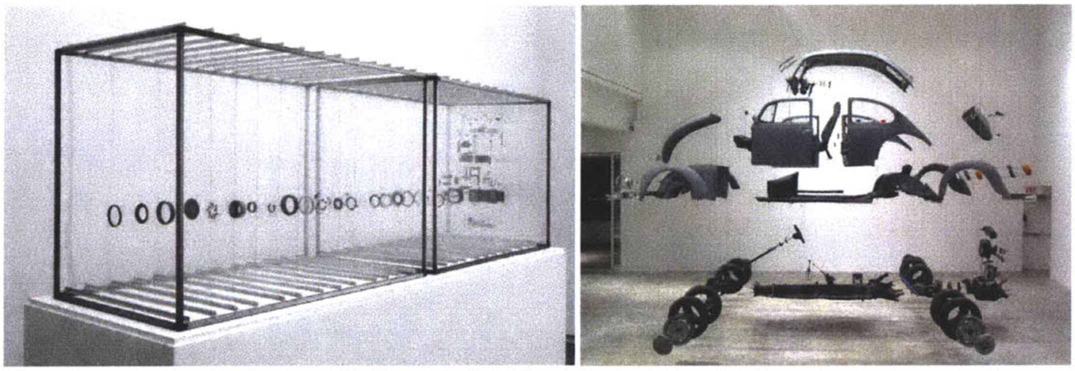


Figure 8: Object decomposition, D.Ortega [28][23]

The artist has here a didactic role. He reveals to us the true content of the object, which is usually not accessible to us, by deconstructing the object. In a similar way Design for Disassembly in architecture allows the designer and the user to better understand the whole system. This readability is multi-scale as it concerns the scale of the whole system itself but also at the scale of every component individually.

That way there is more information available that permits smarter choices with a better comprehension of the complex design, which becomes simpler. It also implies an increase of the responsibility due the transparency of the process.

In continuity with those previous ideas, figure 10 could be interpreted as a dynamic in the construction process and disassembly where things can be adapted in a very fast way. This last work was exposed at the Institute of Contemporary Art exhibition of Boston in 2010 named Do it yourself. Here again we can see that the visual decomposition of the objects invite the visitor/user to take part in the construction that he now understands at least mentally.

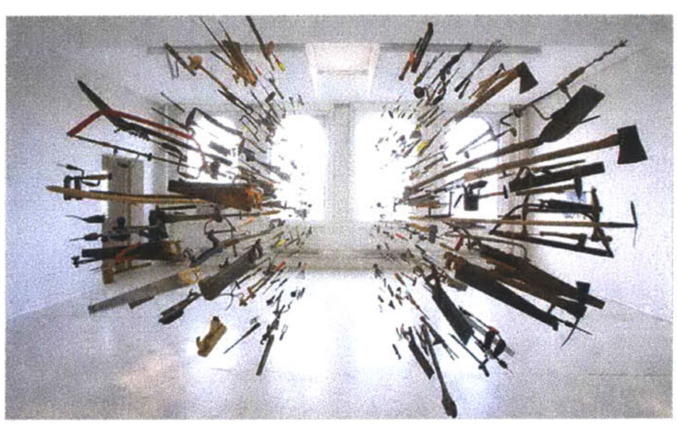


Figure 9: Do it yourself exposition at ICA, Boston [29]

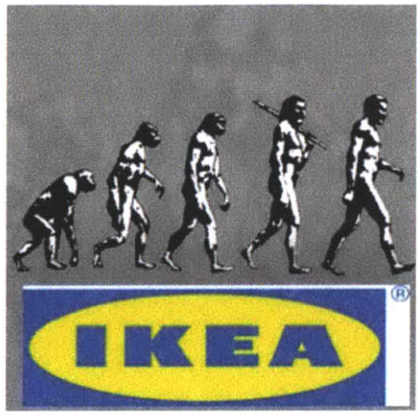


Figure 10: IKEA advertising campaign [30]

We cannot talk about the importance of the 'Do it yourself' movement through education without talking about one of the biggest pioneers in the field: IKEA, that gave the user the tools and possibility to make choices in construction and take part in their own design.

b). Right and responsibility

By giving more visual transparency in the construction process to the user and inhabitant of the building, the user can therefore make more choices. This leads us to assess the question of the right and responsibility of the user. Who is responsible of an architecture that is harmful to the environment: the user or the designer? Today, none of them have a real choice among the selection of materials and components.

More visual transparency will results in a growing demand from the user to get more involved in the choice of his own construction. This can certainly affect the market and suppliers in the field in a significant way. This pressure from the user will push the market to develop greener and higher quality products. Today, the customer has a right to know the composition of alimentary products he consumes. Labels are mandatory so that the client buys responsibly while being informed of the harm that the product could have on his health or on the environment with its carbon footprint for example. It should in the same manner be a fundamental right for the inhabitant to get information on the components and materials of the house he will buy and in which he is going to live all his life.

The next question should then be which type of information should the available and how much do we want to know about a specific building 's components. As always there is a balance to find on information provided so that the user can understand it to make a choice. Recent software such as Gabi Software gives Life Cycle Assessment (LCA) information that could be considered as a start in this network of information resource.

In parallel, as the user and inhabitant get more rights he is shifting toward a more responsible and active position where he turns from being a 'passive' user to an active 'user'. This phenomenon can be reflected notably in the energy sector where with individual and independent installation, such as solar panel, the user can be a producer as well.

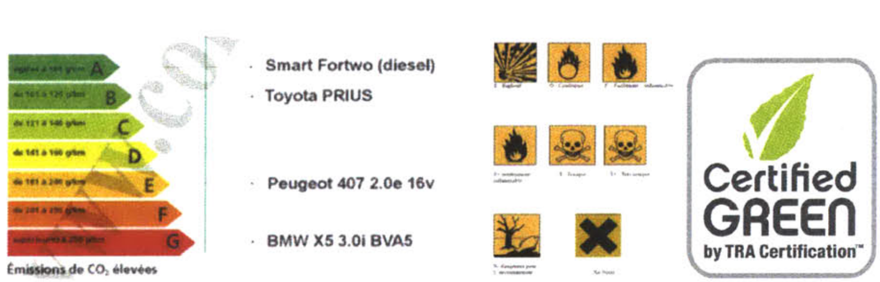


Figure 11: Different type of product labeling (LCA, toxicity, general label) [31][32][33]

Chapter 3: Case Studies

3.1 General case study, built projects [2]:

3.1.1. The Marie Short House

Design for disassembly, as we said previously, is not very common in building design. It is then very interesting to study how much has been done in terms of buildings and how.

The Marie Short House is an interesting case because it is a residential house that was designed to be flexible in terms of use and space. It's worth noting that the design constrains came from the client itself who asked the Australian architect Glenn Murcutt to meet his required standard. Thus, the client has a strong impact on the design; he is involved in the design before the construction of the house as well as after.

Beyond the fact that the house is designed for adaptability in time, it is also designed for adaptability relatively to its environment. Indeed, the house is oriented on the site to maximize passive ventilation and solar benefit, reducing the need for heating and cooling, showing us that there is a real adaptation from the house to its context and its environment. This is also symbolized in the way that the architect designed the house so that it touches the earth lightly with a pier foundation and the use of a raised floor system. It shows one more time the concept of the house, which takes advantage of its environment. This can also be reinforced by the fact that all materials used within the design are locally available.

Regarding the structure, the house relies on a system of a modular structural grid. However, the expansion of the story is only possible in one direction that is the horizontal direction. Also, open floor plan is possible within the structural modular grid. In 1980, the building was indeed expanded by the user using this grid framework. The architect had designed the gables and verandahs at the ends of the building and allowed them to be easily dismounted. That way, they could be removed at the end, allowing the building to expand while the veranda and gables could easily be remounted on the new extended building ends. The use of dry structural connection details such as bolts, made the dismantling process and reconstruction possible with limited waste. Also, in the expansion process, diagonal steel tension rods were thought to ensure the lateral stability while minimizing the use of material for the structure.

Furthermore, the building skin design illustrates the fact that the building is adaptable to both its environment and to its user. Indeed, the skin presents openings in order to take the maximum advantage of its environment and of its natural element such as sun and wind. Not only, is the skin is designed for natural light and natural ventilation but also for manageability of the user itself. Indeed, the infill panels for skylight and the louvers composing the skin of the façade are adjustable and moveable.

Figure 12: Marie Short House elevation & Interior [2]

3.1.2. The "Two- Family" House

The "Two- Family House" which was also constructed in Australia, is a good example of a prefabricated house for ease of construction and future adaptability. This house that was designed by the KFN firm is representative of a modern effort of a prefabricated residential project. This house has a degree of adaptability that is superior to the one of the Marie short house. Indeed, not only the house can extend laterally/horizontally, it can also extend vertically. Indeed, the 3D system allows change both in size and form. This 3D expansion of the house is designed for up to 3 stories and is possible thanks to a timber framing module structural system. The modular timber-frame is based on a 5m x 5m x 2.7m (16.4' x 16.4' x 8.8') three-dimensional grid. What is interesting is the independence of the structural system from the building envelop and interior finish system which allow for flexibility and convertibility of the building design.

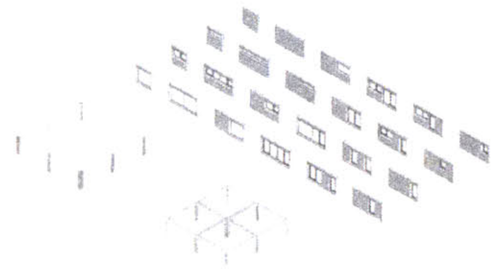


Figure 13: Grid and Panel system of the house [2]

Furthermore, the spatial organization is very important in this process and attention should be given to the adaptable design in function of the different uses of the rooms. Indeed, the part that required the main mechanical elements for water supplies such as the kitchen and the bathroom are the room that would certainly not want to be removed or expanded as bedrooms or living rooms. Therefore, they were placed in the core of the house. Also, the kitchen and bathroom units were entirely prefabricated and delivered on the site. The house space around the core can then be easily extended according to the inhabitants needs. Regarding the floor and ceilings, they are composed by a panelized system that matches the wood grid of the structural system. The KFN system provides up to ten fundamental exterior panels that allow the building envelop to be customized while, at the same time, using standardized components for ease of construction and cost efficiency. The fact that they are made of wood gives a sort of logic and homogeneity in the final design.

Finally, it is always interesting to look at the foundation system for prefabricated buildings because it is the part of the building that ultimately have to take into account the site it is assembled in; it literally represents the building contact with the site. In this case, the system used is a slab on grade foundation that is the antithesis of pier and footing foundation of the previous design. This solution is interesting because it combines foundation and floor structure leading to the achievement of a single and unique system.

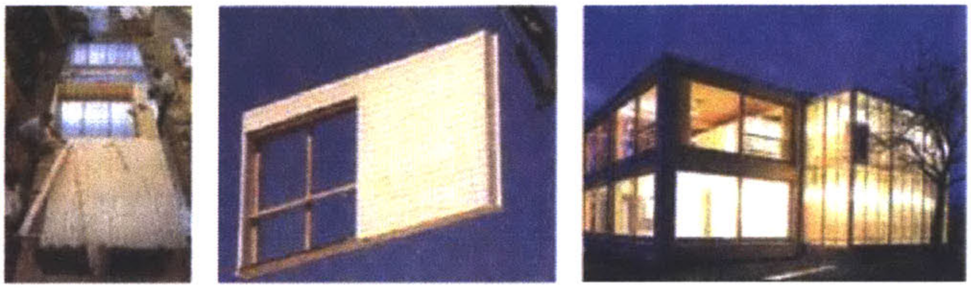


Figure 14: Off-site construction of panels and assembly [2]

3.1.3 The R128 House

The R 128 House design by the architect Eames is very representative of contemporary architecture and is an example of mass-produced house. One of the primary goals of the house was explicitly the ability to be dismantled, allowing its material to be either reused or recycled.

The structure of the building is made of steel as opposed to the two previous house examples. Steel is a material that has a great recyclability potential. Also, using steel is often a way of minimizing the use of material while optimizing the structure efficiency. The steel pieces of the structures are linked by a bolt system. This system is very convenient because this is a reversible process. It is very easy to unbolt pieces and this allows replacement of a defective piece, maintenance, reuse or recyclability. The columns and beams are connected using bolts that use threaded holes in the columns themselves. Finally, the larger structure is braced diagonally on three sides by tension rods to provide lateral stability. In addition, we have a structure that is part of the interior design: "the steel frame is articulated within the interior of the building facade with attention to the connection detail." Inside, the floors are composed of panels placed by gravity into channels between the floor structural beams with use of nails or screws. Removability of the panels is possible through the ceiling that is made of steel panels that match the structure and are placed by a clipping system.

The shape of the house itself was designed to maximize structural and material efficiency as well as energy efficiency in a cold Northern Europe climate. Here we talk about an " efficient volume to surface area". It is interesting to notice that besides the fact that this ratio volume/surface area could be good because of the compact and cubic form that the house is shaped, the material used is not helping on that side. In particular, the very thin steel structure coupled with the very large glass opening of the house are not necessary the best options for thermal isolation in this same climate. However, there was a real effort to overcome this difficulty and find answers to this challenging façade. Triple glazed glass panel were indeed installed along with operable windows for natural ventilation. The possibility of temperature modification was provided by an additional system consisting of a water based heat exchange system circulation in the ceiling.

Because of the site itself, and the significant slope of the plot, the house required a terrace-style foundation that is very specific to the topography. Concerning the foundation of the house, there is no clue about any reuse of the old foundation of the previous house on this same emplacement. That would have been interesting to start this project of adaptability and recyclability by recycling the foundation of the previous house.

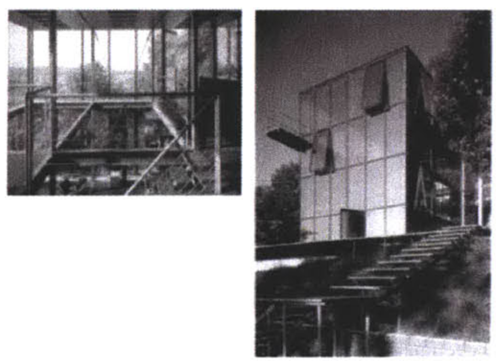


Figure 15: R 128 House, Interior and façade [2]

3.2 Case study of MIT YourHouse project, research project at MIT [10][8][3]

3.2.1. Construction methods

We have seen in the three previous study cases different degrees of adaptability that were possible while designing for assembly: from a 1D horizontal extension to a 3D extension house designed for being totally dismantled and almost entirely recyclable. Here we will go further in exploring with the MIT Professor Larry Sass Project YourHouse an ultimate degree of Design for Disassembly: customization of components by the user [8].

a). Individual customization and cultural context:

This method is powerful in that it allows houses to be customized in a very simple and accessible way. Looking at a plan of a typical house we can distinguish the central core of the house from the façade. The latter can be adapted to the cultural environs or customer's tastes [10][8].

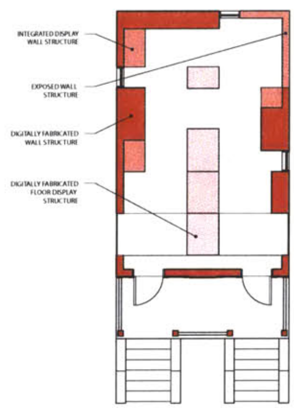


Figure 16: YourHouse Project-Typical floor plan [10]

Figure 17: Façade adaptation of YourHouse [10]

We are revisiting the question of layers for other purposes. It is for environmental factors but not necessary for recyclability. In this situation, the layers are meant to be unique and adaptable at the same time; there is the core layer and the exterior layers that are customizable by the user, the inhabitant that can express himself in the design of his own house.

Figure 18:House for disassembly and adaptation, Kieran Timberlake [34]

b). Construction method of the project:

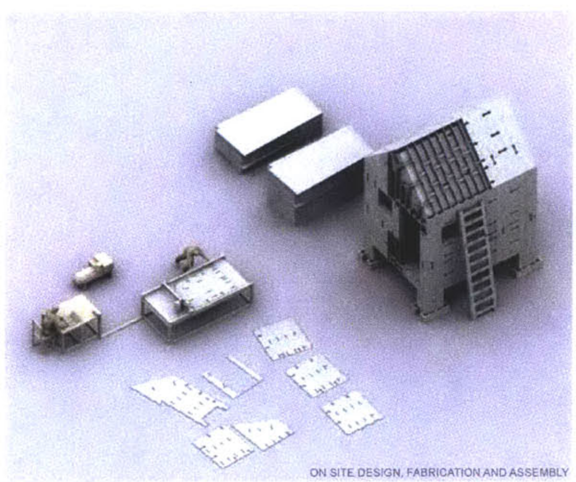


Figure 19:Your House, Prof. Larry Sass- Construction Steps [10][8]

The construction process is being rethought in a very innovative way in Professor Larry's Sass Research Project at MIT. Indeed, while bringing his expertise of computation he is introducing a new idea for the construction process in architecture. The innovation consists in using computer technologies to drastically simplify the construction steps for the building. Indeed, in all industries simplifying the construction steps and methods has always been a way to optimize efficiency, material use, and decrease cost.

In architecture, this approach is considered new. Indeed, it is a real challenge to have simple steps that could be understood and controlled by a unique person from the design phase to the assembly phase. Currently, the steps and methods of the architecture construction make the construction process so complex that it would be difficult to imagine the conception and orchestration of architecture by one single person.

In particular, Professor Larry Sass is simplifying the whole architecture process into only 3 construction steps that have a direct relationship and can be managed by one person.

First, the Architect or Designer is conceiving the virtual building in 3D though a computer using a software interface. He can send a 2D file obtained from the 2D model to a machine that would cut the different components which assembled will constitute the entire model in 3D.

Second, once the information is sent to the CNC machine, the 2D pieces are cut directly from the machine. Finally the last step in terms of manufacturing is the assembly stage; once the different pieces have been transported on site.

This simplification of manufacturing steps for the building through computing technologies is crucial for the efficiency of the construction. It has an effect on time but also has a huge impact on the designer role. As we said, it is because the chain of steps is easy to relate that the designer itself can manage them in an easier way. Thus, the designer has then more control on the construction part and this results in a smarter architecture in the design stage itself. Therefore, we can say that it has a direct impact on the designer role.

Moreover, this construction and design process is possible because of the specific use of wood as a construction material. First, the material is easy to cut and can be cut at high speed: (speed of the cutting drill of the CNC). In addition, complementary pieces of wood can be assembled together without the need of any liaison components (nails, angles, etc). Indeed, because of the propriety of the material itself the friction permits pieces to be assembled and hold together [3].

c). Social design, low cost housing:

The project of Larry has been realized precisely in the aim of obtaining low-cost housing as a final end that could be installed and constructed really fast. The context of the project was indeed, a poor neighborhood touched in New Orleans that needed to deploy housings and construction in a short amount of time[13] [8].

As shown on the map, there were 4 different specific locations that were chosen in the region. Each of the different locations belongs to a specific neighborhood and has a specify history and social context. One of the strength of this approach is the ability to bring a different answer to the table for each of those specific situations while respecting the diversity and uniqueness of the different contexts. Professor Sass suggested different facades for all of those different houses. Each of those facades could relate to their environment through the house that was there before. This is a work not only on memory but also on the identity of housing that place back the human at the heart of the reflection in this digitalized manufacturing process [10][8].

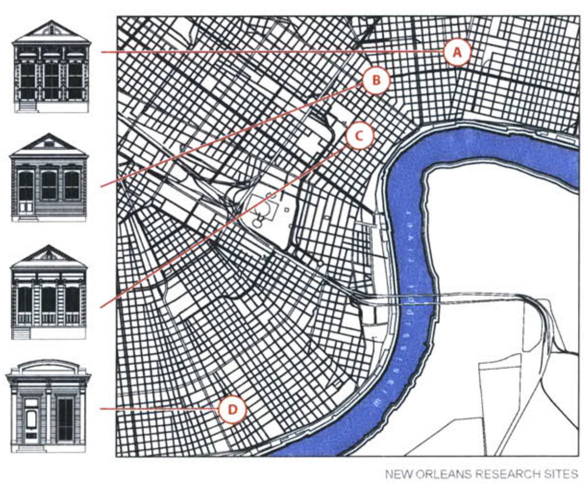


Figure 20: YourHouse Project-New Orleans research sites [10]

Chapter 4: Design experiments

4.1 Existing DfD techniques

4.1.1 Assembly/disassembly techniques

To achieve a Design for Disassembly in order to optimize maintenance, replacement, and recyclability it requires using specific design and manufacturing methods.

Some specific guidelines can be followed to facilitate removability and disassembly of components. First, one of the main guidelines would be to use attachments that are easy to disassemble. This means using simple type of mechanical connections instead of more complex shapes. A second guideline would be to minimize the number of fasteners. Using similar types of fasteners can also participate in simplifying the process. Ensuring access for disassembly is also one of most important disassembly techniques. Other important techniques include avoiding long disassembly paths, using the same tool for assembly and disassembly, using one disassembly direction to avoid reorientations, and finally designing for multiple detachments with one operation [3] [2].

If the type of connection will play a crucial role in this process it is important to notice that almost all of them have their advantages and disadvantages. For example, a screw connection has the advantages of being easily removable but has the disadvantage of having a limited reuse of both hole and screws cost. Bolt on the other hand has the advantage to be strong and could also be reused a number of times. However, they would have the disadvantage of being most expensive at first. Nail connections have the advantage of being easy, fast and cheap. Nevertheless, nails are difficult to remove and the removal usually destroys a key area of the component. Friction on the other hand has the interesting advantage of keeping the construction element whole during removal. It is a relatively undeveloped type of connection because it requires an important manufacturing precision as seen previously [18].

4.1.2 Materials and Structural systems:

Materials will also influence and help in choosing the type of connection to use or the type of structure systems that would be the most suitable.

The types of connection that are the most used for steel are bolt and weld connections. Steel is a very friendly material to use regarding disassembly as the types of connections that it requires are very easy to disassemble and the material itself has a great potential for recyclability. The material has other advantages such its robustness, strength and capacity of being used for long span structures. However, the material is mainly limited by an economic factor [7].

The most important market shares for timber construction materials are renovation, packaging, temporary formwork, joinery, floor, ceiling joists and fencing. Beams, railway sleepers, doors, flooring and windows are the most commonly reused timber components. Timber framing is most of the time a right fit for reuse because it maintains large member sizes and usually uses less large connections. However, some products like fencing, garden structures, cladding, fixtures, and floorboard can require processing before reuse.

There is a lot of variety concerning the type of connections for wood components. The most common connection types are: nails, screws, bolts, staples, metal plate connector, mechanical bonding in masonry.

Timber has many other qualities that make it favorable for DfD. In fact, timber is a non-toxic, homogeneous and light weight material. Furthermore, it has a high potential for reusability and recyclability. On top of that, wood carries the lowest embodied energy (C02 emission) of all the materials. Finally, wood is the only truly renewable and biodegradable material. Alternative wood composites can on the other hand carry toxic materials in their glue and will generally have a higher embodied energy [14][5].

As seen previously, certain material such as timber and steel are preferable for allowing DfD. Others such as Concrete and Masonry are very unfavorable to such a process even if with the adoption of prefabricated panels they are able to increase their potential of reusability as well.

Here, the table shows a lifespan of different materials that can be used to assist in material selection and permit focus for connection detailing [2][14].

Building Materials Types	Repair (yrs.)	Total Replacement (yrs.)
Flat roof BUR membrane	10	20
Pitched roof, cement composite shingles	20	50
Pitched roof steel sheet	usually not required	30
Brick cladding	25	75+
Acrylic stucco	20	?
Interior gypsum board	3 to 10	25
Interior concrete or block	10 to 20	75+
Metal or vinyl windows	10 to 20	40
Clad wood windows	10 to 15	25 to 50
Solid wood interior doors	4 to 8	15
Metal doors	5 to 15	25
Terrazzo	0 to 15	60+
Ceramic floors	10 to 15	40+
Vinyl composition tile	8 to 15	20
Hardwood floors	5 to 10	40+
Carpet	3 to 8	5 to 15

Figure 21: Repair & replacement cycles for typical building materials Santa Monica Green Program [2]

4.2 Design experiments, Digital fabrication

4.2.1. Wood connection, CNC

In this section we choose to experiment and explore friction techniques for wood assembly/ disassembly. As said previously, it requires using advanced manufacturing process for great precision. This is why we will be using the CNC machine at the MIT woodshop.

a). Wood friction assembly:

New manufacturing methods change our way of constructing and allow us to push further the design exploration of connection detail. Here I am looking at possible wood connections using CNC computing method. This technique is part of the new tool that will revolutionize the way we construct. Indeed, with CNC methods we moved from a complex system to a computer based system where the drawings are being read and drawn by the machine itself. The architectural components are being printed and instead of ink there is a drill that cuts the pieces from the wood sheet. This method has many advantages and one of the most important is the drastic increase in the construction time.

In this case, because we are using wood the parts will be cut in such manner that they can directly hold together by friction. This also simplifies the construction process and thus increases the construction time by reducing the number of pieces used. In particular, no liaison pieces are needed at all. In the framework of a design for adaptability and flexibility I designed wood pieces that could be linked together in a different way. On the left figure I cut different holes in the circle to be able to adapt the angle of rotation between the two others pieces of wood. The wood circle here is a major component that allows a change in the relationship between two other components and their inclinations.

On the right image there is also three pieces together that can all get a different inclination, angle and distance from each other allowing a multitude of possibilities regarding the kind of connection detailed chosen. As a detail it is interesting to notice that while cutting the wood pieces with the machine I realized that for more ease in the assembly you need to drill small holes at the angles of the inside cut parts. This allows a better assembly process and also optimizes the assembly time. Finally what is powerful with this technique is that by a printing phenomenon you can turn 2D into 3D while the components are assembled.

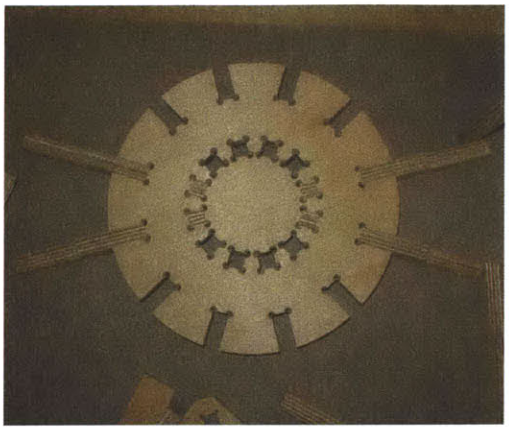
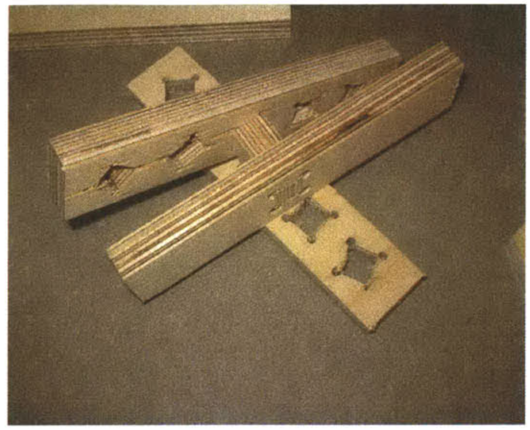
 

Figure 22: Wood connection experiment with CNC

Summary of results of wood connection experiment:

Positive results	Trades-off
Easy and cheap to assemble 2D pieces to make 3D	Size of detail depending on minimum thickness of plywood, difficult for smaller scale detail
Creation of different pattern possible on a unique piece for more standardization	
Assembly by friction very strong (thanks to the help of simple tool as a hammer)	

b). Chair experiment

Here, the design was a little more complex. I explored the possibility of making a finite object. As a first scale of interest, I choose the scale of the human body while making a chair. Therefore, I tried to use this idea of flexibility and adaptability developed in the wood connection experiment and invest it in the chair design.

The whole concept of the chair is based on the previous wood junction previously that is repeated for variation. Thus, all the connection between pieces is meant to allow angled junction. Here the idea is to explore the limit of this technique and see how far we can go in terms of assembly possibility through the scope of the angle. To allow this angled junction, that is difficult with 2D pieces, we choose to introduce a third plan so that each connection is the result of the intersection of 3 plans.

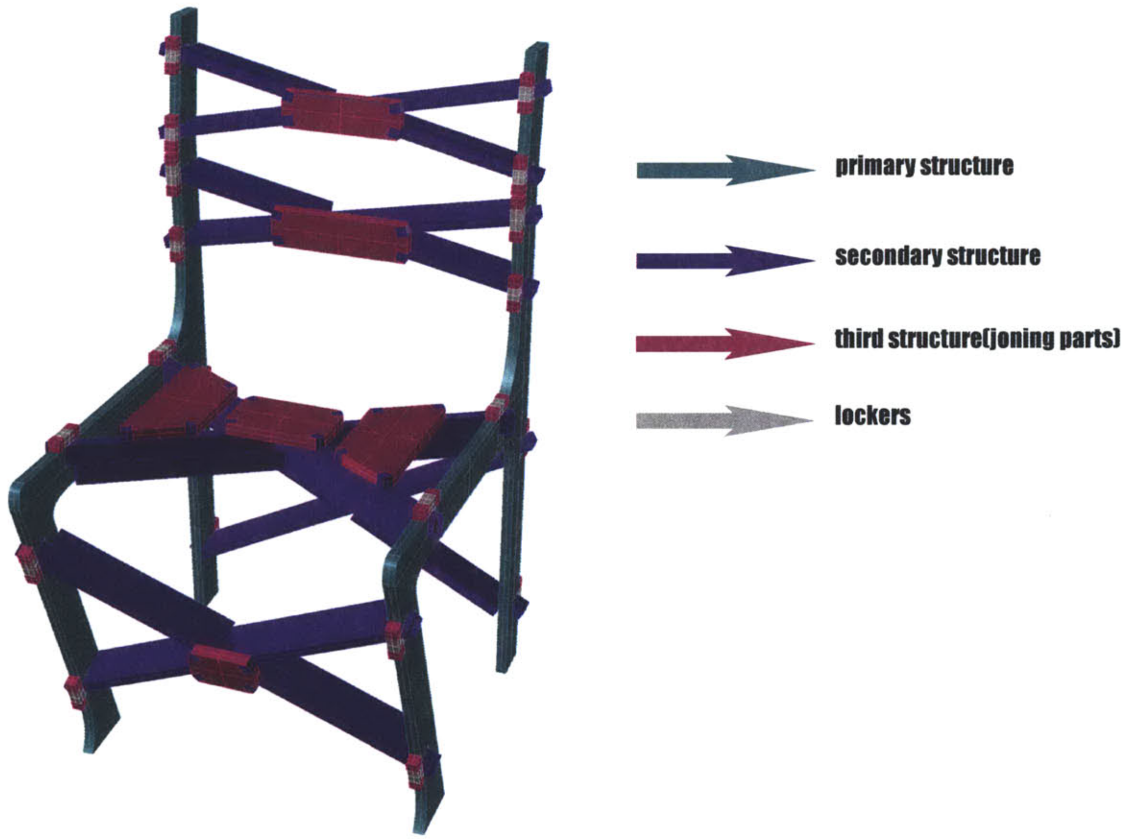


Figure 23: Structural layers of the chair constructed

This results in a chair that has three different layers of structures. They could also be compared to layers of a house where you have the primary structure (blue), the secondary structure (purple) and the last layer (red) that constitutes the third plan and is the liaison.

Once the virtual model is modelized in 3D the next step consisted in translating this into 2D drawings of the different parts. This process is interesting because it requires the designer to think of how to arrange the pieces on the 2D sheet in such a way that we lose as little material as possible.

The next level of design would be to think of a design that would also ease the cut process and limit the waste during the cutting process.

One interesting observation looking at figure 24 is that the blue indicates the drill hole at the edge in addition of the cutting red line in order to ease the separation process when the pieces are cut. We can also note that because the drill has a specific thickness it is important to calibrate the machine for what is inside and outside of the drawing so that the thickness of the drill does not affect the cutting.

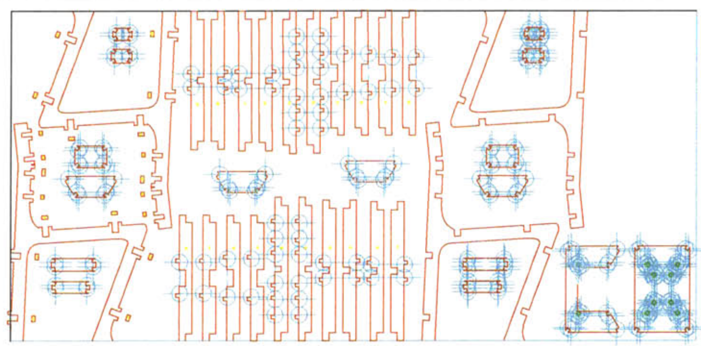


Figure 24:CNC file and organization on wood sheet to avoid waste

Besides the virtual process that allows a back and forth method between the drawing documents and the construction documents, we worked with a physical model too: the mockup. This particularity of the computing method was used in Professor Larry Sass project. It is a way to test the final model with a scaled down model called a mock-up. This step is very beneficial and could improve the design while leading to better iterations. It can also play a role in helping with the organization and optimization of the assembly phase of the final design. Knowing which parts should be assembled first permits a gain in time and leads to a construction optimization.

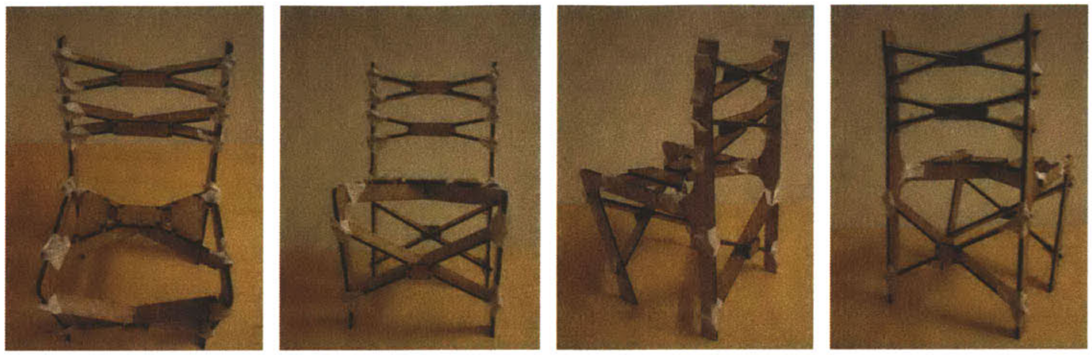


Figure 25: Chair Mock-up

Beyond the assembly goal there is this idea of structural efficiency. Indeed, this miniaturization is a real benefit for testing the prototype and allows testing of the structure's wood resistance. Because the model is going to be scaled down with the same material properties and scaled thickness it will be a very reliable model for structural testing which is a considerable advantage for the design optimization.

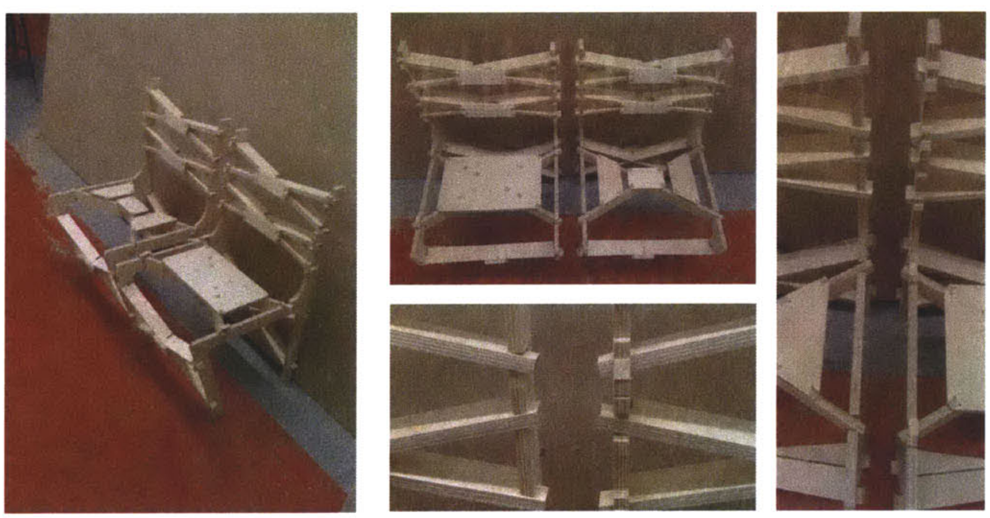


Figure 26: Chair experiment-Full Scale

Summary of results for the chair experiment:

Positive results	Trades-off
Pieces of the chair that can be dismantled by hand in order to ship the chair very easily (take less space).	
Management of waste possible in a manufacturing method when there are many chairs arranged together on a plywood sheet to limit waste.	
Connections fast to assemble and disassemble to each other when angled.	Less strength structurally

Figure 27: Assembly of the Chair at the MIT woodshop

4.2.2. Different material, connections

In this part, we will do experiments of assembly and disassembly for different materials. In particular we will look at the relationship between wood, steel and glass.

a). Interconnection between different materials

An additional degree in scale is being explored through the design of a coffee shop. The fact that we are looking at a larger scale results in a more complex design.

However, we are still dealing with the same type of geometry. We will indeed be focusing on a geometry involving irregular angles (versus right angles) to push further the research of construction at a larger scale. Here the concept of the coffee house consists of taking the geometry of a simple cube and cutting the sides to obtain angles. The idea is to remove those triangular volumes from the cube to reuse them as furniture in the inside of the box. The architecture of the coffeeshop is meant to symbolize the process of disassembly and reuse while exploring manufacturing challenges such as dealing with angles using 2D printing methods.

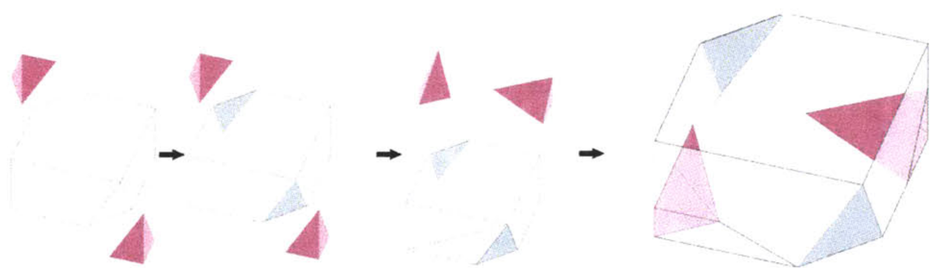


Figure 28: Concept coffe shop-space organization

What makes this scale more complex is also the fact that we are now dealing with different types of materials and that their interrelations have to be thought for disassembly as well. In particular, the cut parts of the initial cube create windows openings in the volume. This results in glass integration in addition to the initial skin.

To better understand the relationship between the different materials, the volumes and emptiness we were dealing with, we decided to realize physical models at a reduced scale (mock up) using a 3D printer here at MIT.

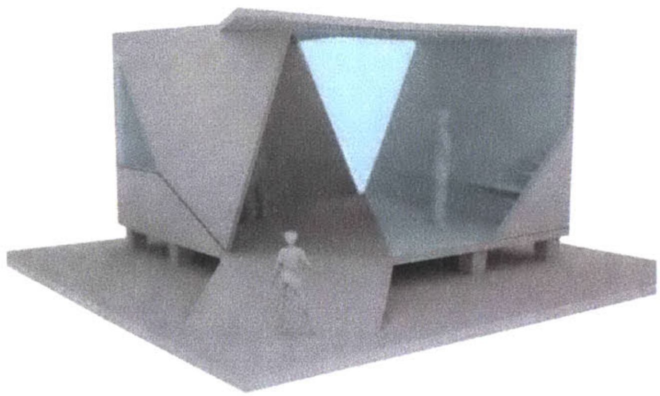


Figure 29:Model realized with 3D printer

b). Coffee building

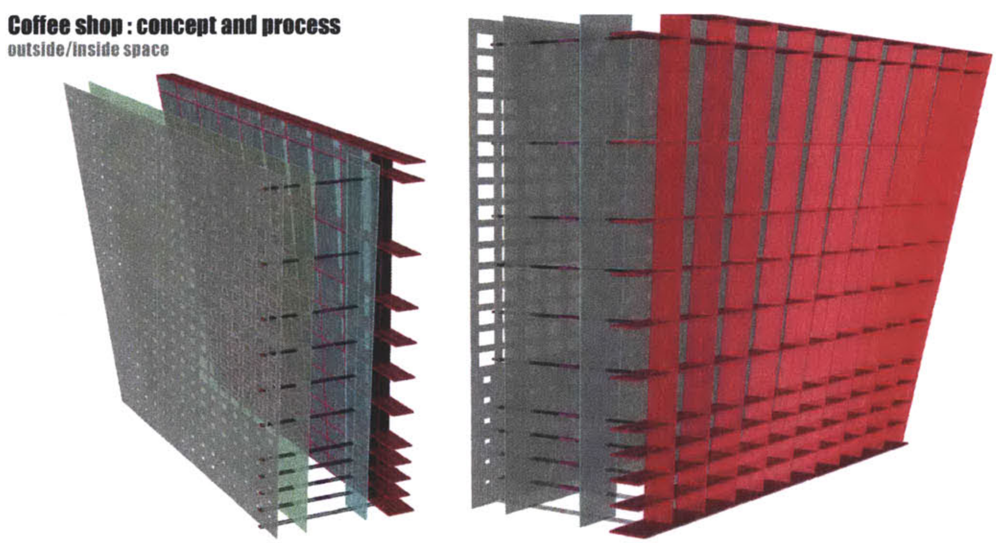


Figure 30:Facade layers interconnection

The complexity that we have to deal with has an important impact on the degree of complexity regarding the manufacturing process and design for assembly/disassembly. To actually think of this project as if it was going to be built we need to consider the different layers of constructions. Here, we are trying to innovate and reverse the usual role and position of the layers. For example, we want to valorize the structure of the building to show it and therefore we have it inside of the building. The other layers will all be exterior to the structure itself. After the structure, we then have a layer of glass so that we can see through the structure and a transparent protective layer for water and finally a metallic grid that will have a changing pattern. This layer of the façade creates different types of view in enlarging or reducing the pattern opening. Thus, we can really say that this scheme of design arrangement leads us to deal with various materials and think about their relation to each other.

In order to experiment the construction possibilities of such a design we are using rapid prototyping technologies such as CNC for Wood (layer printer for the cardboard of the mockups), Water Jet at the MIT hobby Shop for metal and glass. Then, the experimentation consists in a continual back and forth between different scales to actually make the system work. Below is an experiment of clamp system inspired from traditional Japanese wood connections. On the right of the image is a model at a smaller scale of the entire facade. By using full scale detail and coming back to smaller and more general models of the buildings we are able to understand better the connection between the different material and foresee a level of accuracy for construction optimization in a later stage.

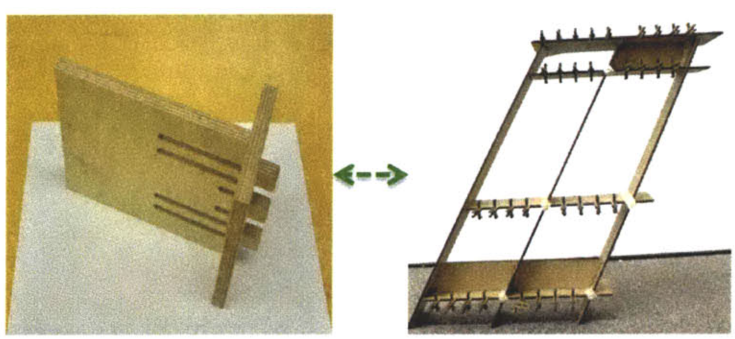


Figure 31:Wood models-Different scale work for the facade

If this back and forth process can be practiced in different scale of physical model it can also be done between the virtual model and the physical model. Indeed, the virtual has to be updated regularly so that the new computer files can be edited and cut the right way the next time.

Summary of results for the facade experiment:

Positive results	Trades-off
Clamp for wood that worked greatly Wood perfect for this application no deformation after use and the clamped get back to initial shape and get blocked.	However required a little bit of force to unclamp.
Two scales made possible the understanding of the facade structural system: scaled down model and real scale model for the connection detail	

Below are some experimentations regarding the facade detail and relationship between the different components. The clamped is designed as the liaison components connecting the different layers. Therefore it is a real challenge to design such a component that could reply to two different material properties (wood and metal).

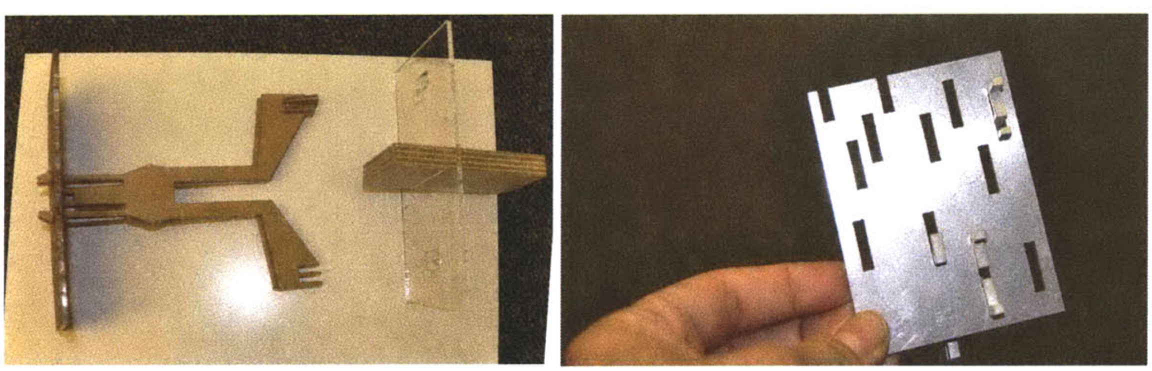


Figure 32: Connection piece-liaison between different layers & Facade Pattern experiment

Summary of results for the connection facade detail experiment:

Positive results	Trades-off
Detail connection is very easily to assemble and disassembly from the facade	Clamp system does' t work that well for steel because of deformation
Good liaison with wood though	

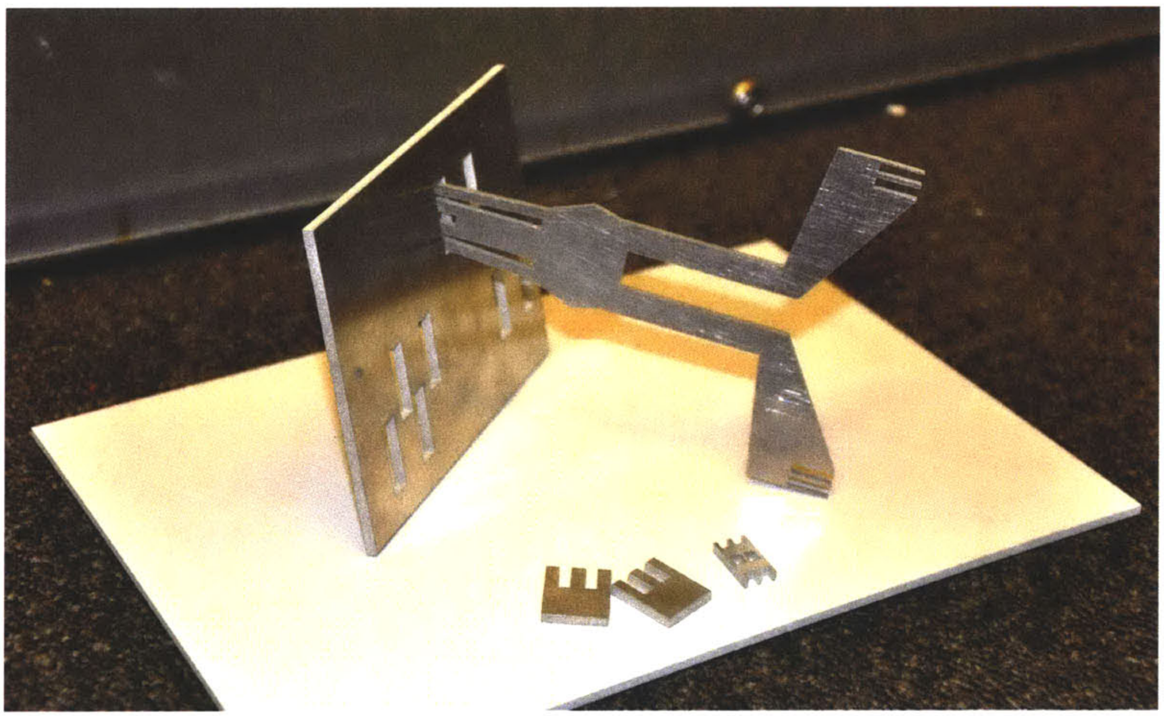


Figure 33:Relation clamp/facade

For those tests, the clamps were cut in metal sheet in full scale. Several tests were made focusing on this major liaison piece that is linking the different layers. The idea was to make a clamp so that this piece could be fixed to the other layer but could also be removed or decamped easily. For example, the external façade could be changed with an updated pattern if needed in case of change of use/program of the building for example. For instance, in a house you would need more obstruction for a privacy zone as opposed of a coffee house where you want people to see and be seen as much as possible.

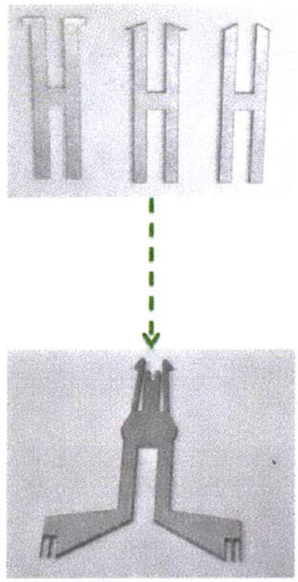
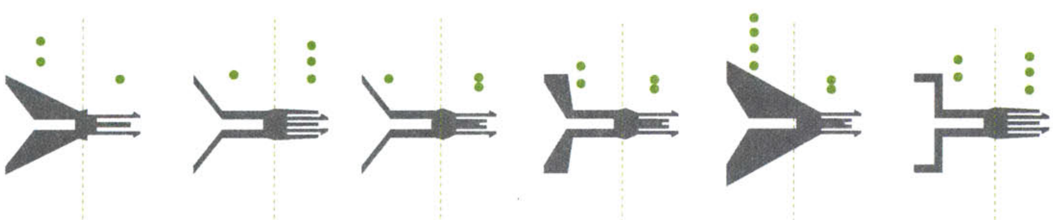


Figure 34: Liaison Piece-Shape experiment

Summary of results for the connection facade detail experiment, iteration on the ends of the components:

Positive results and trade-off for each position:
Different endings for different positions on the structure:  What was observed as a result of the experiments of many design iterations for this structure was that there wasn't a unique connection detail working for the façade. Indeed, there were no good or bad endings for the connection detail but endings that were preferable at specific locations.

Beyond the facts that there was not one solution, we found that one specific shape could be used at a specific location of the structure. Looking at the results of the experimentation we can see that we tried different types of endings for the clamp each time in both sides to find the best combination. This would result in a changing pattern of the liaison in function of its location. This way, each piece of the structure is unique and can reach higher efficiency both in terms of material saving and cost saving. Each piece of connection can be designed for specific amounts of charge it is carrying. Finally, this is only possible through the development of technologies that are entering the market such as the ones we used in our experimentation. Those technologies will revolutionize the way we build and the role of the user in its design. Indeed, we are moving from mass production where all the pieces produced where the same to mass customization where all pieces can be different in effortless manner with predesigned computing files ready to be cut.

Chapter 5: Conclusion

5.1 Conclusion

5.1.1 Summary

To conclude, DfD for building is a Design strategy that integrates new design criteria for a smarter and more responsible design. This design method rethinks buildings both as products composed of different layers and as products part of a larger environment.

Rethinking the interaction between different building layers and components of different lifetimes allows repair, replacement, reuse and recyclability. This flexibility results in a drastic decrease in waste, environmental footprint, as well as overall construction cost.

DfD also has an impact on the building designer's role by the intense organization it requires. DfD intensifies collaboration between architects and engineers while stimulating a change in their respective role where for example the architect has to be more technical.
Also, DfD changes the role of the designer who has to know more about the different components separately and is now more responsible in the construction process. The inhabitant can therefore have more information on all the different components and materials of houses to get more involved in material and component choice of his own house while being more aware and responsible about their impact on health or on the environment.

Furthermore, we have seen through the 4 study cases that DfD could be implemented at various degrees of adaptability: from a 1D horizontal extension house to a 3D extension house designed for being totally dismantled and almost entirely recycled. MIT Professor Larry Sass Project YourHouse demonstrated the possibility to go further with customization of components by the user in function of a specific socio-cultural context.

Finally, the variety of experiments showed that DfD could be explored through different scales and materials. In particular, connection by friction for wood showed that it allowed 100% disassembly and therefore reuse or recyclability. However, there is always a balance to find between strength of the connection versus ease of the disassembly. For the steel connection experiments and notably the clamped studies we found that each shape could correspond to a specific location in the structures. We have seen also how customization of pieces was possible with digital fabrication methods and how they will provide innovation in design for disassembly in the future.

Lastly, by increasing recyclability and reuse, by gaining efficiency in the construction process, by encouraging tight collaboration between architects and engineers and thus technology design integration, by allowing space flexibility, by democratizing architecture in individual expression of the inhabitant and managing data information, DfD architecture could drastically decrease the construction cost and thus provide suitable architecture answers to the major mutations of our transforming world.

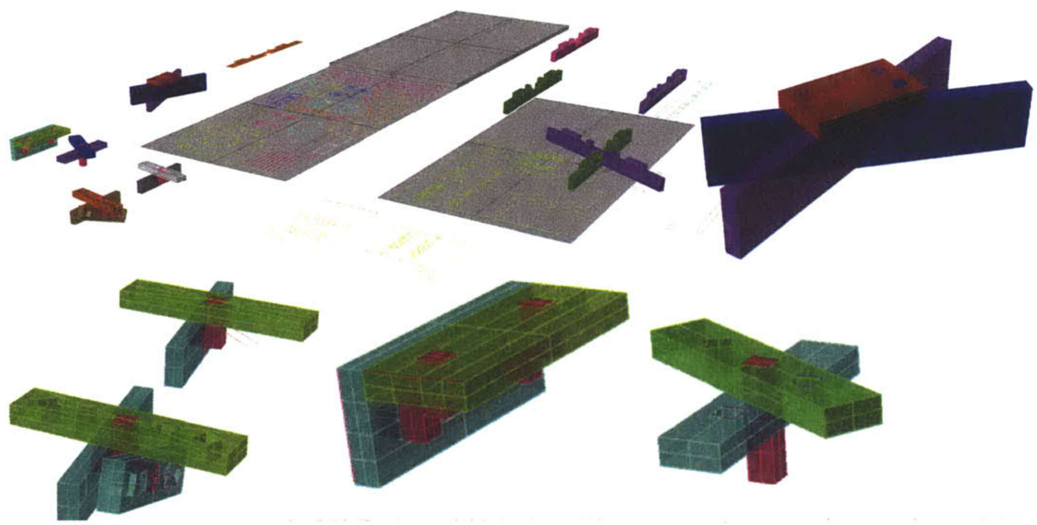
5.1.2 Recommendations:

In encouraging standardization for economic purposes, DfD do not fully participate in an innovative way in an evolution in the construction field. Therefore, one of the last principles of DfD that relies on modularity should not rely on standardization but should integrate new digital fabrication in its guideline for innovation.

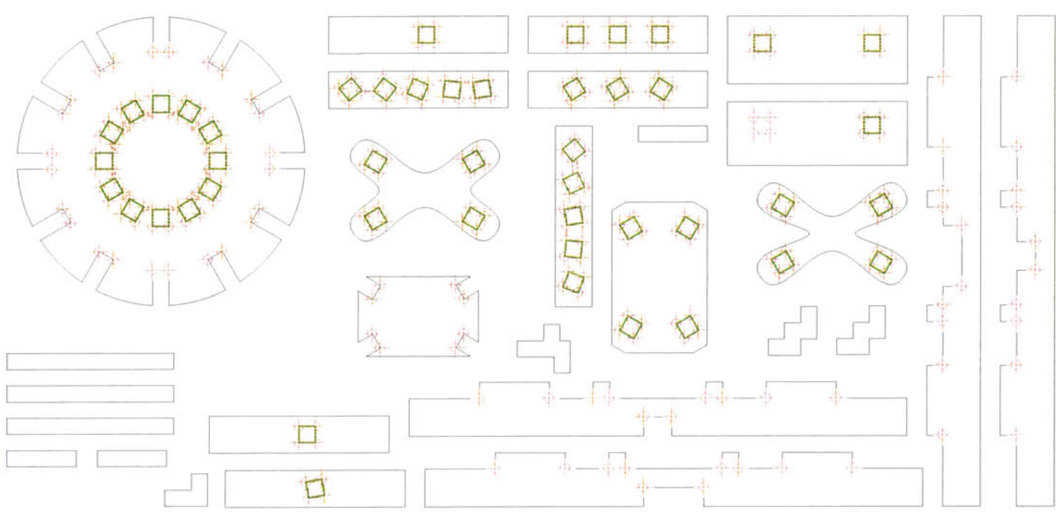
Furthermore, for a better implementation of DfD, we need to introduce new design criteria without preventing creativity and innovation in the Design. DfD could be implemented in many manners and there should not be drastic rules in design for disassembly.

LEED system could encourage DfD by putting more emphasis on it in its program (HQE in France).

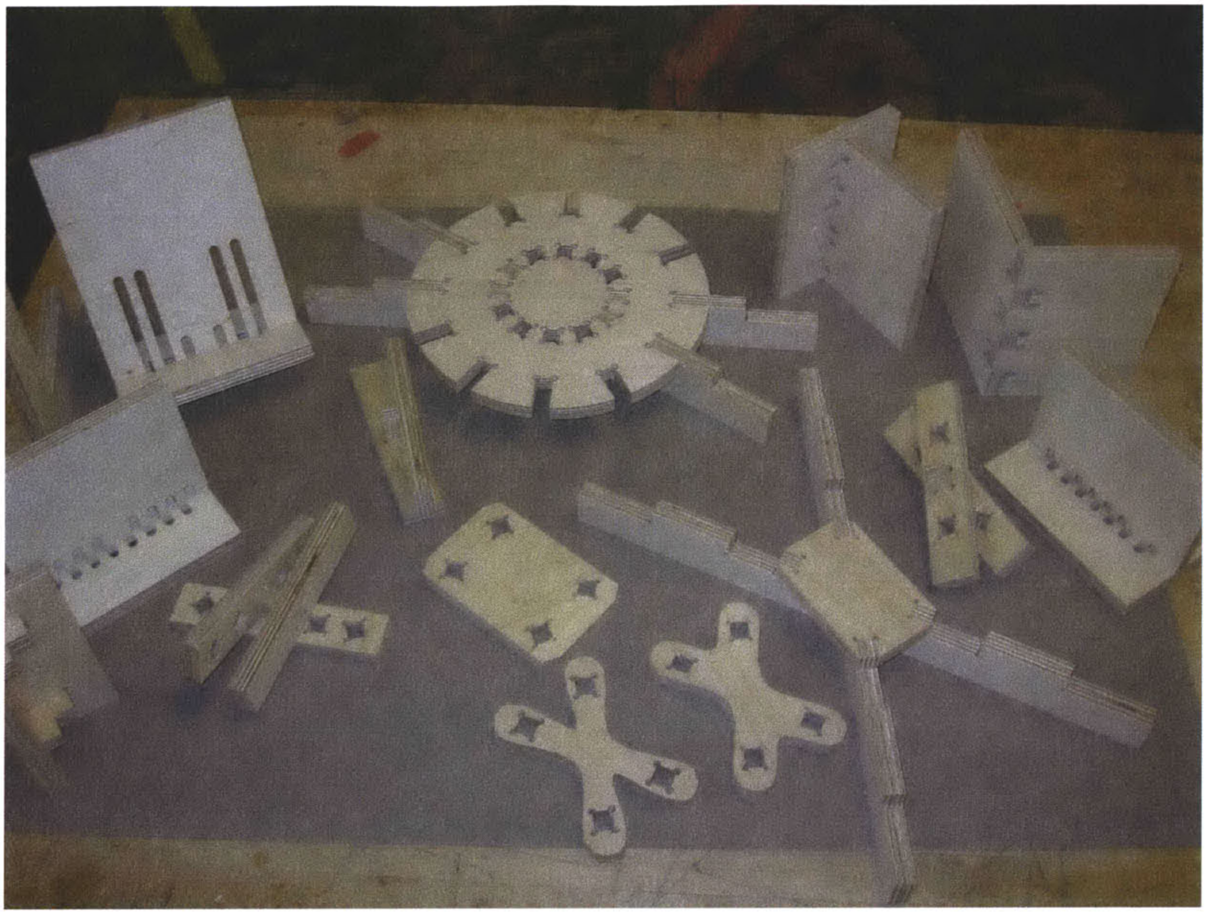
5.2 Appendices:



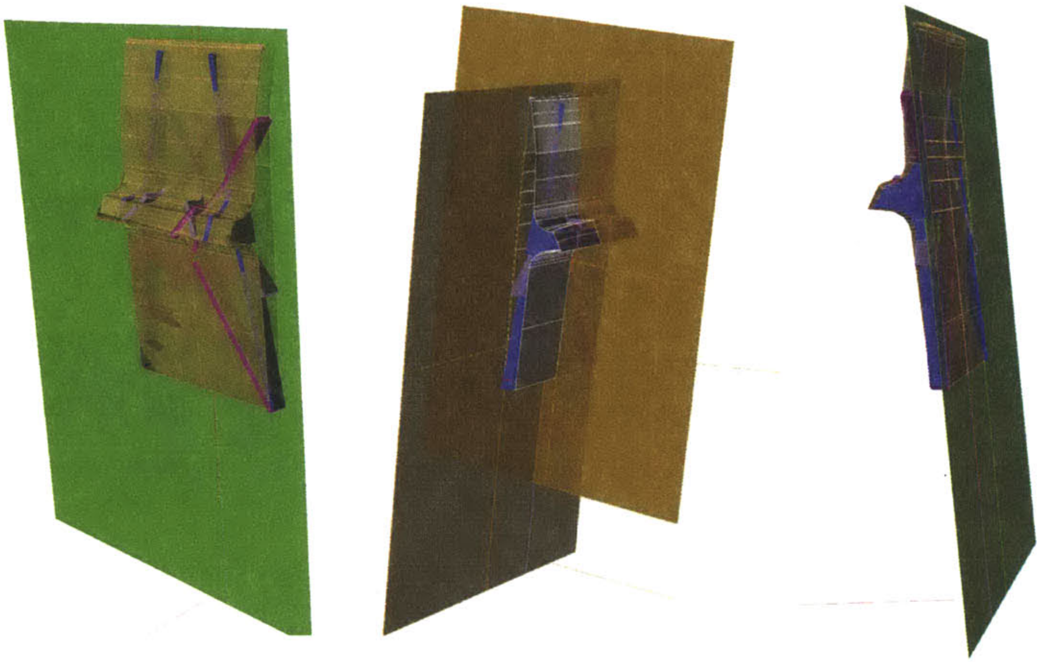
Appendix A: Rhino 3D model of wood connection



Appendix B: AutoCAD 2D file of wood connection and organization on the sheet

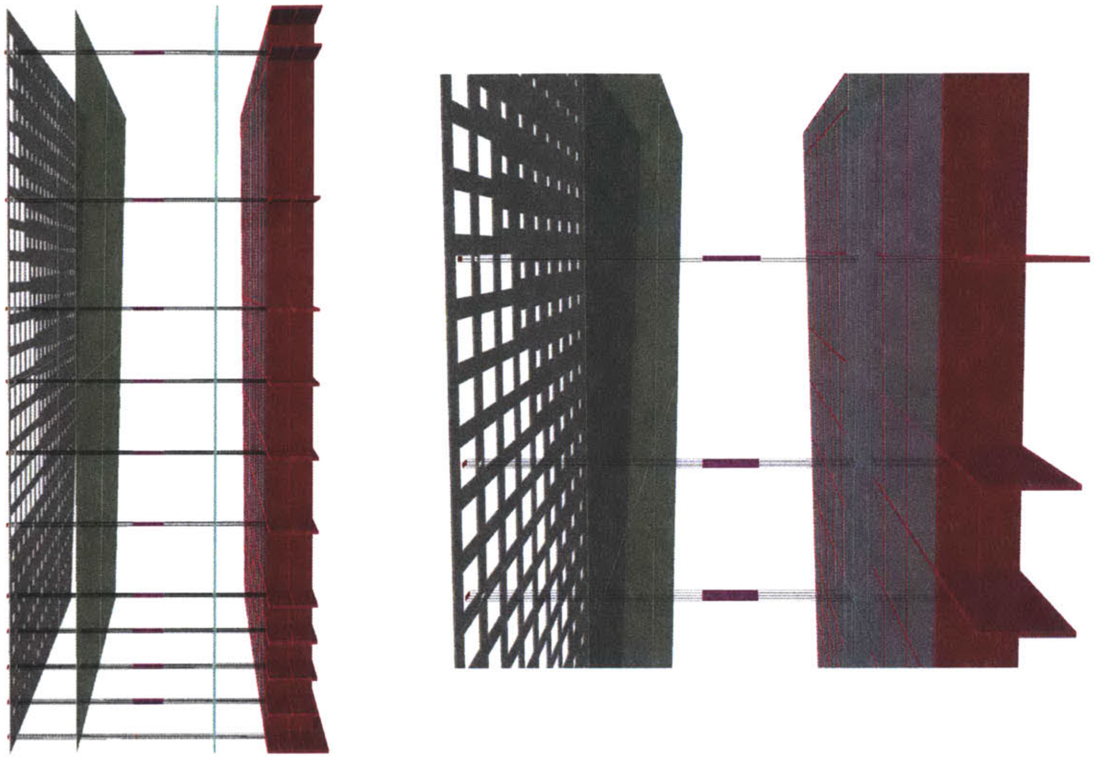


Appendix C: Physical cut and assembled wood connection for DfD testing

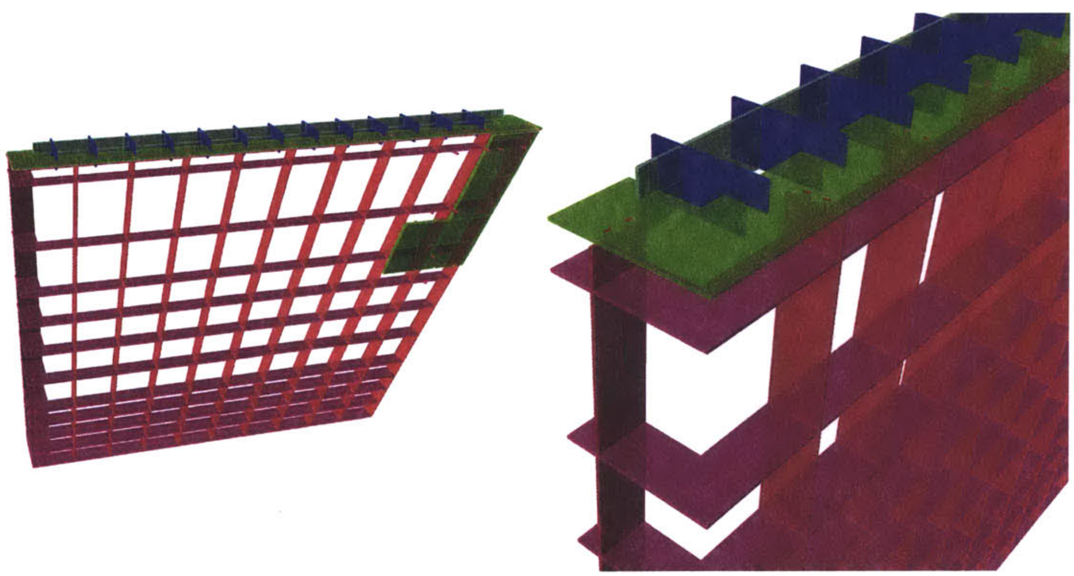


Appendix D: Chair detail, work on intersection of plans, virtual Rhino models

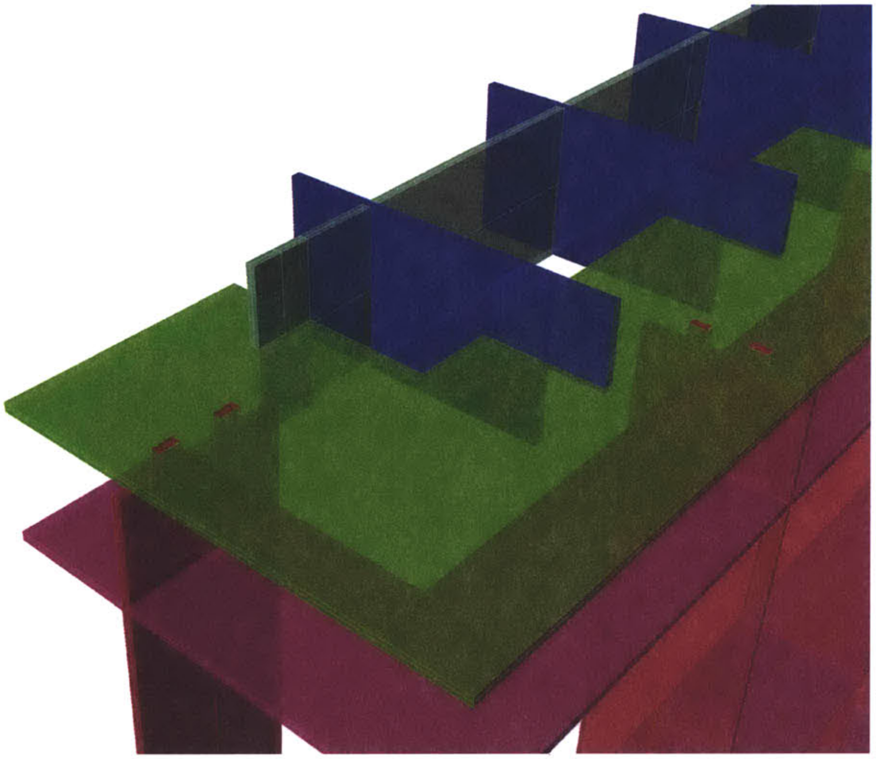
Appendix E: Chair detail, results of the intersection plans: wood connections, virtual Rhino model.



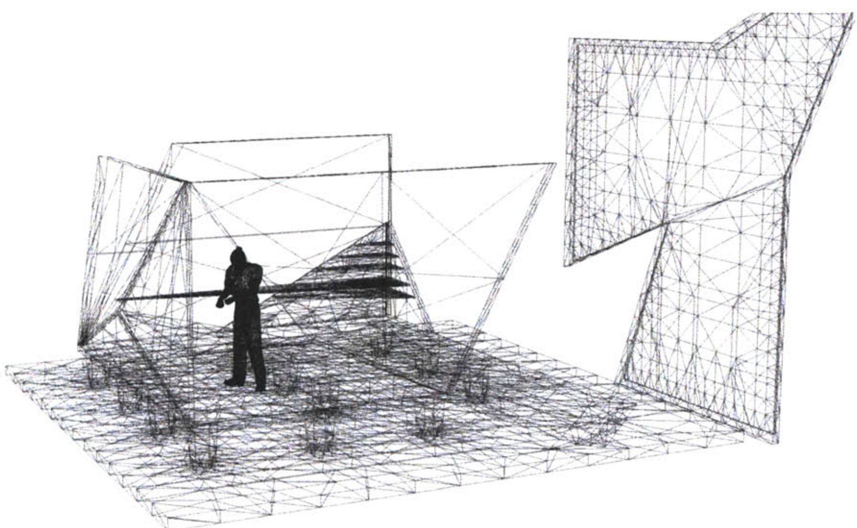
Appendix F: Different layer of the building facade of the study



Appendix G: Structure of building



Appendix H: Detail of the top of structure, interaction between the wood components



Appendix I: 3D file for 3D printing for general understanding of the building volume

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