Timber Tower: A flexible fabrication method for reconfigurable housing

by

James Coleman

B.S., Environmental Design
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Submitted to the MIT Department of Architecture and the Department of Mechanical Engineering in Partial Fulfillment of the Requirments for the Degrees

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Signature of Author ______ Signature redacted ______
James Coleman
Department of Architecture
Department of Mechanical Engineering
May 20, 2014

Certified by ______ Signature redacted ______
Sheila Kennedy
Professor of the Practice of Architecture
Thesis Supervisor

Certified by ______ Signature redacted ______
Daniel Frey
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ______ Signature redacted ______
Takehiko Nagakura
Associate Professor of Design and Computation
Chair of the Department Committee on Graduate Students

Accepted by ______ Signature redacted ______
David Hardt
Professor of Mechanical Engineering
Graduate Officer

THESIS COMMITTEE

Thesis Advisors:

Sheila Kennedy
Professor of the Practice of Architecture

Daniel Frey
Professor of Mechanical Engineering

Thesis Reader:

Neri Oxman
Associate Professor of Media Arts and Sciences

Signature redacted

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Submitted to the Department of Architecture and Department of Mechanical Engineering, May 28 ,2014 in partial fulfillment of the requirements for the degree of Master of Architecture and Master of Science in Mechanical Engineering at the Massachusetts Institute of Technology.

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ABSTRACT

"Prefabricating Housing...again", this time it's going to be different.

Fabrication machine functionality is bracketed by the physical configuration and componentry of the system. Traditionally, a machine designer engineers a system to deliver a specified range of operational metrics such as speed, stiffness, and accuracy. The end goal of this process being that these metrics satisfy a desired functionality. This work-flow generates specific machines for specific tasks. Task specific machines require thorough design, engineering and testing. Once this process is complete, these highly specialized machines most often do not lend themselves well to alternative or non specified use.

Multi purpose tooling and component based machinery are areas of research that aim to provide flexibility in machine operation. While this approach has proven successful in slowing machine obsolescence, alterations to these machines are often difficult and still confined to specific tasks.

So what happens when the desired task is not known and how can new fabrication methods be prototyped and explored by designers?

This theme of inflexibility in machine engineering can naturally be extended to the architectural design of prefabricated housing. Housing projects, especially prefabricated housing projects, are highly specific solutions that do not lend themselves well to personalization or customization (unintended uses). As occupant requirements and tastes change over time, a singular solution becomes increasingly under serving. The root of this inflexibility can be traced to material configurations, methods and metrics of production, and the stages at which user input is integrated.

How can a housing project promote personalization and in turn be enriched by the creative capital of it's occupants?

This thesis proposes a prefabricated housing architecture that delivers configurational flexibility through a strategic union between industrial manufacturing and the burgeoning DIY culture of personal fabrication. The combination of mass produced standard components with the ability to locally customize, via personal digital fabrication tooling, provides a personal housing protocol with true flexibility. Half Mechanical Engineering, half Architecture this joint thesis proposes both a wooden housing tower and a series of novel fabrication machines that together catalyze variation in prefabricated housing without sacrificing the economic advantages of mass production.

ACKNOWLEDGMENTS

I owe many thanks to MIT as a whole, its been a great 4 years.

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Bridget Rice you've come through during the toughest of times and always with a smile. You're literally, The Best.

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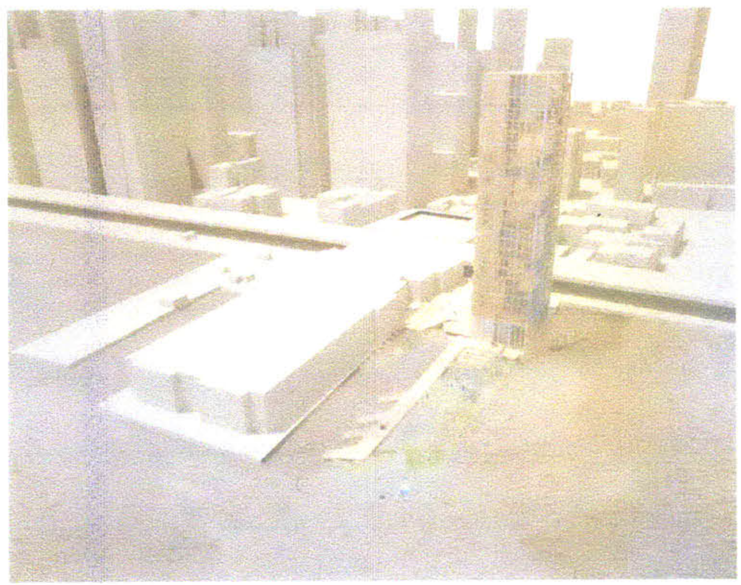


PART ONE

The problem

The long history of prefab, standardization, and the caveats of flexibility.

SECTION 1.00
Delivering more for less

Figure 1: Konrad Wachsmann and Walter Groupius "Packaged House" prototype 1942-1952 Harvard Art Museums/Busch-Reisinger Museum

The long lineage of Prefab housing

Over the last 120 years there have been hundreds of attempts to mass produce housing through prefabrication, each punctuating a moment in architectural history. Catalyzed by the appearance of the Ford assembly line in 1907 this trend was rigorously pursued by modernists as a means of delivering low cost universal housing. The rapid post war population growth and subsequent housing booms further encouraged designers to pursue mass production in architecture. Desperately trying to appease housing demand, US Governmental housing programs, like the National Housing Agency's 153 million sponsorship of 'demountable housing' in 1942, offered support and funding to anyone who could crack the code of low cost housing. Nearly all of the attempts can be categorized into:

-Rapid housing growth: like post war housing booms
-Technological innovation: development of new materials and or processes
-Disaster relief: readily deployable, fast, and "cheap"

All of which are typically governmentally sponsored and subsidized. The appeal of mass produced housing is widespread, interest ebbing and flowing for the previous 200+ years. Projects that reside in this category are numerous and their levels of success are diverse. Each chases the elusive troupe of 'more for less' leveraging the inherent efficiencies of systematic mass production to provide a higher level of quality to the masses.

Figure 2

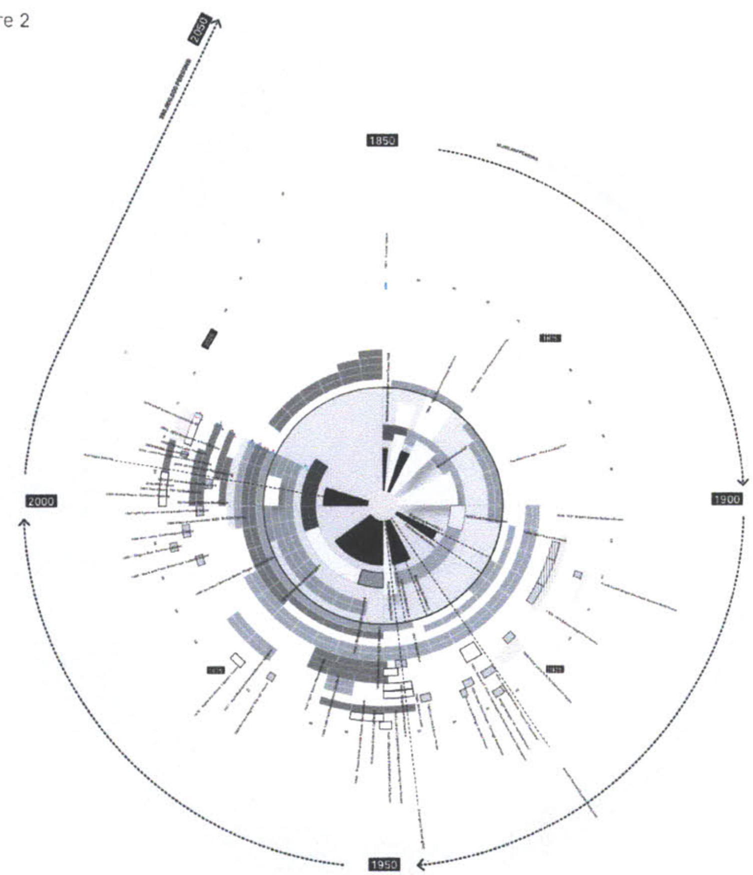


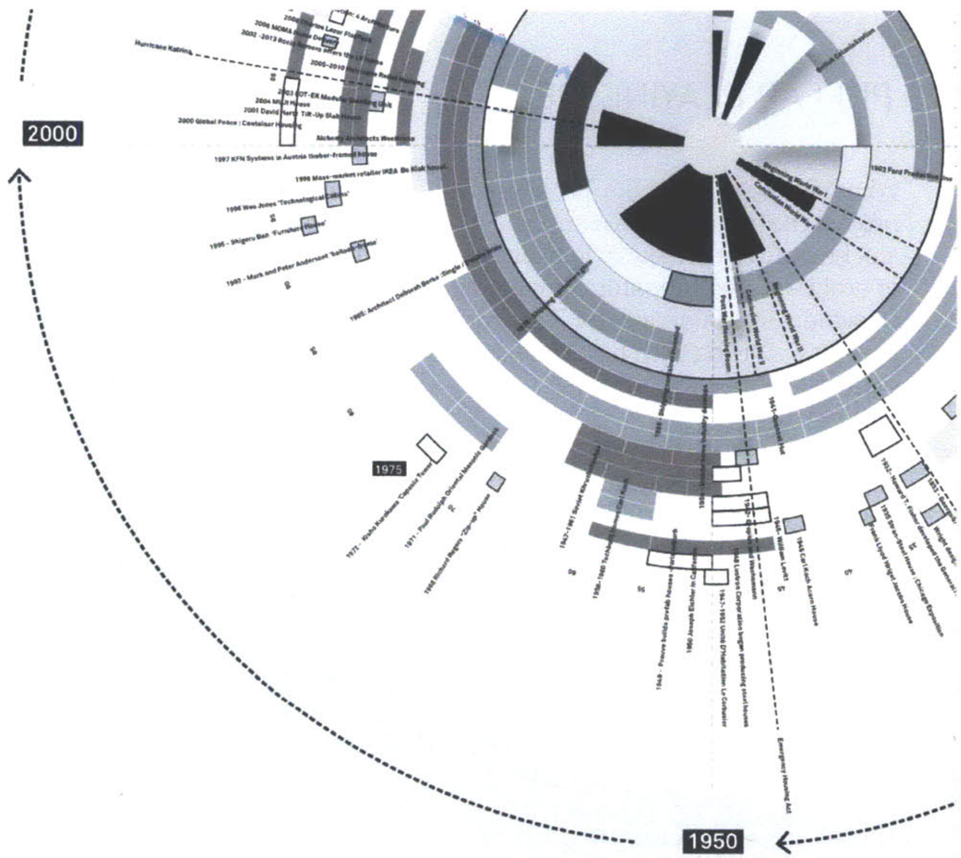
Figure 2: Radial timeline of prefabricated housing projects

PREFAB PLAYING FIELD

What is prefab? What kind of housing can be classified as being 'manufactured'?

Traditionally a project can be classified as being prefabricated when a significant portion of the project has been created within a factory(offsite), unlike conventional projects where the majority of the work takes place on site. There exist two primary streams of development in factory produced housing; one that emulates the automobile industry by producing 'complete buildings' in a variety of predetermined variations, the other is the production of discrete elements with and embedded assembly logic that allows for the structured recombination of parts and thus variability in the final house design.

With onsite fabrication and construction, workers must rely on transportable low precision tools in unpredictable environments. This delays construction and lowers project quality. Working within a factory setting holds a number of advantages in the realms of, quality control, environmental predictability, energy, and labor. A factory made home arrives on site as a series of well calibrated parts that are quickly assembled, not constructed. With factory produced projects the amount of time required on site is very short compared to conventional projects.



PREFAB PLAYING FIELD

When a designer works on a prefabricated housing project the implications extend beyond that of the typical house. The project is less about designing a piece of architecture but instead imagining a mode of living. Designers like Buckminster Fuller proposed a radically new way of living with his Dymaxion house, painting a picture of a modern future.

Walter Groupius disagreed with the mass production of "total" design solutions like the Dymaxion house because it "imposed unity which excludes free choice and personal preference." forcing the occupants to fit into a single "model" of living.

Technical innovations and projects of prefabrication go hand in hand, whether they are material, mechanism, or geometric. The addition of mass manufacturing, and thus mass occupation, has implications well beyond that of a singular project.

These projects were never produced in bulk but demonstrate how prefabrication processes punctuate architectural history as a nexus of technology, economics, and demographics. Each projecting a possible future, speculating on not only architecture but the larger contextual forces of the time.

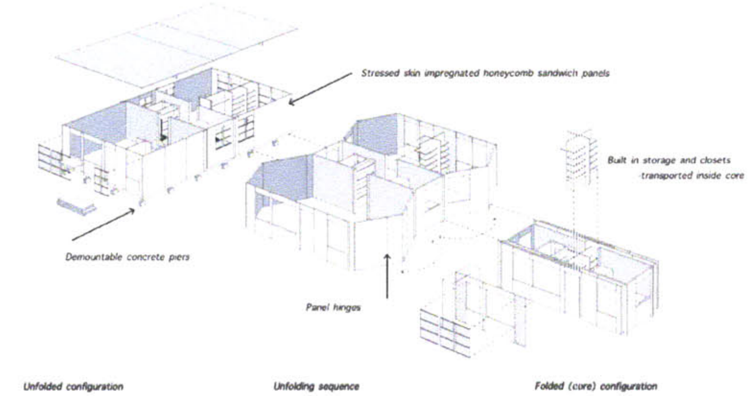


Figure 3

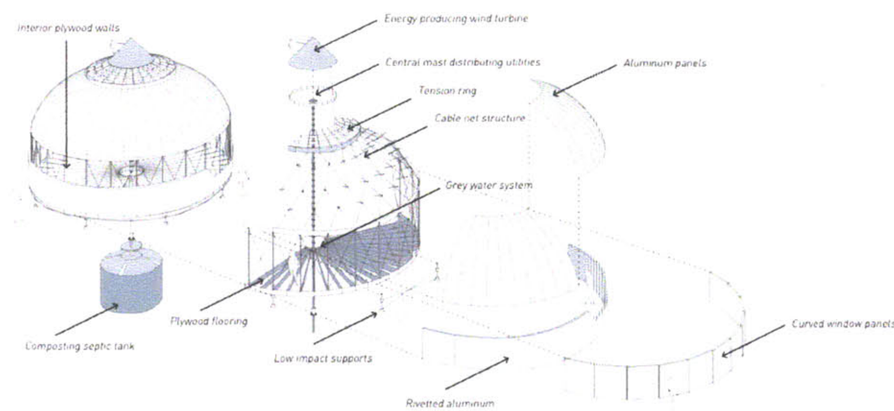


Figure 4

Figure 3, Figure 4: Exploded axonometric drawings of Carl Koch's "Acorn House" and Buckminster Fuller's "Dymaxion Home"

Sears Roebuck and Aladdin Homes both offered mail order kit homes. Here each part was labeled and stamped with a symbol denoting it's corresponding position. Aladdin Homes gained much of their success through relations with large companies that often needed to build entire towns to support business pursuits in an under developed area. The Kit homes were quick to assemble, inexpensive, and readily available.

The Aladdin homes vary little in construction from other houses produced during that time, the only difference being the way in which the parts were produced and delivered. Aladdin Homes were in business from 1906-1987 selling over 75,000 homes in over 400 different configurations including some customer designed. These custom homes are the first example of industrially produced custom housing, options were limited, but they possessed a level variability none the less.

The Lustron Home was an attempt to accommodate returning GIs post WWII. Composed entirely of metal and enameled steel the Lustron homes were a departure from prefabrication projects of the time, mainly stick built houses like those sold by Aladdin homes and Sears and Roebuck.

The Lustron project took advantage of the metal processing plants setup for the war effort, fully equipped to manufacture sheet metal goods. The Lustron Home is based around a steel skeleton frame that are factory welded with pressed metal panels assembled on site. The Lustron corporation was heavily subsidized by the Federal Housing Authority promising 10,000 homes per year. A one million square foot factory was setup with +53 million dollars from the Federal Government. The factory

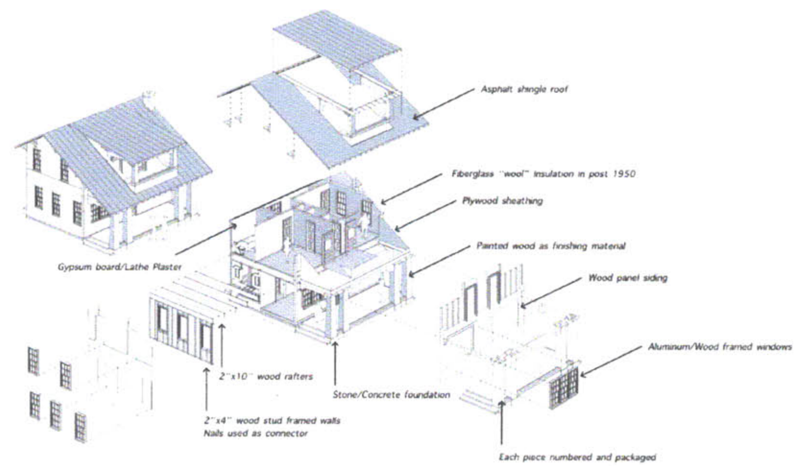


Figure 5

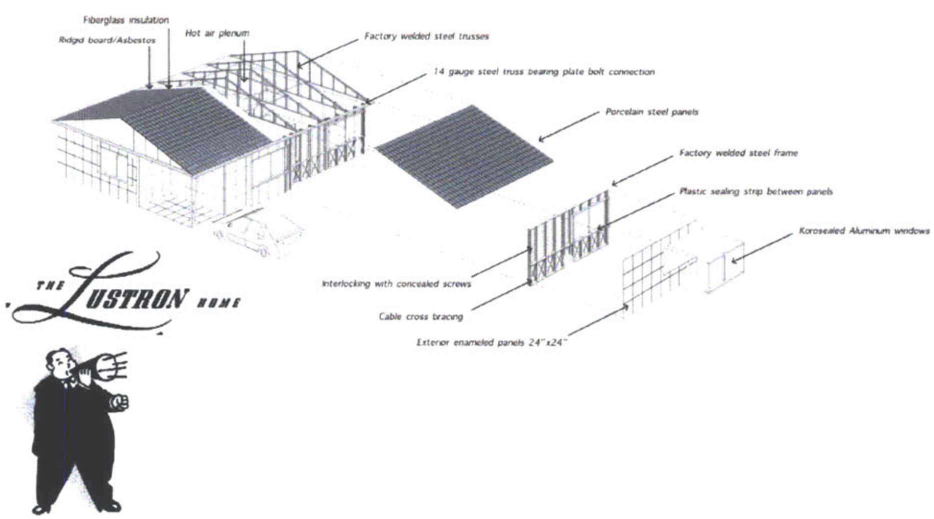


Figure 6

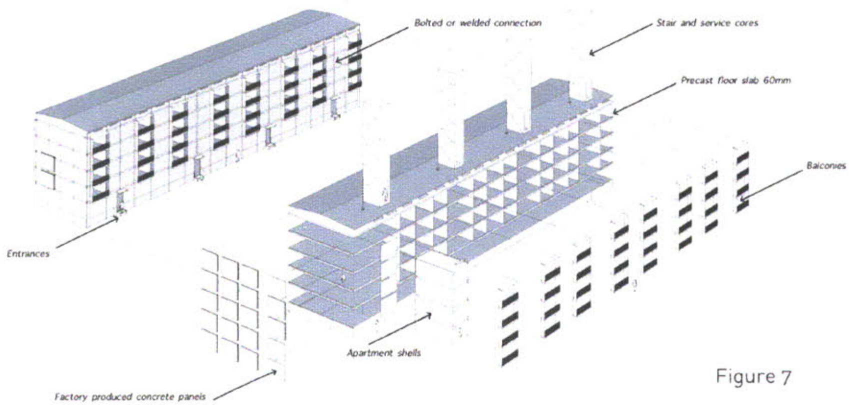


Figure 7

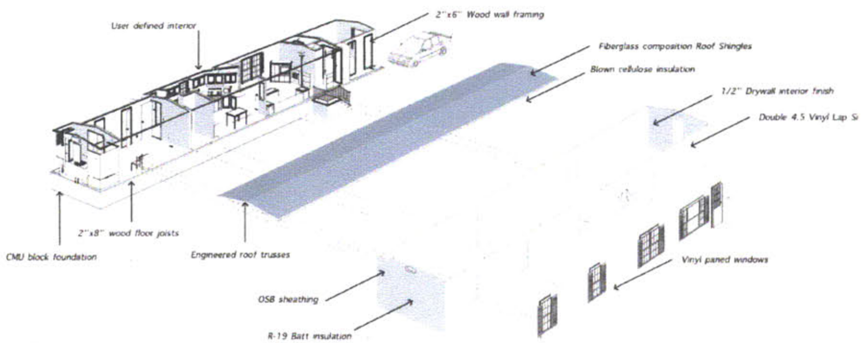


Figure8

housed 8 miles of automated conveyors, 163 presses, 11 enameling furnaces with an army of laborers. Due to an overly complex design and an elaborate delivery system only 2,680 homes were created in total before the company went bankrupt.

During the 1960's the Eastern Bloc was desperately short on housing. This housing crisis prompted governmental action in the form of mass produced precast concrete housing blocks. The housing units were 5 story buildings composed of precast concrete panels, lifted into place with a crane and bolted into place. The system of erection was extremely quick and between the years of 1961 and 1967 over 3,000,000 square meters of residential space was created with this method. Khrushchovkas are ubiquitous in the former Soviet Union, providing housing for vast populations. Even though they were designed to only have a life span of 20 years they are still the primary housing model to this day.

Mobile homes became prevalent during the mid 1950's and have gained steadily in popularity through the years. Designed within the restrictions of transportability their long thin plan is based around a caravan typology. The majority of mobile homes are produced entirely within a factory and although mobile, are never moved through their lifetime.

Figure 5: Alladin precut home exploded axon
Figure 6: Lustron house exploded axon
Figure 7: Soviet Khrushchovkas exploded Axon
Figure 8: Standard mobile home exploded Axon

SECTION 1.02

Influence of standardization

Image: artist rendition of Levvittown

Notes on mass production

"Industrialization of the housing process inevitably means standardization; we should not resist this, for standards are the norms of a civilized community and give it unity of expression. However, we must not forget that individual needs and desires vary, and within the limits of social consensus man must be given choice.

Man and his world are not static but in a stage of dynamic flux, and the dwelling produced by industry must be adaptable and responsive to demands for change and growth. Industrialized housing must therefore be designed for maximum utility, standardization, and interchangeability of the parts and maximum variability of the whole, the house as final product.

This industrialized building system moreover is not and end in itself but an integrated part of a larger whole, one level in a hierarchical environmental-social-economic system. "

Walter Gropius

A contributing factor to the low popularity of mass produced housing is inflexibility. Designs become standardized as a result of industrialized production, eventually leading to monotony. The inability of large scale interventions to demonstrate individuality of the occupants leads to alienation and "a loss of personal identity" (John Habraken).

Design flexibility within an industrialized manufacturing processes is difficult for a number of factors but it is informative when compared with the manufacturing practice of 'Kaizen' and lean manufacturing. The Japanese term Kaizen literally means "Change for the better" or continuous improvement. Kaizen is still a popular manufacturing methodology born in post WWII Japan based around rigorous optimization. The successful implementation of Kaizen leads to a highly efficient factory with continuously increasing productivity, but this comes at the cost of flexibility. If a design was to change under Kaizen all the gathered metrics of optimization become obsolete.

> "Low mass customization capability is associated either with mass production, where operational performance is preserved but products are standardized, or with custom manufacturing, where products are individualized, but operational performance deteriorates (Duray 2002, Squire et al. 2006).

TYPICAL MANUFACTURING SCHEME

Figure 10: Typical production schedule for 'Made to forecast' products

Production and personalization

In a typical manufacturing scheme for 'made to forecast' products market research drives the design and production strategies. As shown in Figure 10, the design phase is foundational for the process of mass production. Any change to the design disrupts the following processes, making customization logistically and financially impossible.

The Levittown "Same home, varied decor" competition of 1952 demonstrates a technique for eliminating the dreaded monotony often associated with mass produced housing. The competition demonstrates to the larger public that even though the homes are identical, they are still personal and individual to the occupant through interior decoration. By passing the responsibility of personalization to the consumer, the production strategy of the Levitt Brothers was not disrupted.

Similar to the kit houses that proceeded Levittown and the products available from Alladin homes and Sears and Roebuck at the time, the Levittown homes were often constructed by the occupants. Neighborhoods came together to lend a hand during the construction process, further simplifying the production schedule of Levitt products.

Figure 11-13: Levittown "Same home, varied decor" competition. Life Magazine 1952

Design integrated production

The design strategy deployed by Charles and Ray Eames is exemplary of their knowledge of mass production and it's effect on design. While still a 'Made to Forecast' model, the Eames design process integrated consumer data, manufacturing standards, and distribution metrics to fluidly deliver products. The result of this integration was a mass produced product that retained high levels of design intent.

The trouble with this approach when related to housing is the number of assumptions being made and the duration for which those assumptions must remain true. The lifecycle of a product is drastically different than a housing project, which makes "an understanding of family behavior" infinitely more complex over time. Incorrect or outdated assumptions about the consumer are the crux of many prefab projects.

Currently consumers are only indirectly involved in the production of prefabricated housing, through market research and statistical analysis. This provides a static generalized picture of the consumer. This one size fits all approach produces an averaged result that at best only partially satisfies the needs and desires of the consumer. This phenomenon is illustrated in the Eames' furniture 'design to production' diagram. The strategy of research, design, produce, and distribute is fundamentally incapable for providing tailored products. An 'Open loop' strategy such as the Eames' is only proficient if the initial assumptions perfectly reflect

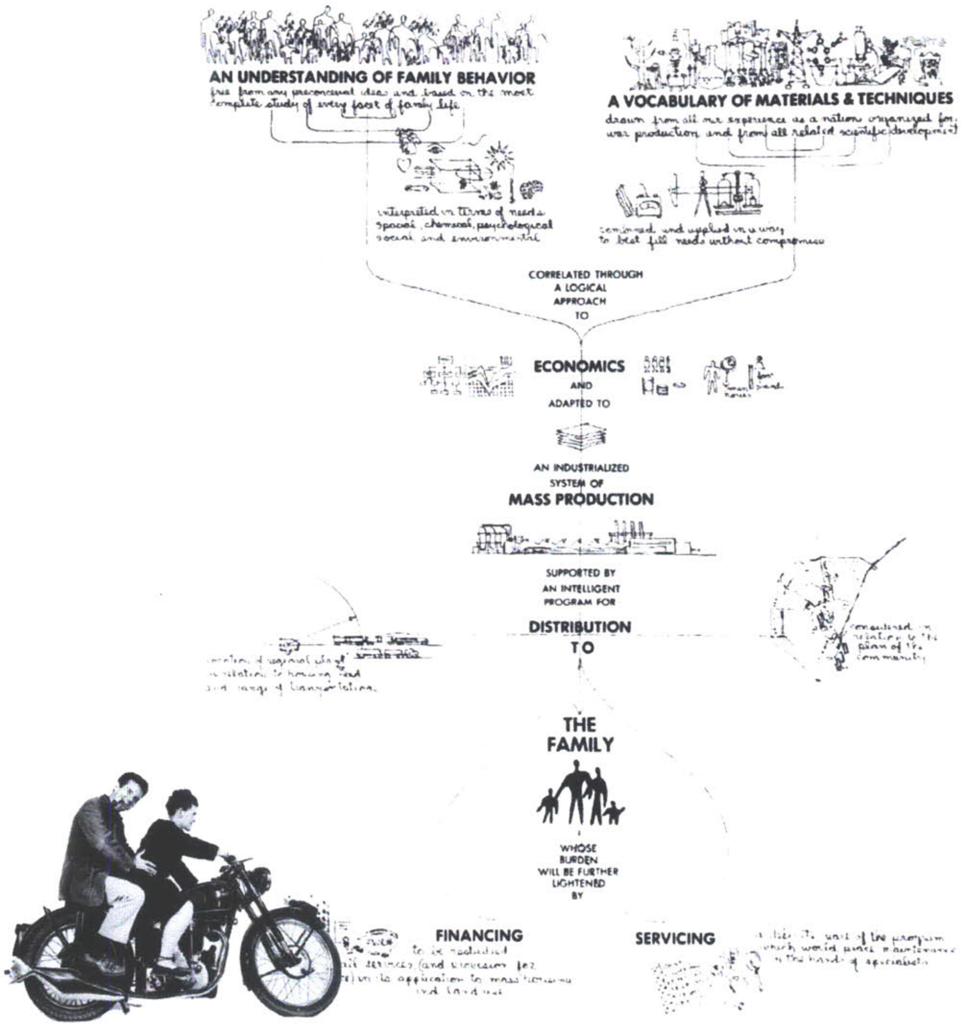


Figure 14 : Eames diagram explaining the role of family in mass production

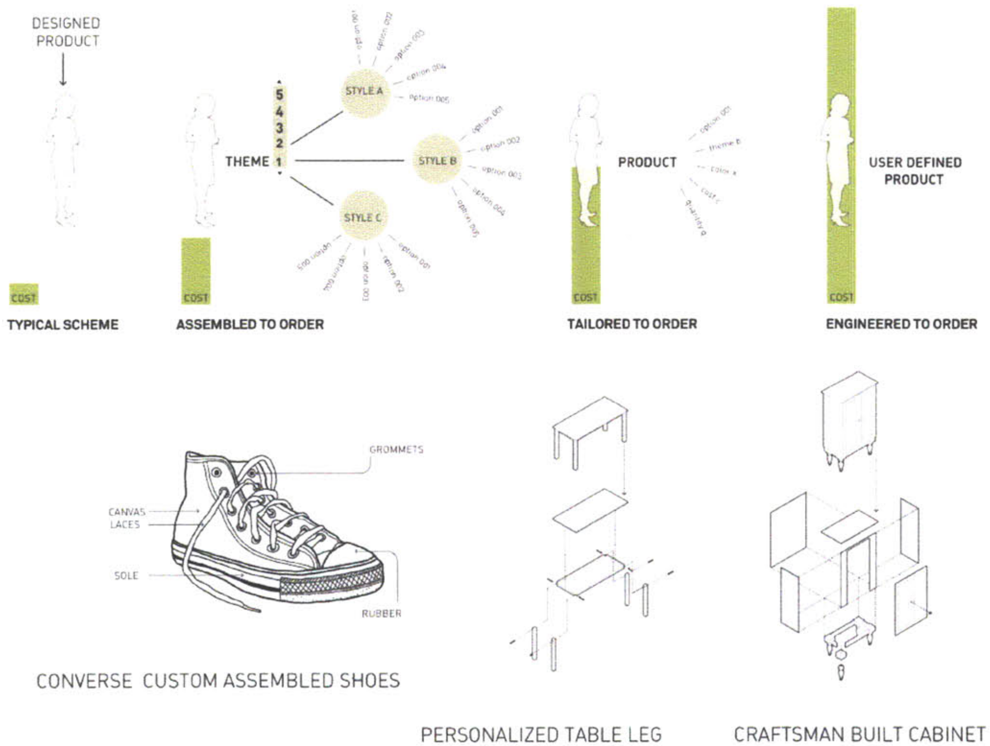


Figure 15 : Production diagrams for 'assembled to order' 'tailored to order' and 'engineered to order'

the conditions at the end of the cycle. The advantage of a closed loop system is 'feedback' where the initial state is informed by the end condition at a specified frequency, a common technique in computing.

This disconnect between consumer and mass produced design often leads to highly specific and engineered solution to a problem that no one has.

Looking through alternative product delivery schemes that better integrate users and provide variation is informative in avoiding a universal housing model that under-serves.

Production model comparison

There exist a number of different production models that allow for personalization and customization, each with their own benefits and ailments. Figure 15 illustrates the amount of personalization possible with 3 differing production schemes and the relative costs.

Custom assembled products such as shoes are increasingly more popular due to advancements in automation and digital communication possibilities.

With a rise in DIY CNC facilities ‘tailored to order’ products that utilize online interfaces to alter the production process are more and more feasible. An example of this strategy is personalized etching where a user chooses letters or phrasing to be etched onto an object via an online application. The capabilities of the machine accomplishing the personalization are accounted for and bracketed by the online user interface.

Engineered to order products are uniquely designed, manufactured, and delivered, making this process typically the most expensive and only used for small production volumes. These goods also hold the largest potential for originality.

Figure 16 communicates a production strategy where the consumer accomplishes the final level of production themselves, configuring it to suit their preference. Here the designer delivers the product “unfinished” but with design potential embedded in the product.

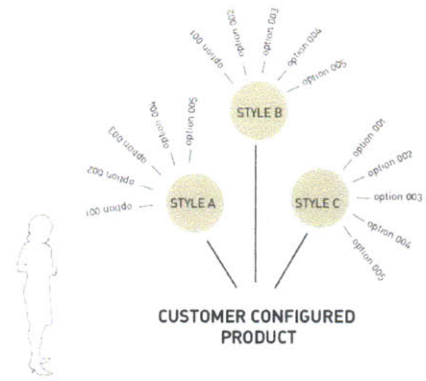


Figure 16

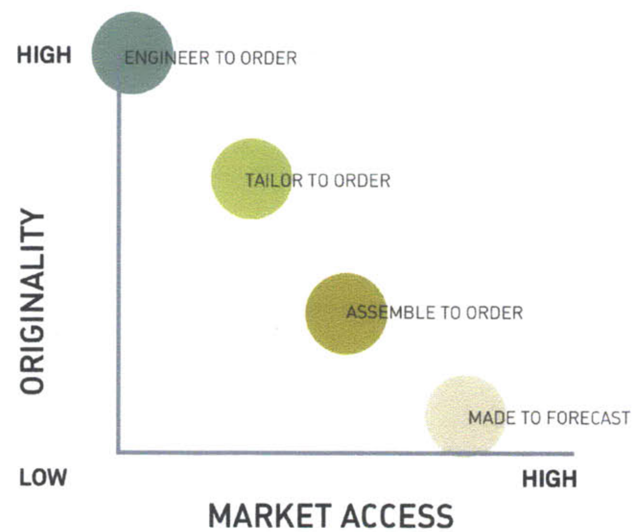


Figure 17

Figure 16: Customer configured product production scheme
Figure 17: Market access vs originality of typical production schemes

SECTION 1.03
Pre-configured flexibility: Groupius and Wachsmann

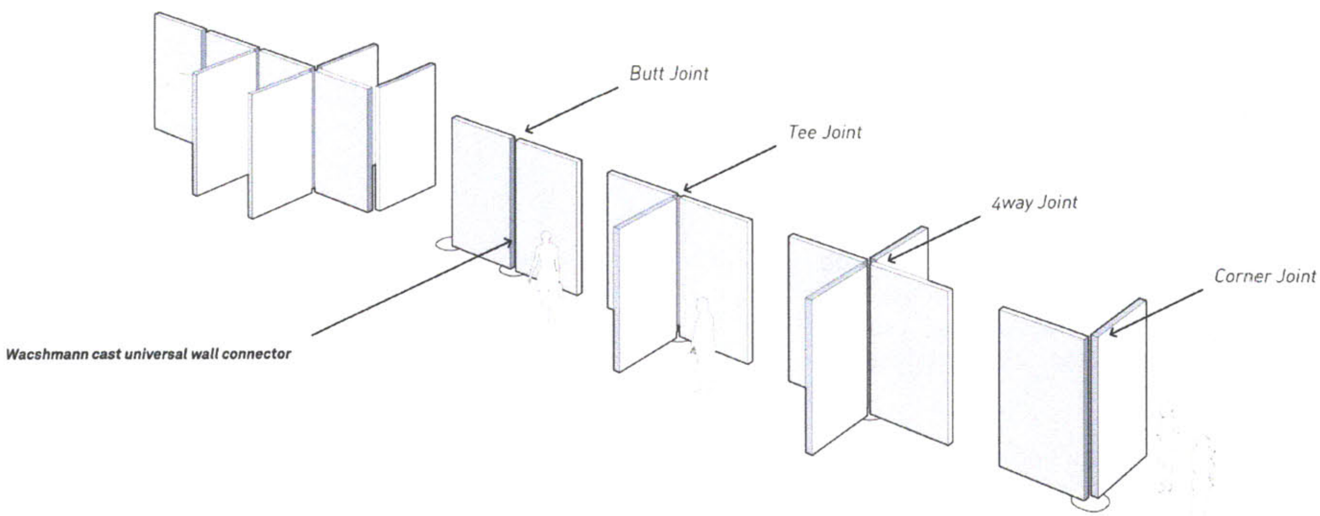


Figure 18: Wachsmann corner conditions "kit of parts"

Smart connection and module

Walter Gropius's hesitancy to create a "total solution" in the form of prefabricated housing is evident in his and Konrad Wachsmann's Packaged House design. The Packaged house is not so much of a house but instead a system of parts that can be reconfigured to form a family of houses based on an orthogonal grid. This model of project delivery most resembles the 'customer configured product" where the user works within the constraints of set by the designer to create a "personalized" solution.

The parts of the Packaged house system are wall panels each assigned a function and connected together with custom interlocking hardware.

The joint in the Packaged House was the only aspect deemed patentable. Wall panels and partitions had been seen in numerous projects but the means by which the panels celebrated the joint and subsequent seam was truly independent. If a project is going to celebrate flexibility in both configuration and function it must not be of monolithic construction, like that of the Khrushchovkas, it must be full of joints.

The Packaged House was designed on an orthogonal grid, meaning there could be 5 separate scenarios of connection outlined in Figure 18.

1. Butt Joint
2. Tee Joint

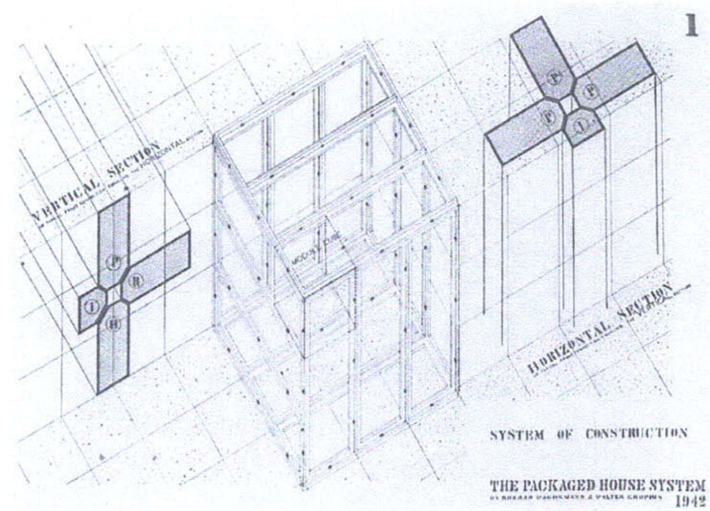
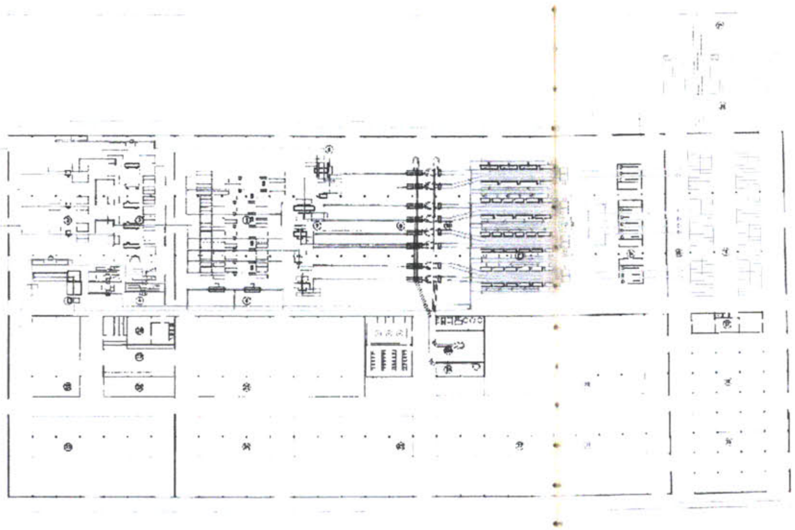


Figure 19

Figure 20

Figure 19: System of Construction. "The Turning Point of Building" Konrad Wachsmann
Figure 20: General Panel Corporation case study house. Harvard Museum Archive



230 A special truck transports all the prefabricated ... small one-family house, including built-in units and ... bathroom fixtures, to building sites within a radius ... 300 miles. The horizontal boom mounted to the rear of ... is used to place the individual groups of building ... strategic points around the site

229 Layout of the General Panel factory

1 Automatic plywood panel cutter
2 Rip and pendulum saws
3 High-speed matchers and molders
4 Plywood cutters for special sizes
5 High-frequency gluing of frame sections
6 Router for electrical receptacles and other ... plywood
7 Automatic chain-cutter slotting machines
8 End profiler
9 Automatic machines for inserting metal ... into slots
9a Store for metal parts
10 Micrometric, double-action coating machine ... ing synthetic adhesive
10a Preparation of synthetic adhesive
11 Jig tables with mechanical conveyer system
12 Central control station for the whole of the ... plant
13 High-frequency presses with generators
14 Automatic spraying installation and electric ... channels
15 The finished products pass through 8 small wall ... into the storage area
16 Small temporary storage area for floor, wall, ... roof panels and accessory elements
17 Staff office
18 Assembly of aluminum windows and doors
19 Store for built-in units
20 Store for raw materials; insulation
21 Production of standard installation units
22 Assembly of built-in units
23 Fabrication of built-in units
24 Store for raw materials; lumber
25 Store for raw materials; plywood
26 Packing materials
27 Repair shop and tool store
28 First aid
29 Track of loading crane
30 Loading platforms and siding

Figure 21: Factory Layout and panel delivery. "The Turning Point of Building" Konrad Wachsmann

3. 4way Joint
4. Corner Joint
5. End Condition "Cap"

The mechanism of connection in the Packages House was composed of 8 pieces of cast steel that interlock to form a tight hidden latch. The four interior parts are inlayed into the trimmed ends and oriented orthogonally to one another. Once the interlocking rings are assembled 4 securing pins are inserted to eliminate any chance of separation.

The General Panel Corporation had goals to mass produce the panels and panel connectors inside of a highly optimized production facility that was capable of producing a highly diverse product without hindering the production cycle.

Timing for GPC was unfortunate and the project missed out on Federal funding and thus was never widely implemented and tested. The project questions the roles of architect and occupant, blurring where and by whom design decisions are made. Determining the constraints and freedoms of a consumer driven housing model is of primary concern and discussed more thoroughly in later sections.

SECTION 000

Unfettered flexibility and how to orchestrate reconfiguration: Torre David

Figure 22: Torre David informal vertical community. Photograph by Iwan Bann

Balance of (design)power

A consumer configured production scheme splits design responsibility between architect and occupant. This requires special consideration in order to ensure success during user customization. If the system is over constrained the outcome is predetermined and the occupant does not feel the product is truly personal to them.

The informal vertical settlement Torre David in Caracas is an extreme example of an occupant configured architectural project. The original structure was never intended for personalization and thus contained no embedded design intent like that exhibited in the Packaged House. If occupants assume total control of the configuration and reconfiguration of an architecture, variation and flexibility are very much apparent, but at the cost of safety, quality, and spatial congruency.

While much of the Torre David is unarchitectural or even anti-architecture the diversity of space, use, and material are exemplary of a dissipated approach to architectural design that is highly responsive to use and context.

Is there a way to choreograph this diversity of use and invention architecturally? To provide a framework from which users can invent and personalize that eventually informs the larger architectural discourse and housing typology? A framework that catalyzes design and provides a truly customized housing model for the occupant is of primary concern of this thesis.

Figure 23

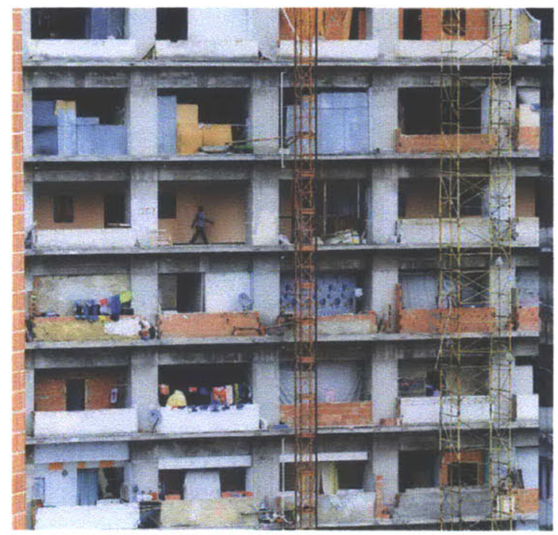


Figure 24

Figure 23-24: Torre David: Informal Vertical Community. Photograph by Iwan Bann

PART TWO

A proposal

Tools, makers, and housing flexibility

SECTION 2.01

Prefabricating housing again.. this time it's going to be different

"Transformative change happens when industries democratize, when they're ripped from sole domain of companies, governments, and other institutions and handed over to regular folks.

We've seen this picture before: it's happens just before monolithic industries fragment in the face of countless small entrants, from the music industry to newspapers. Low barriers to entry and the crowd pours in.

That's the power of democratization: it puts tools in the hands of those who know best how to use them. WE all have our own needs, our own expertise, our own ideas. If we are all empowered to use tools to meet those needs, or modify them with our own ideas, we will collectively find the full range of what a tool can do. "

Chris Anderson "Makers: The New Industrial Revolution"

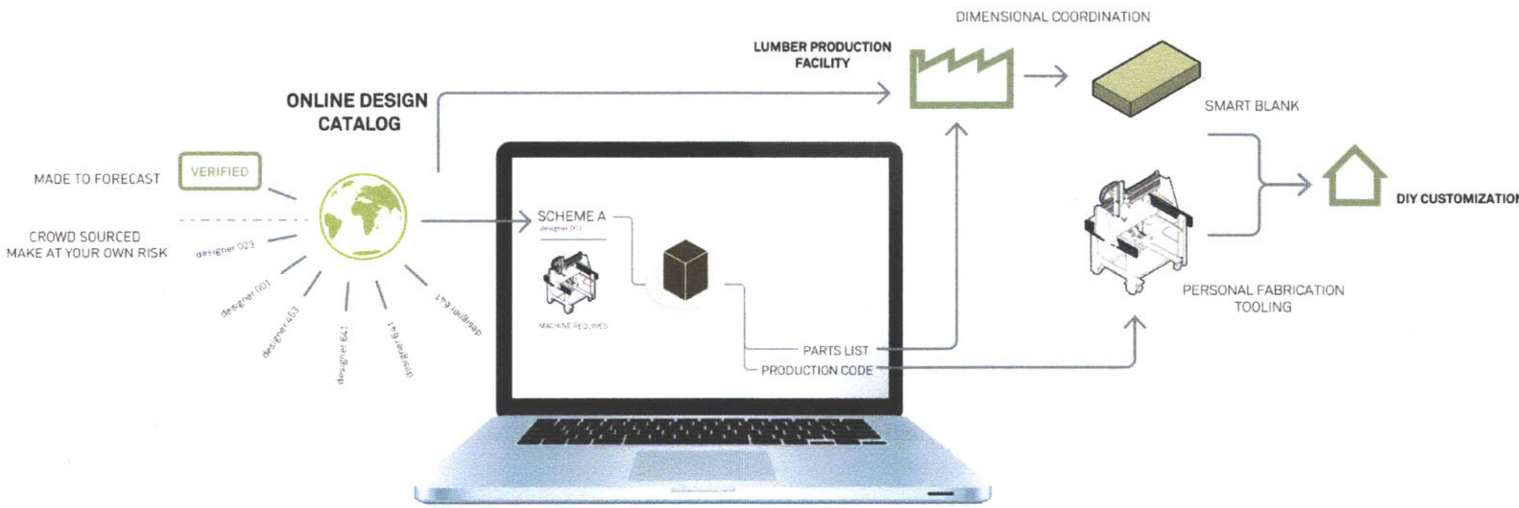


Figure 25: Proposed production sequence for DIY Manufactured housing

Globally produced, locally customized

The web has liberated an army of designers primarily in the realm of product design and fashion with platforms like Etsy. Architectural schools are fascinated with the idea of digital fabrication and "Fablabs" as a means of regaining creative control, but few projects are scalable to create widespread change in the realm of conventional building.

With dispersed fabrication facilities like TechShop architectural designers can also take advantage of the web based design resurgence. If the architectural details are translated into machine code they can be distributed online and produced locally either within the home or at a makerspace.

Figure 25 describes a production sequence where industrially produced standard parts are customized onsite with digital fabrication tooling. This process is similar to other "customer configured" products discussed earlier but allows for much more sophisticated results.

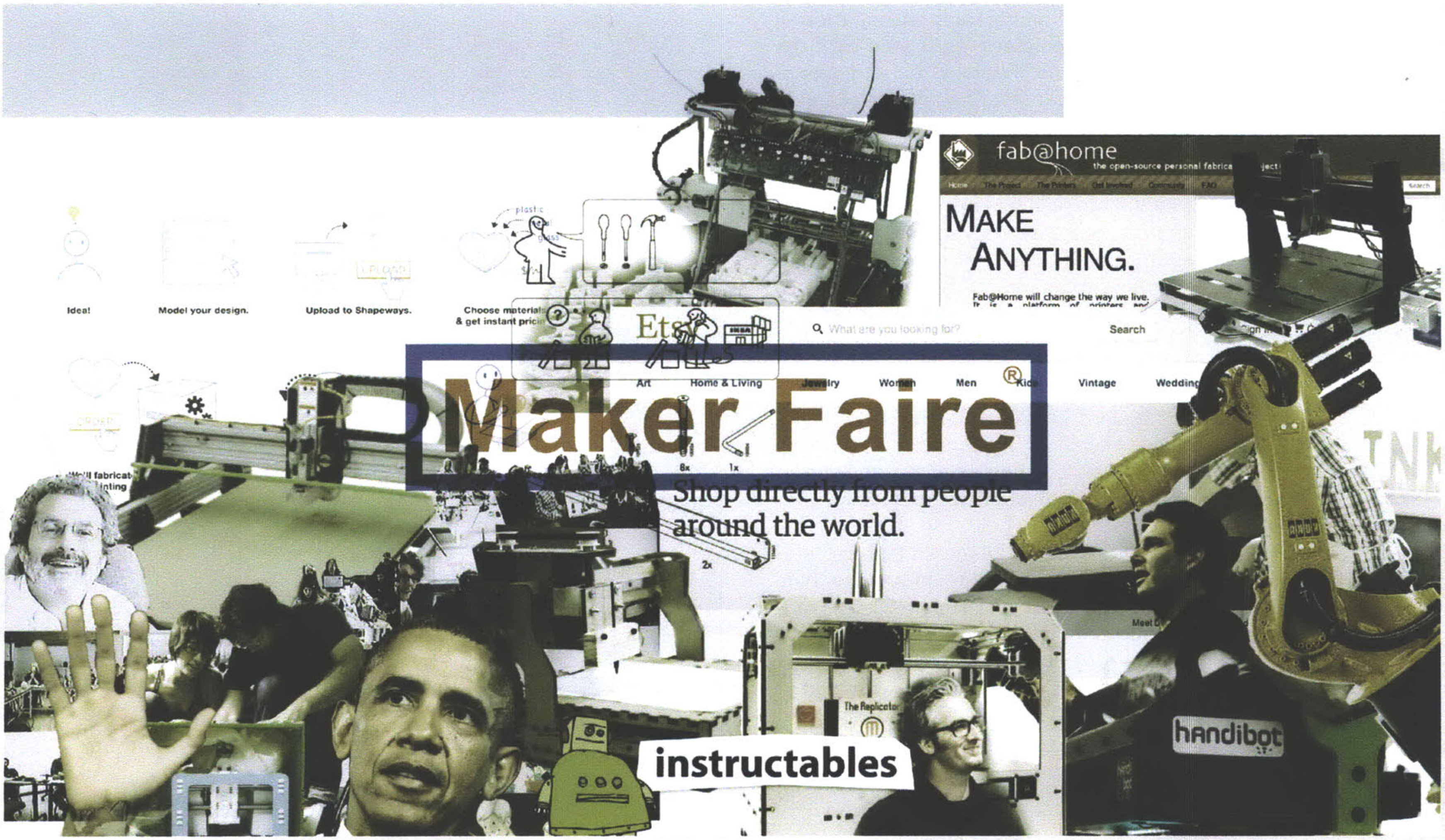
In this scenario architecture is commoditized and distributed online. Part lists can be obtained and machine code easily downloaded and executed onsite via DIY fabrication tools. This strategy not only liberates manufacturers of costly custom/flexible production but empowers a world of designers who's ideas can be delivered at the touch of a keystroke.

"It is easier to ship recipes than cakes and biscuits."

Economist John Maynard Keynes

SECTION 2.02

Makers and Machines that Make



DIY Manufactured home

A housing project capable of small scale custom fabrication contains the potential for a product that is both highly original (personalized by the occupant) and with high market access because it does not disrupt the larger production cycle.

The typical impediment of such a scheme would typically be the skill necessary to execute the final customization. For instance, a recipe is only valuable if the chef has the skill to execute it. With digital fabrication tooling this scenario is flipped. The fabrication machine provides the precision motion and the original designer embeds the machine code with the information about material, geometry, tolerance, and engineering. The occupant need only execute the file based on the designers specifications.

Embedded within this strategy is a synergy between housing and small scale production. This programmatic relationship will be discussed in later sections but holds the potential for a personal housing protocol with true flexibility. "A factory in every home" is not a means of replacing industrial practices, but it holds the potential for widespread experimentation while satisfying a market of one, and in turn re-informing the system as a whole.

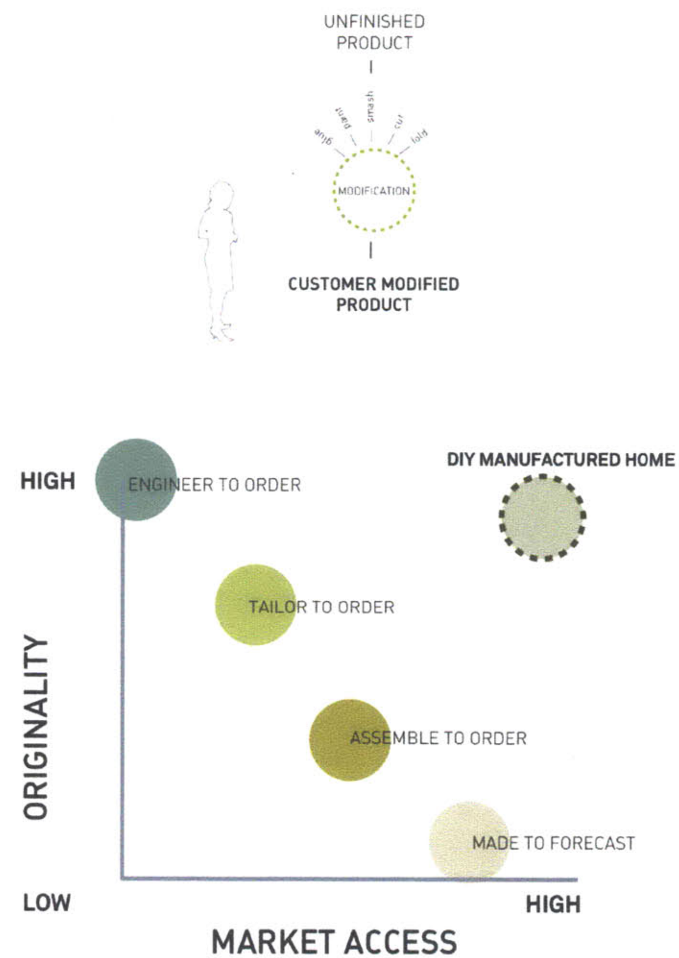


Figure 26

Figure 26: Diagram of the production sequence for DIY manufactured products

SECTION 2.03

Background info: A very brief history of digital fabrication

"Transformative change happens when industries democratize, when they're ripped from sole domain of companies, governments, and other institutions and handed over to regular folks.

We've seen this picture before: it's happens just before monolithic industries fragment in the face of countless small entrants, from the music industry to newspapers. Low barriers to entry and the crowd pours in.

That's the power of democratization: it puts tools in the hands of those who know best how to use them. WE all have our own needs, our own expertise, our own ideas. If we are all empowered to use tools to meet those needs, or modify them with our own ideas, we will collectively find the full range of what a tool can do."

Chris Anderson 'Makers: The New Industrial Revolution"

Numerically controlled tools

Since the invention of Computer Numerically Controlled machines in the mid 1950's a number of hurdles have halted their mass adoption by design professionals.

Machines such as the 1949 3 axis milling machine developed at MIT in conjunction with Parsons was sent instructions via punch card and transformed into move commands for the machine. This machine was remarkable because it could repeatedly move with precision typically demonstrated by only the most skilled of machinists.

The instructional punch cards were created on a machine much like a typewriter by a skilled technician. Like documents created on a typewriter, the content of these punch cards were either impossible or difficult to edit. Due to the difficulty in both creating and iterating through machine instructions these original CNC machines were primarily used for repetitive tasks that utilized the same set of instructions repetitively.

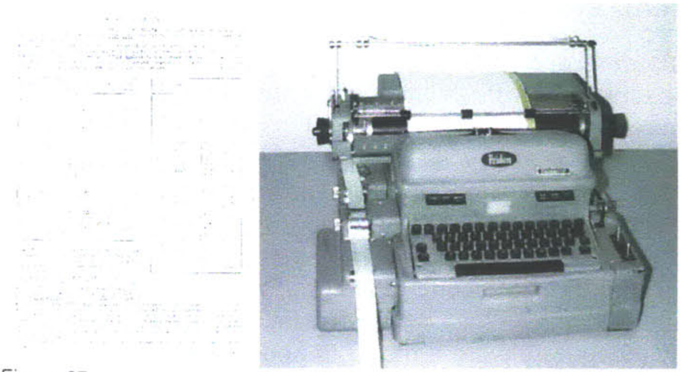
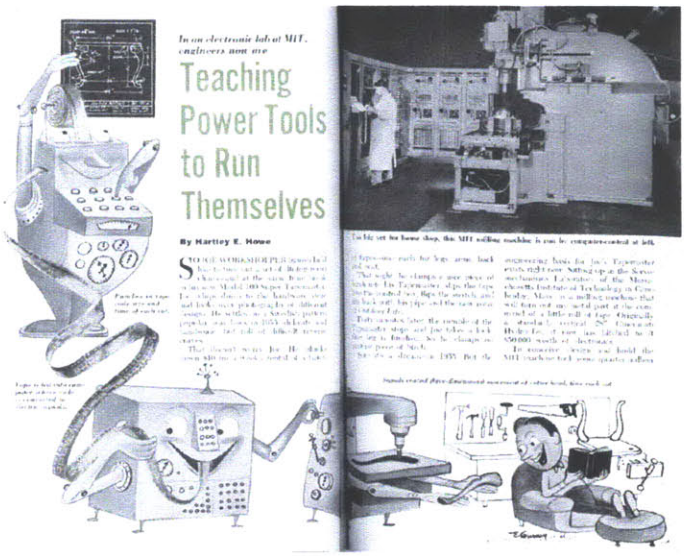


Figure 27



In an electronic lab at MIT, engineers now are

Teaching Power Tools to Run Themselves

By Hartley E. Howe

Figure 28

Figure 27: Flexowriter and punching code index
Figure 28: By Hartley E. Howe POPULAR SCIENCE, August 1955 Pages, 106,107,108,109, 222

Early CAD systems

As computers and software developed, later machines were no longer instructed via punch card, instead directions were input directly into a control computer adjacent to the fabrication machine. This transition shortened the production time by eliminating the arduous creation of punch cards and increased precision of the controlled apparatus. With instructions being created and delivered via computer, the emergence of computer aided design(-CAD) and manufacturing(CAM) software developed. Just as early computers were difficult to operate and implement, early CAD softwares were equally difficult and often times required a trained operator to perform tasks.

These early software and hardware packages were primarily purchased by large companies interested in optimized work-flows, increased production, or some other systematic advancement, not the average citizen or small company. One such reason for this exclusivity is the cost of such systems, an early CAD system and computer in 1970 were cost prohibitive to non affiliated persons.

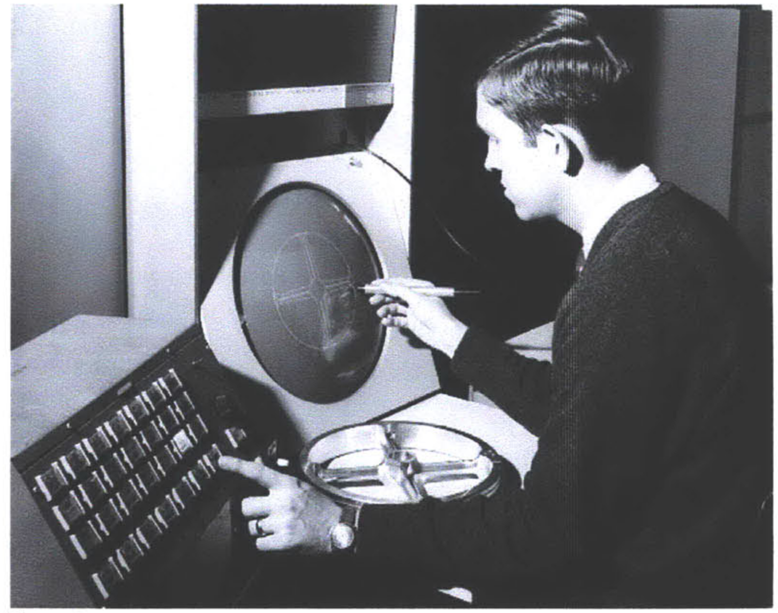


Figure 29

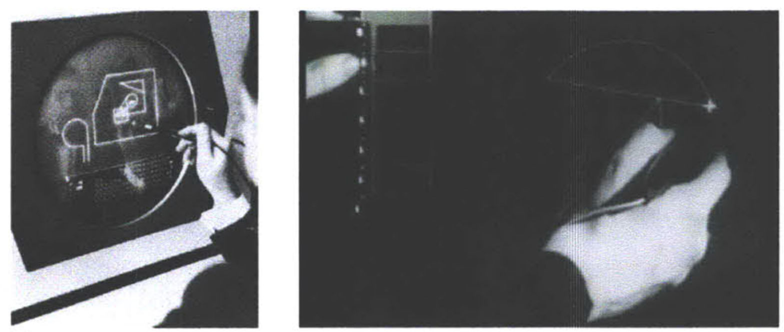


Figure 30

Figure 29-30: Early CAD systems. DEC Type 340 Display. SketchPad Ivan Sutherland Computer History Museum

CAD accessibility

Today CAD/CAM softwares have undergone rapid development and deployment. While high priced software packages geared toward large companies still exist, there is also a trend toward low cost or no cost (open-source) software aimed at extending the capabilities of the individual. Communities of makers gather around such packages, using online forums to discuss and distribute ideas and projects. While online forums, chatrooms, and other text based discussion platforms have existed since (1990s) the rapid sharing of digital representations(3d models) has only recently developed.

Websites that act as reservoirs of 3d models are of two primary varieties, one of production and one of representation. Sites the Google 3DWarehouse allow users to upload 3d models of nearly any object with the primary intention of visualization. Instructables, is one such community where participants create tutorials for the production of projects. Thingiverse is a similar online forum where members upload digital files and machine instructions for the creation of projects. An interested visitor from anywhere in the world with access to the internet can upload and download digital models of interest.

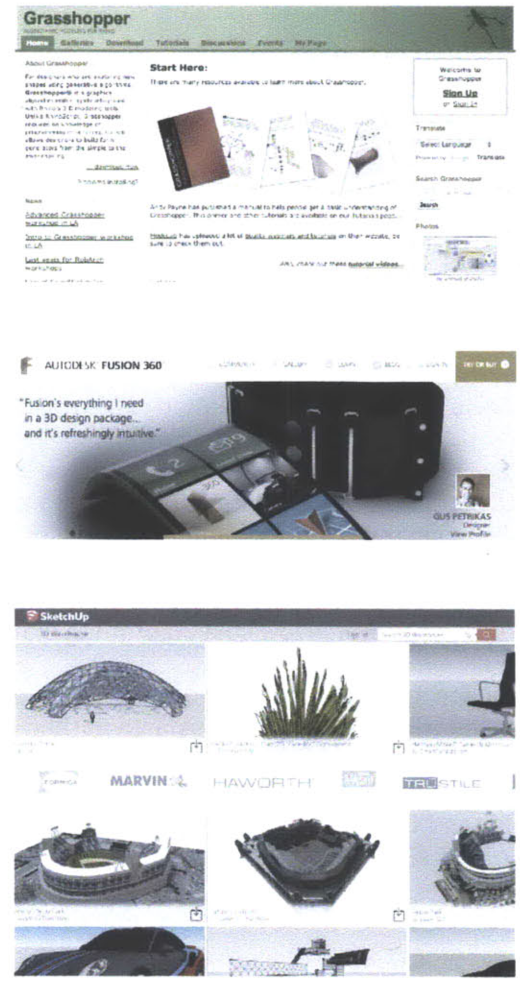


Figure 31

Figure 31: Example consumer CAD systems McNeel, Autodesk, Google Sketchup

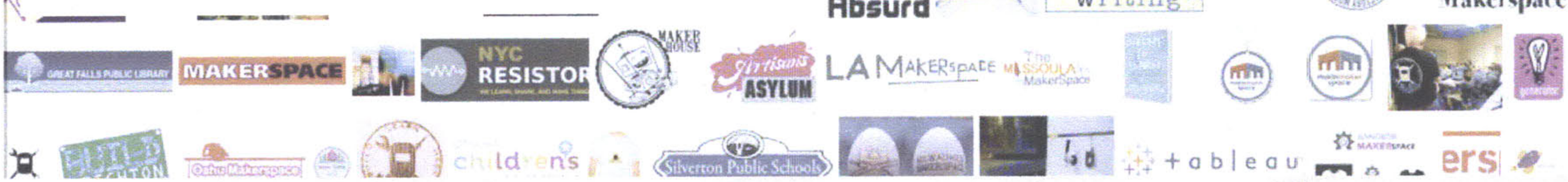
A world of makers

Digital fabrication tools and their accompanying softwares have made many objects less difficult to create, in turn multiplying the number of potential participants in the field of making.

Alongside the development of low cost digital design software packages is a hacker culture composed of engineers, designers, and craft enthusiasts interested in the physical production of objects. The combination of these movements has spawned a huge number of low cost hardware projects, most common being 3d printers, that allows for the physical creation of the digital models.

The New York Resistors is one such 'hacker community' that brought together enthusiasts from a number of disciplines including but not limited to; engineering, art, science, computer science, and electronics. One of the Resistors most notable contributions is the origins of the Makerbot Replicator, a low cost 3d printing platform.

Makerspace has become a ubiquitous term describing the spaces where making enthusiasts gather. Commercial ventures such as TechShop and the 3rdWard, as well as communities driven initiatives within libraries, schools, and community centers, aim to replicate such environments.



Makerspaces as a new typology

As online communities of 'makers' and tinkers develop as places of information and expertise exchange, physical spaces of making are multiplying. TechShop is a commercial enterprise that provides members access to digital fabrication tools and instructional classes on making.

The key difference between traditional workshops and maker spaces is the goal of production. In a factory/workshop the production goal is a common one, while in a makerspace production goals are diverse and ever changing. Projects begin, die, morph and advance based on the community of support. This non linear work-flow generates a seemingly chaotic environment that is inclusive and collaborative. Ideas and expertise are shared around common tables, discussed on whiteboards and projects consume every inch of open space.

A well equipped makerspace typically has a combination of analog and digital tools that ebb and flow with project interest. Spaces of gathering are essential for the production of collective design intelligence and the spreading and refining of ideas. The makerspace and flexible "hackspace" become crucial organizers of program and production in the design proposal described later.

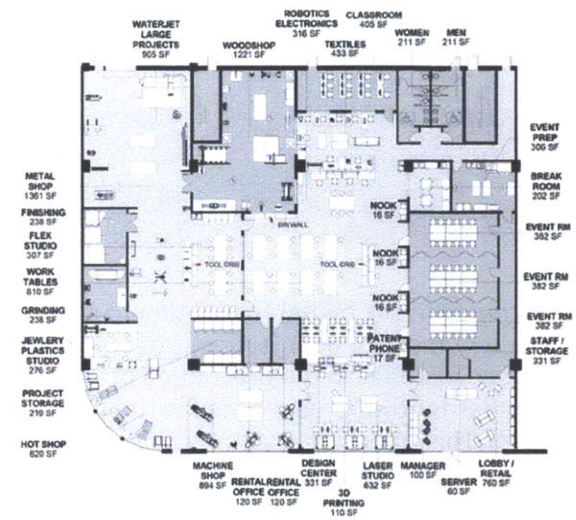


Figure 32

Figure 33

Figure 32: Plan layout of TechShop commercial makerspace
Figure 33: Image of community Makerspace/Hackerspace

SECTION 2.04

The maker revolution, designers and the shifting methods of making

The primary trends in DIY digital fabrication to date, have revolved around desktop milling and 3d printing, with a number of open source projects in existence. With the widespread interest in 3d printing came an increase in the production of their componentry, most notably precision stepper motors and other hardware associated with linear and rotational motion (like motors, bearings, guide rails, etc). This trend has encouraged marketplaces to sell more types machine building components at lower volumes with less lead time. Tapping into these burgeoning material streams generated by the production of consumer grade 3d printers like the Makerbot Replicator or Ultimaker, the potential exists for the development of a diversity of rapid prototyping machines.

These milling and printing projects, while different in their construction are, operate in very similar ways which closely resemble their industrial predecessors. If we are heading toward a time where there exists "a factory in every home" the means and methods of making should be rexamined. Industrial tools were created for high volume production, their replication makes little sense for low volume production possible in the home. The increased acessibility of machine building components creates the potential for production of personal fabrication machines and widespread experimentation.

The production goals of every in-home factory will differ, the fabrication tooling associated with this production should vary accordingly. The key benefit of a factory inside the home is customized production, fabrications machines must be equally as custom and personal.

Task specific machines

DIY fabrication tooling is utilized in a very different manner than industrial, task specific machines. Personal fabrication machines are created for personal production not mass production and thus it is inappropriate to design and evaluate DIY fabrication machines with the same metrics as task specific devices. Doing so stifles creativity and limits the potential for variation in use and configuration. It is time to blowup this one size fits all fabrication scheme (3d printing) for the creation of application specific tools with highly varied output.

Small volume, highly individual operations are the killer application for DIY fabrication machinery. As designers become more savvy in machine control and fabrication methods, a diversity of processes is sure to follow.

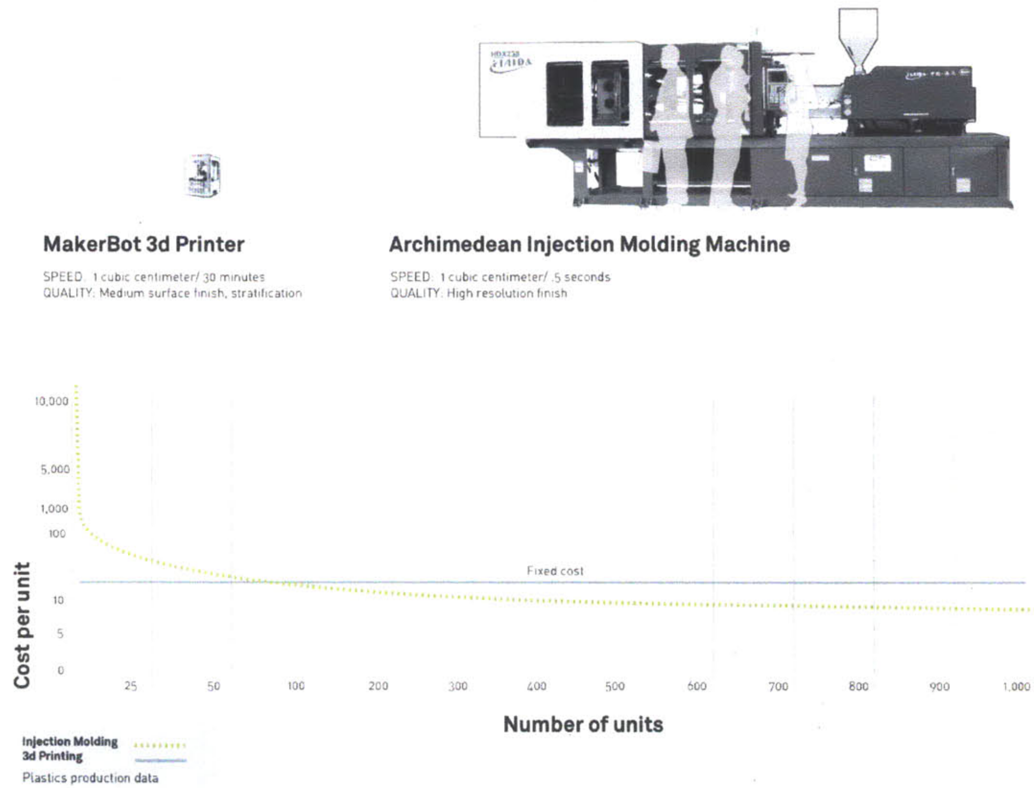


Figure 34

Figure 34: 3d printing vs injection molding diagram. Based on Chris Anderson's figure in "Makers:The New Industrial Revolution"

Machines that Make Project

As designers began experimenting with digital fabrication tools, their limits are tested and machines are adapted to suit these new desires. Regardless of the fluidity between consumer request and machine alteration there fundamentally exists a limit to creative development. A designer is constrained by the tooling they are presented and often design according to the limitations of their production equipment. I would like to argue that if the barrier of entry of machine design were lowered, designers creative potential would be expanded through the creation of bespoke fabrication tooling. Digital fabrication machines would become fluid parts of the design process instead of merely output machines with accepted limitations.

This principle of personal fabrication tooling is demonstrated in the 'Machines that Make' project within The Center for Bits and Atoms at MIT. A diversity of fabrication machines have been created within this project, each filling niche fabrication demands. Here the user, designer, engineer, and customer are one in the same, merging product and process. These projects target new means and methods of making via digital fabrication that are highly personal and diverse.

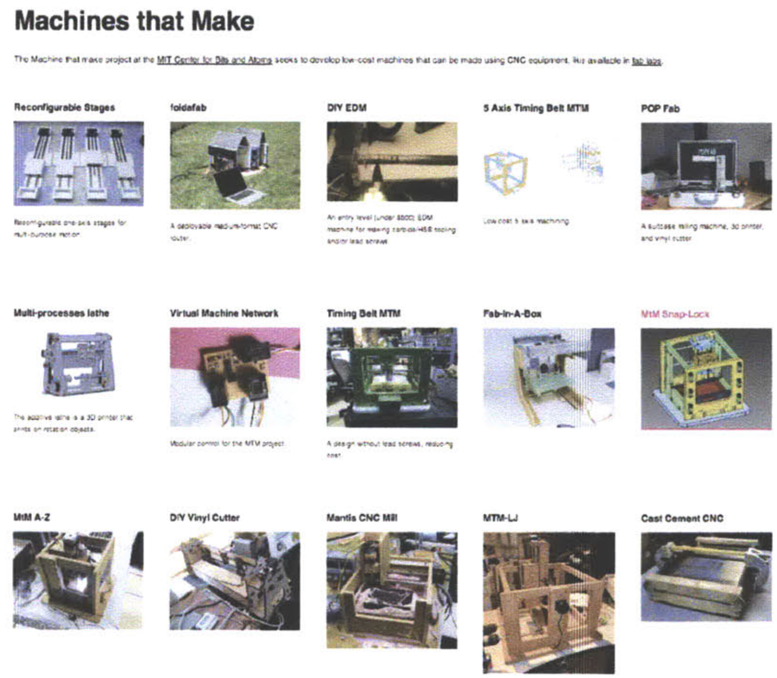


Figure 35

Figure 35: Machines that Make (MTM) project website. The Center for Bits and Atoms

SECTION 2.05

A strategic union: Makerspace and housing

The housing tower: limits and potentials

The production strategies for DIY manufactured housing described in earlier sections depend on the ability to complete the final production of goods onsite and in turn customize the product to the occupant's desires.

The combination of production facilities and housing have traditionally been fraught with problems. Quality of environment and living space are typically undermined by the proximity to production facilities. The union of such disparate programs requires special care and consideration.

The scale of operations is of primary concern. Like the makerspaces discussed earlier, high production cannot be the goal of any hybrid design. A joint fabrication and living facility must be based around highly unique, small volume production that is community driven. Facilities must be limited in order to bracket the scale of production.

A tower typology provides not only a quantity of square footage to validate non residential programs but also provides a redundancy in structure capable of transformation. The following precedent studies evaluate the circulatory, programmatic, flexibility and structural characteristics of three housing projects and speculate on potential for transformation.

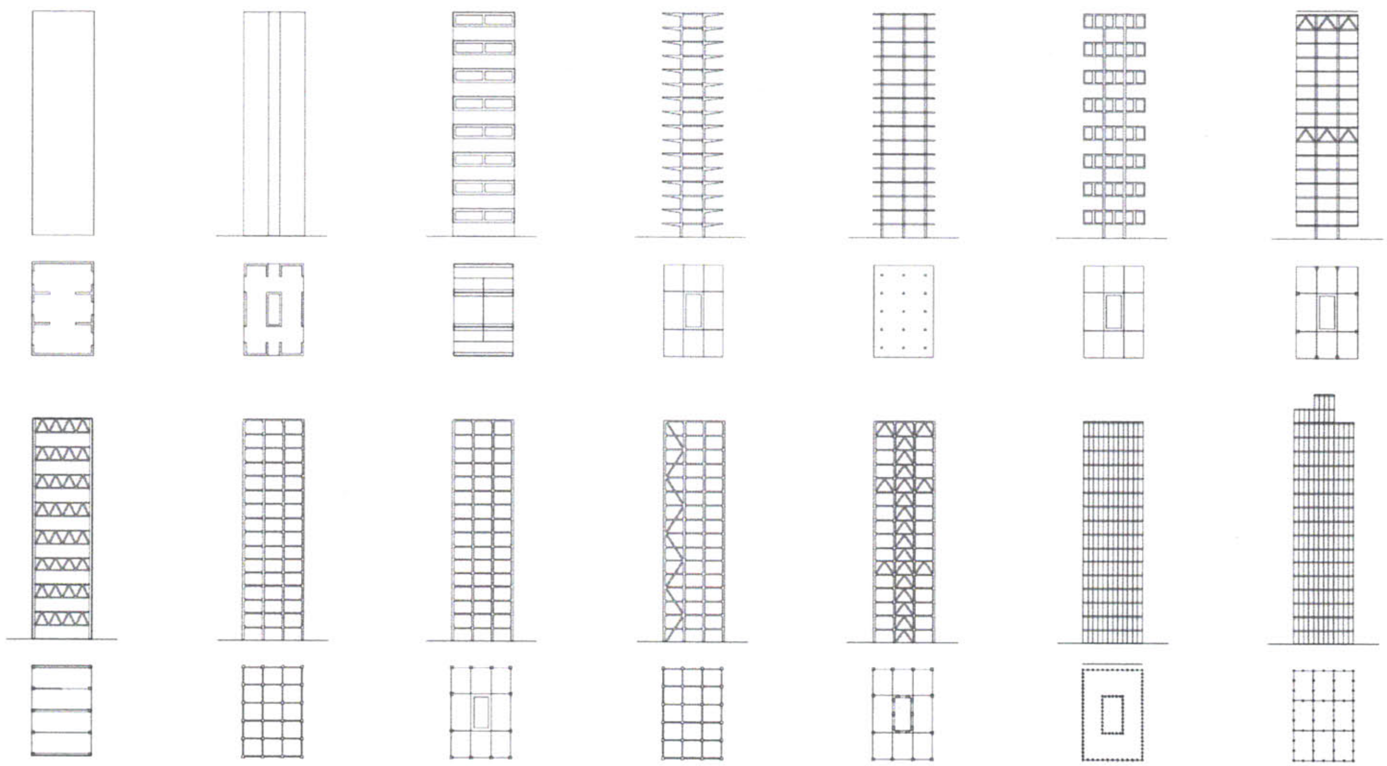
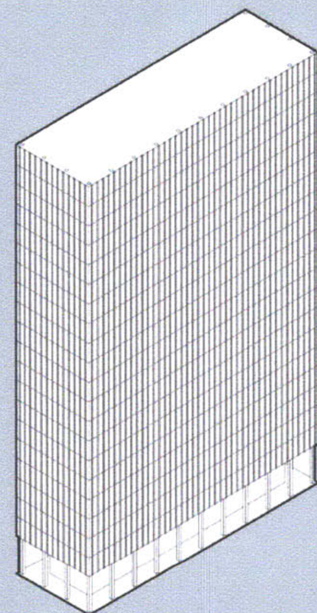
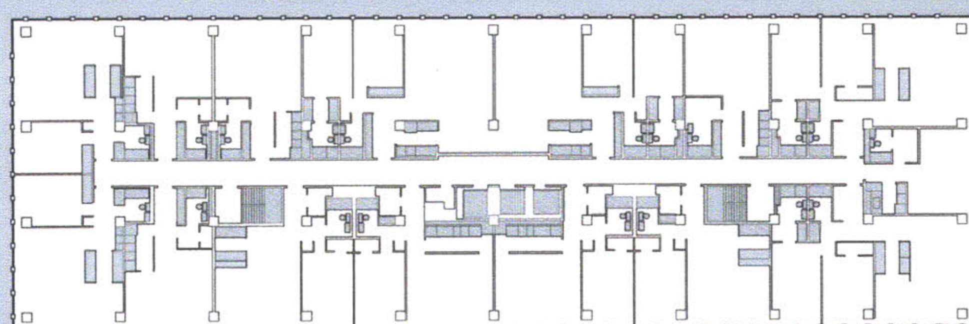


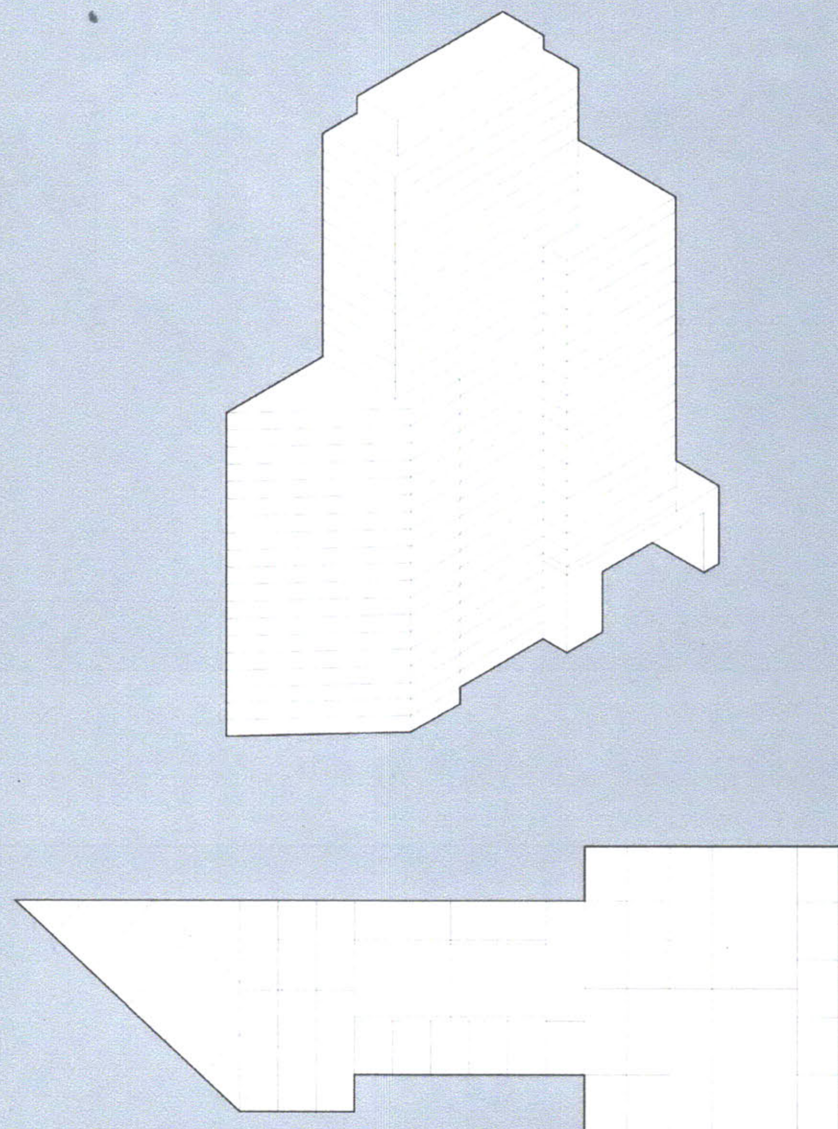
Figure 35

Figure 35: Standard tower structural schemes. Based on the diagram of Schueller in "High Rise Buidling Structures"

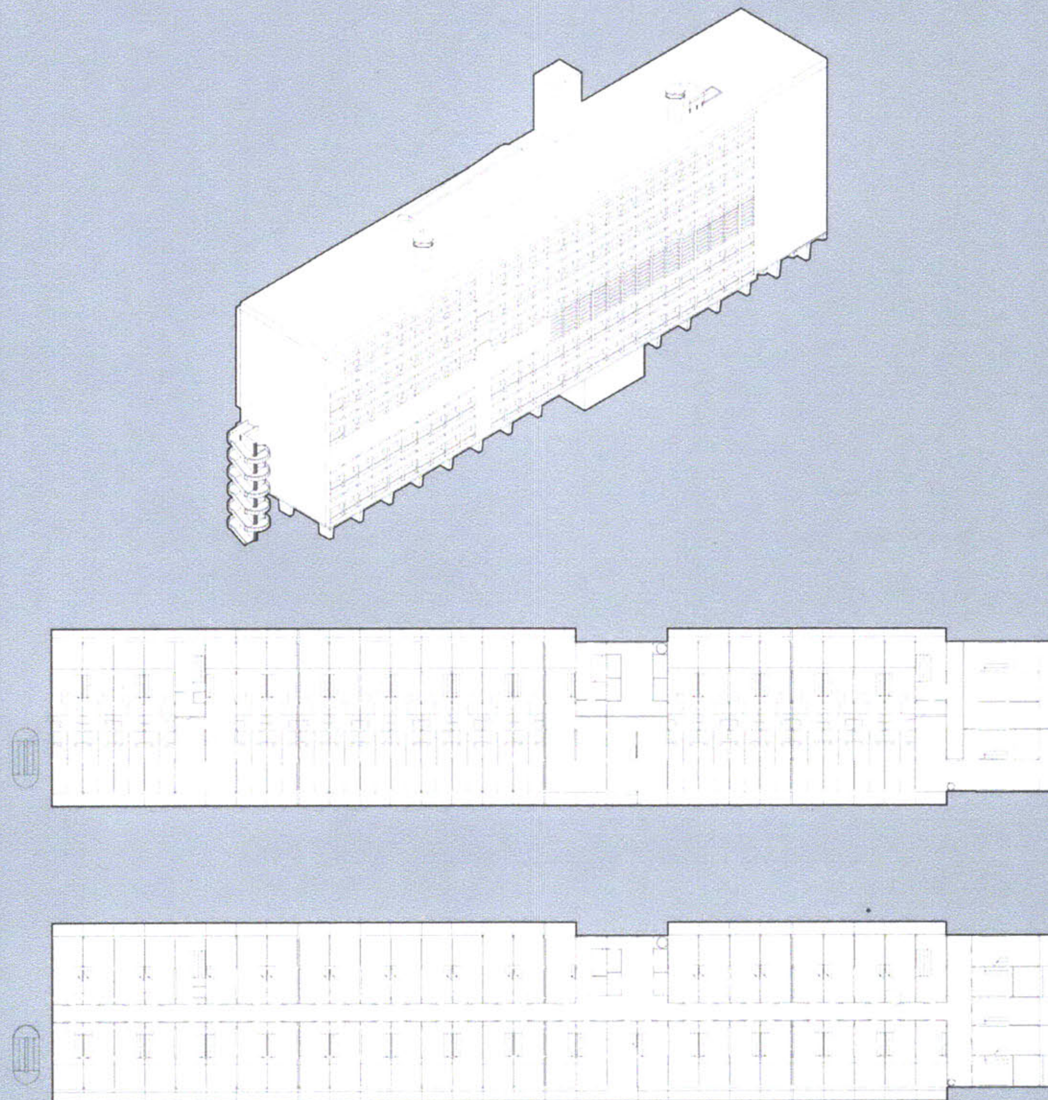




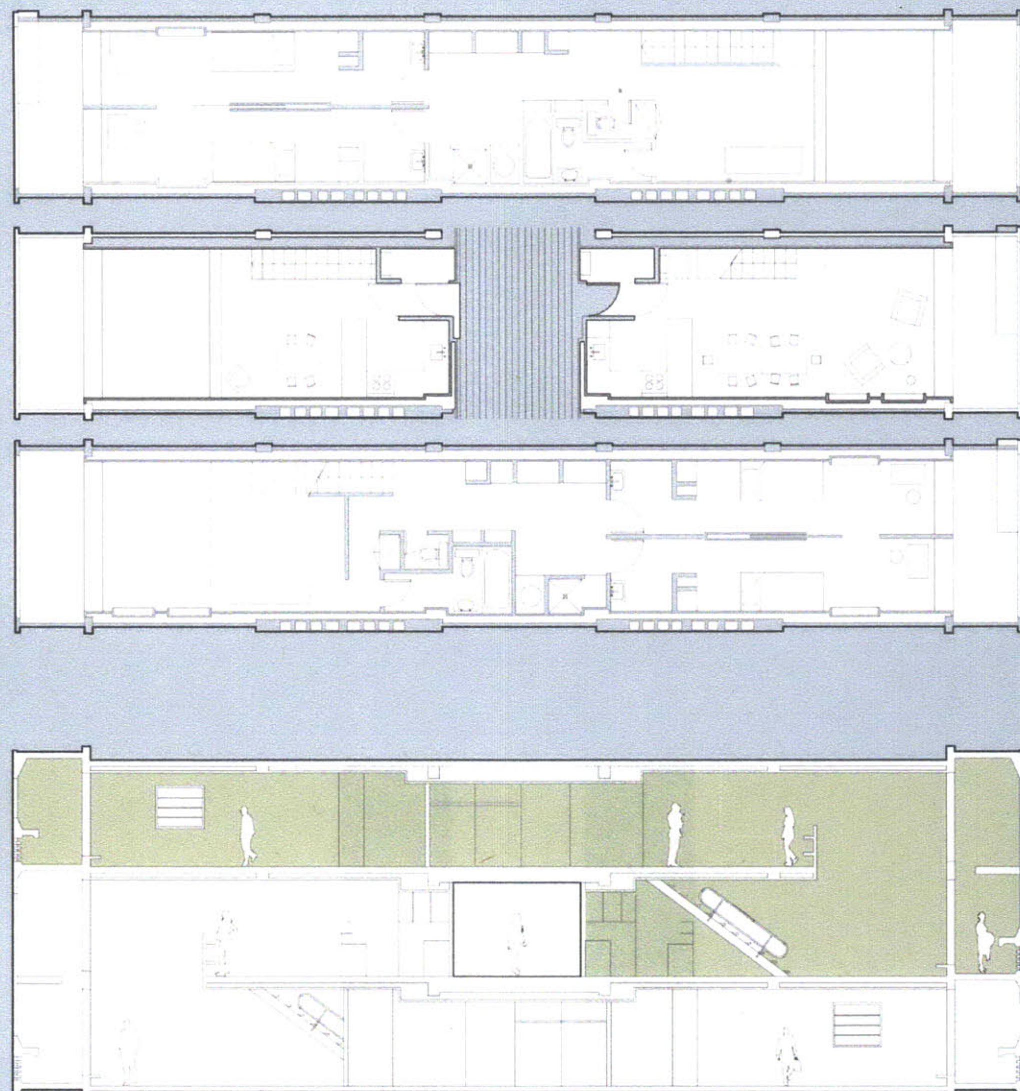
Lafayette Park Towers
Mies Van der Rohe



B22
SHoP Architects



Unite d'Habitation
Le Corbusier



Unite d'Habitation
Le Corbusier

SECTION 2.06

Space making with CNC

Spacemaking with CNC machines

Every architect must adapt his sense of efficiency and elegance to what is commercially available and in quantity."Carl Koch

CNC routers are the primary tool for the DIY production of architecturally scaled objects to date. The processing of sheet goods such as plywood is a straightforward process and it is evidenced by numerous pressfit structures. 2 example structures are the Digitally Fabricated House for New Orleans by Larry Sass and MIT for the MoMA Home Delivery exhibit and more recently the opensource house project Wiki House.

Each of these projects utilize CNC routers to generate a kit of parts that are pressfit together to generate frame, panel, floor, and ceiling. As mentioned before, because of the universality of many CNC machines designs can be easily shared digitally across long distances, the only remaining constraint is access to specified materials.

Even the simple manipulation of plywood provides freedom from what is "commercially available" and allows for the rampant experimentation of joinery, structure, surface, etc. Plywood sheets are the simplest examples of a mass produced product that can be locally customized with DIY tooling in order to personalize space.

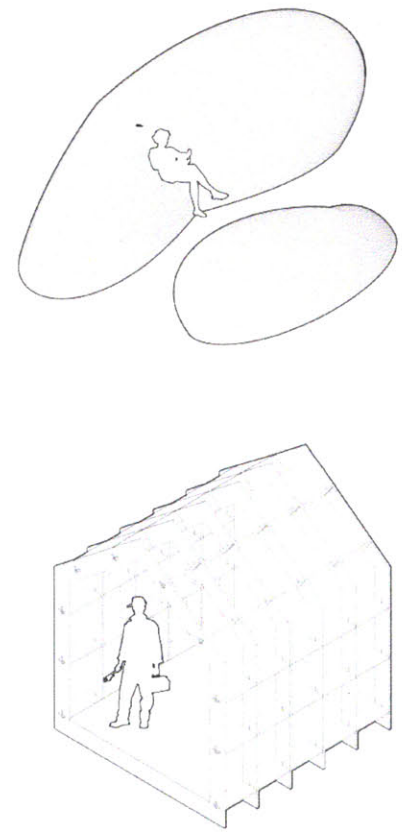
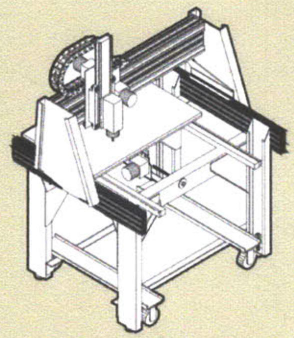
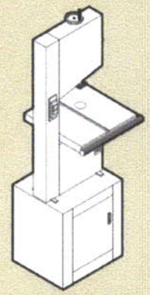


Figure 36

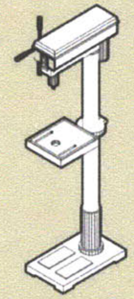
Figure 36: Example structures through the manipulation of sheet goods



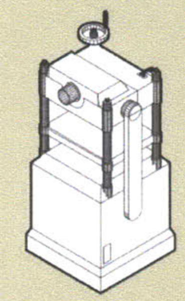
CNC ROUTER SHOPBOT BUDDY



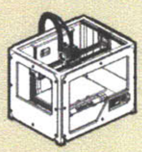
BAND SAW



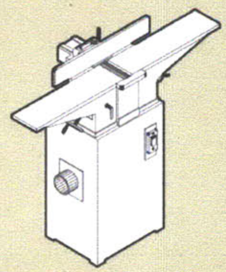
DRILL PRESS



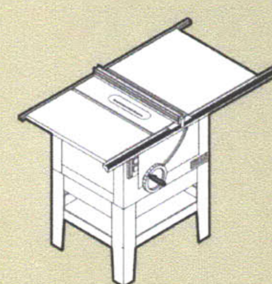
PLANAR



MAKERBOT 3D PRINTER

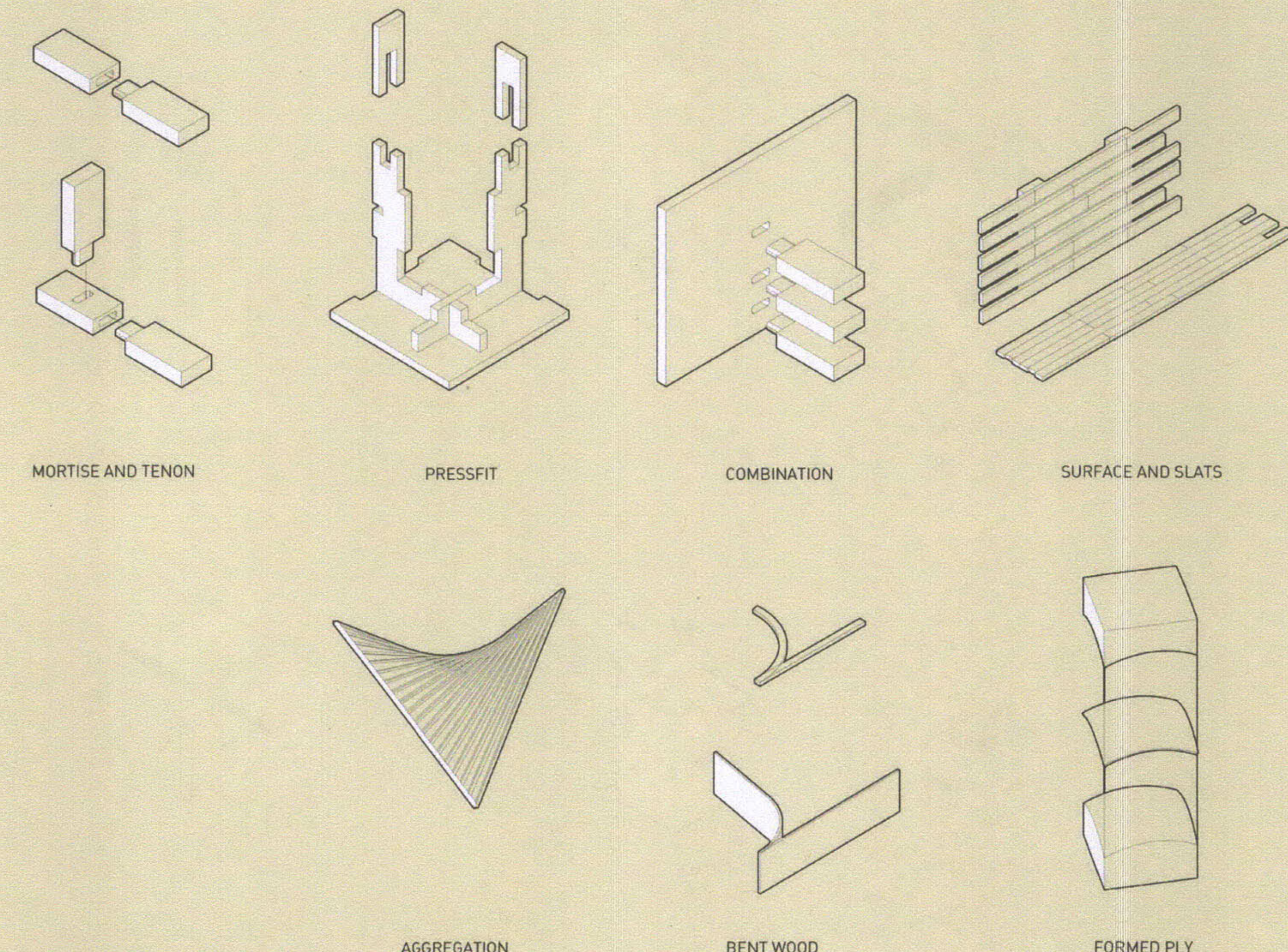


JOINTER

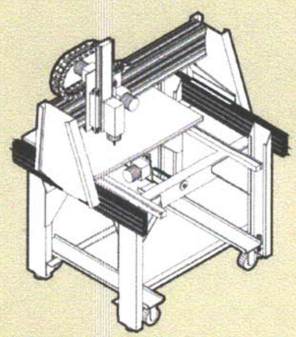


TABLESAW

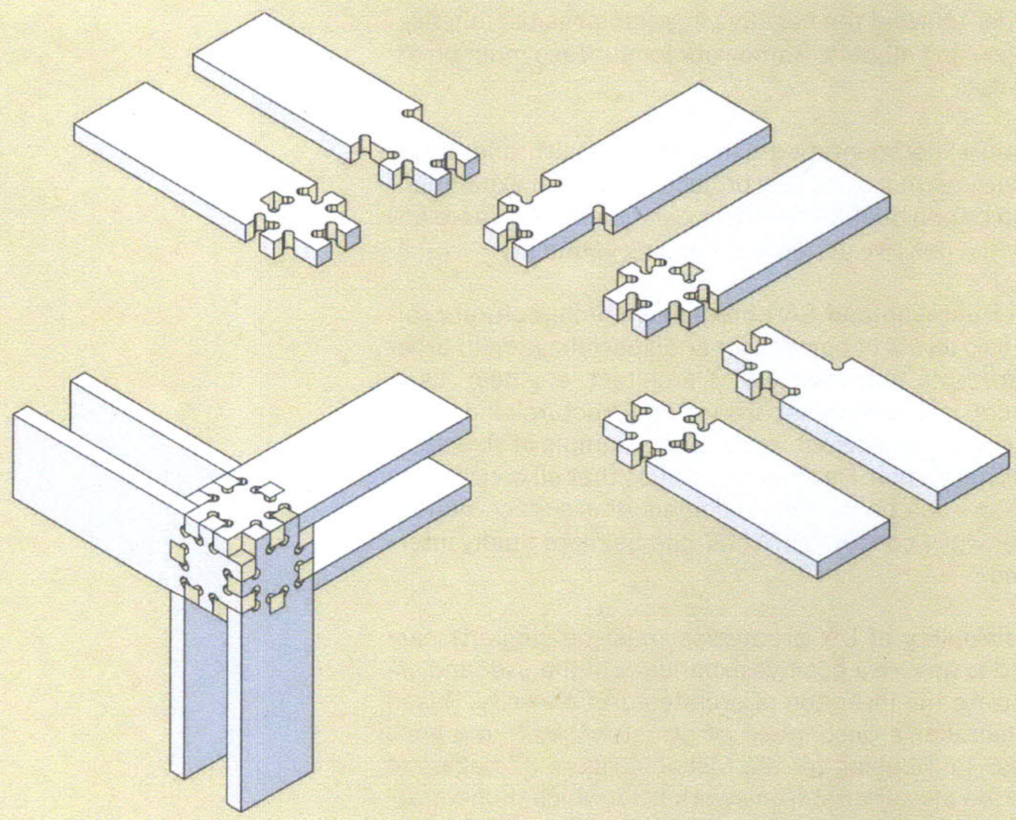
Low barrier to entry for the production of DIY projects



Methods of manipulating wood with digital and manual fabrication techniques



CNC ROUTER SHOPBOT BUDDY



A highly complex joint easily executed by a router that approximates a complex technique in Japanese Joinery

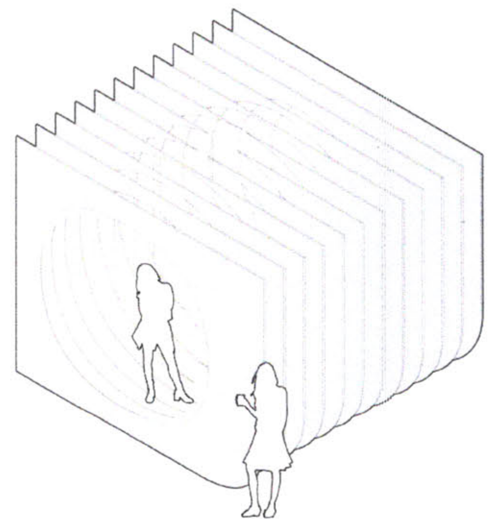
Orchestrated flexibility: Variation and 'Misuse'

In order to avoid the negative impacts possible in a flexible housing model a framework for success must be articulated.

Certain experimentation can lead to health and safety concerns within a housing project. Structural experimentation by non qualified persons can quickly eliminate any potential positive impacts of housing variability.

John Habraken and SAR breakdown architectural projects into levels of complexity and specialization in order to attribute responsibility of architect, engineer, user, city, etc. Habraken's separation of 'Structure' and 'Infill" is of particular interest for the prior example of structural experimentation. Habraken specifies that all concerns of structure will be under the domain of architect and engineer while concerns of 'infill' can be more fluidly interpreted.

The flexibility of DIY production must be similarly narrowed to ensure a positive experience of the user and orchestrate the invention of architectural diversity. Based on Habraken's description of structure, infill, margins, zones, in 'Housing for the Millions" figure 37 begins to describe a structural framework from which orchestrated flexibility can occur within a hybrid production + housing tower.



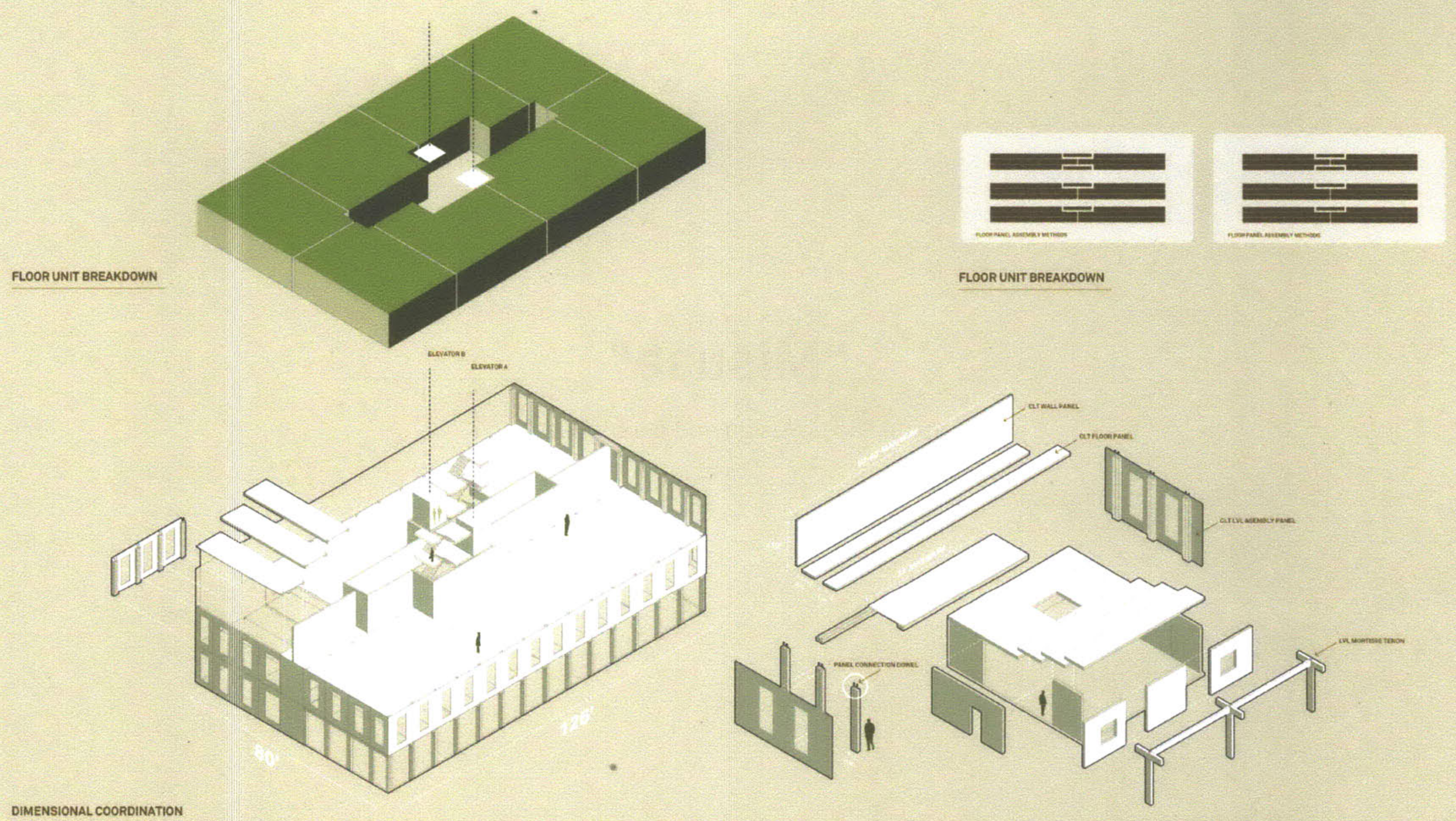


Figure 37: A framework for flexibility and dimensional coordination

PART THREE

“Misuse”

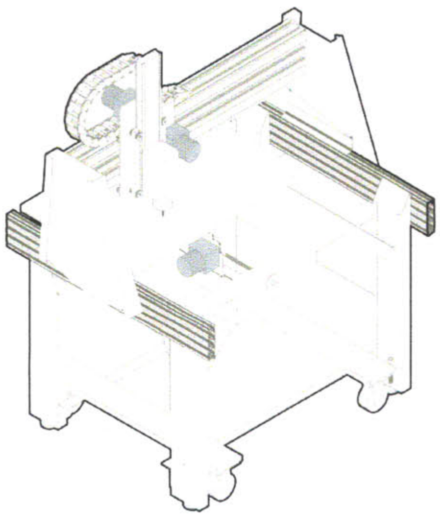
Decentralized design and personalization

SECTION 3.01

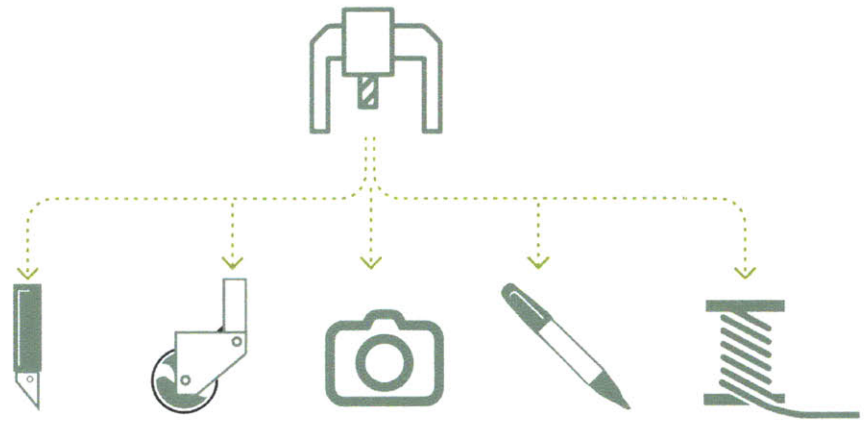
Productive misuse: custom fabrication solutions

The MTM project demonstrates the potential for a diversity of fabrication options through custom machine design, though this is a small subset of the larger pool of custom fabrication solutions. A broader category of these projects can be encompassed in what I define as "Productive misuse". Here designers and operators modify existing tooling to preform non specified operations. The following are examples of this method of machine use. By co-opting the 3 axis motion platform of an existing tool, the user interacts with the machine in a way similar to that of the robotic arm. Avoiding the hurdles of motion control the user can focus on the creation of a custom end effector. Each of the following projects utilize the spindle bearings, integral to the CNC router, to create custom fabrication with diverse results.

This process is illustrative of how a designer can innovate novel manufacturing techniques if the barrier of entry to machine design is lowered. The following examples show how a CNC router can be 'misused' to perform CNC heat sealing, precision cutting with a drag knife, novel weaving with computer controlled string delivery, and finally large format drawing with a simple pen attachment.

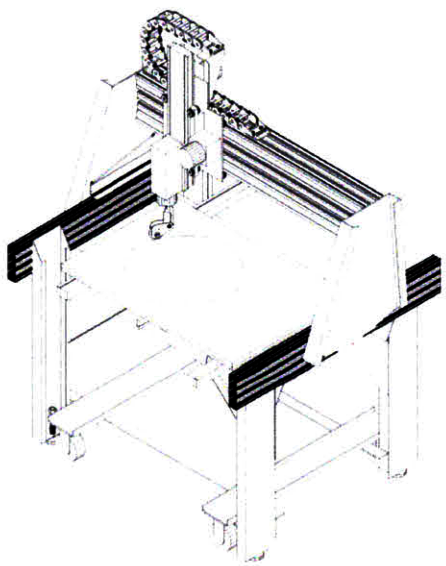


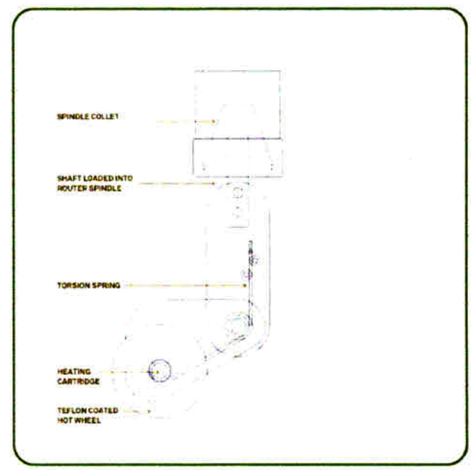
SHOPBOT ROUTER



A FEW SHOPBOT HACKS

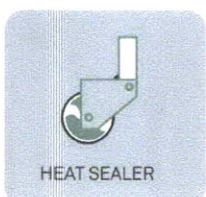
MACHINE [**MIS**]USE: CO-OPTING SHOPBOT MOTION PLATFORM





ROTARY HEAT SEALER

DESIGNER: JAMES COLEMAN



Custom heat sealing implement

CNC heat sealing

As a part of Professor Sheila Kennedy's Architectural Design Studio "Big Data >> BlowUP" at the Massachusetts Institute of Technology, students were asked to create custom inflatable devices.

Here myself and fellow graduate student Alexander Dixon co opted the motion platform of a Shopbot, retrofitting it to create custom inflatables. After machining a custom 'rotary heat sealing wheel' and chucking it into the spindle, thermoplastic sheets could be heat sealed together into nearly any shape. The heating wheel rolls along behind the spindle center behaving similar to a drag knife, sealing as it rolls. The spindle bearings allow the wheel to rotate in the direction of the programmed path.

The Shopbot solved a number of problems associated with heat sealing inflatables by hand. In order to create a robust seal constant heat and pressure must be applied at a constant speed. Sealing the plastic too slow and the plastic melts, too fast and the seal is not adequate. The shopbot allowed for precise motion control and accuracy during the heating process.

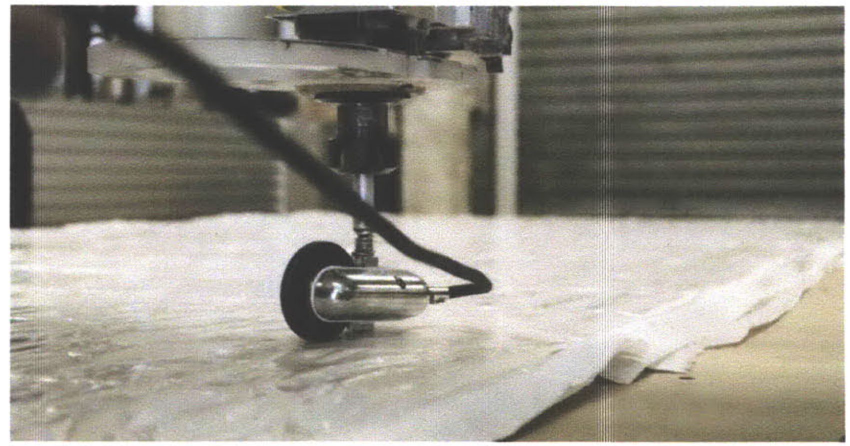
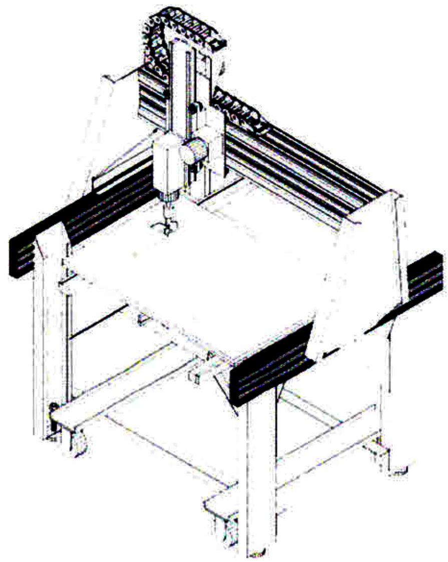
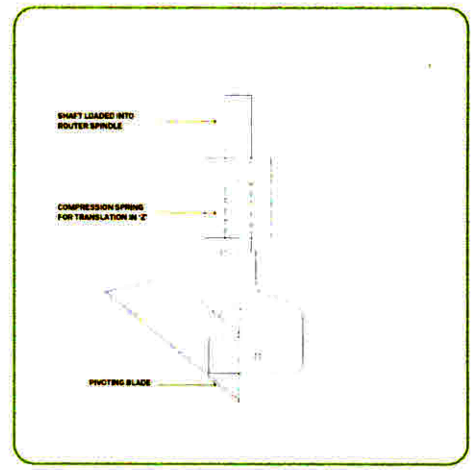


Figure 38

Figure 39

Figure 38: Heat sealing wheel processing thermoplastic
Figure 39: Implement output "Data Diet" Alexander Dixon pictured





DRAG KNIFE

DESIGNER: SEAN MARTIN (DONEK)

Donek Drag knife

Similar to the heat sealing wheel, the Donek drag knife utilizes the spindle bearings of the router to allow for free rotation of the blade. This is a primary example of a minimal addition to an existing CNC device that drastically expands its capabilities. The drag knife allows for the processing of thin films, semi ridgid plastics, fabrics, and many other materials impossible to cut with a spinning tool .

Similar drag knife implements have been released open source and can be readily downloaded and 3d printed. This further exemplifies the productive 'misuse' of existing tooling and the potential for distribution to a community of users.

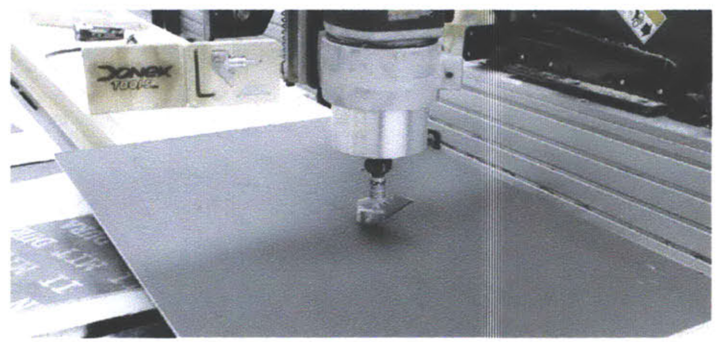
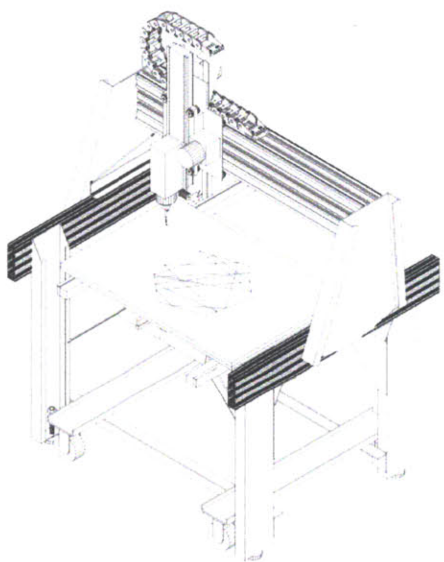
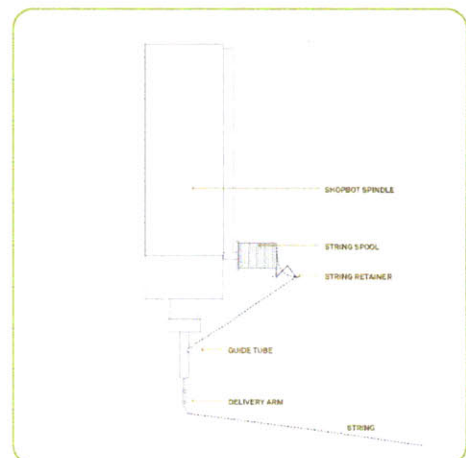


Figure 40

Figure 40: Donek drag knife implement





WEAVING APPARATUS

DESIGNER: JARED LAUCKS, MARKUS KAYSER

CNC string delivery for 'The Silk Worm Pavilion"

The construction of the Silk Worm Pavilion by the Mediated Matter Group at the MIT Media Lab presented a number of sophisticated fabrication techniques, both mechanical and biological. Like the previous projects, this is another demonstration of a creative misuse.

The polygon panels from which the silk worms placed their silk were composed of an aluminum frame with strategically 'woven' silk thread. The team first attached a spool of silk thread to the spindle of a 3 axis router. The router was then used to precisely wrap the thread around a series of aluminum standoffs in computationally derived patterns. This clever deployment streamlined the creation of the panels, each with a unique pattern.

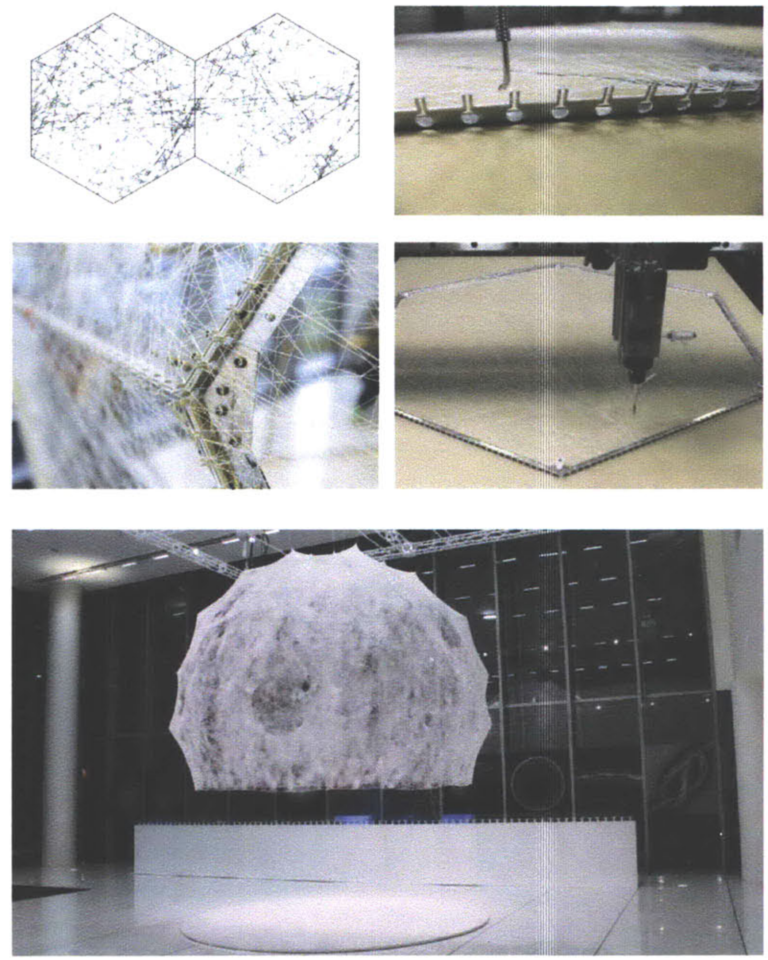
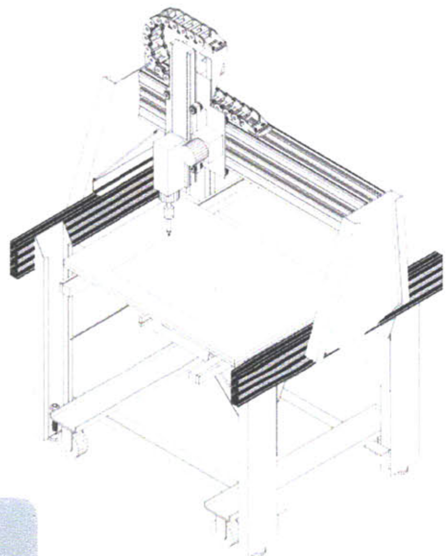
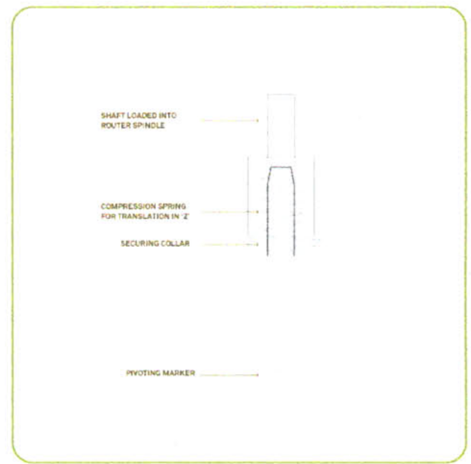


Figure 41

Figure 41: Images of "The Silk Worm Pavilion" by Neri Oxman and Mediated Matter. Shopbot implement by Jared Laucks & Markus Kayser





LARGE FORMAT DRAWING

DESIGNER: N/A

CNC drawing: "Printing"

A new take on an old technique, the CNC drawing machine demonstrates the principle of co-opting in its simplest manifestation. This adaptation requires nothing more than the addition of a sharpie marker to the CNC router. Pen plotters have existed for several decades, so the process is not novel. What is important about this process is the ease at which the machine modification happens.

The prior examples of misuse each required the often sophisticated design and fabrication of the end effector. With the CNC drawing implementation the user can receive instant feedback on the characteristics of the product with very little effort required. The quality of line, speed of application, and physical attributes of the artwork generated can be scrutinized and optimized at initial deployment.

A short feedback loop from design to product is a crucial element for designing of a flexible tool kit discussed later. If a machine is arduous to use, modify, or reconfigure it will not be utilized, regardless of the barriers it has lowered.

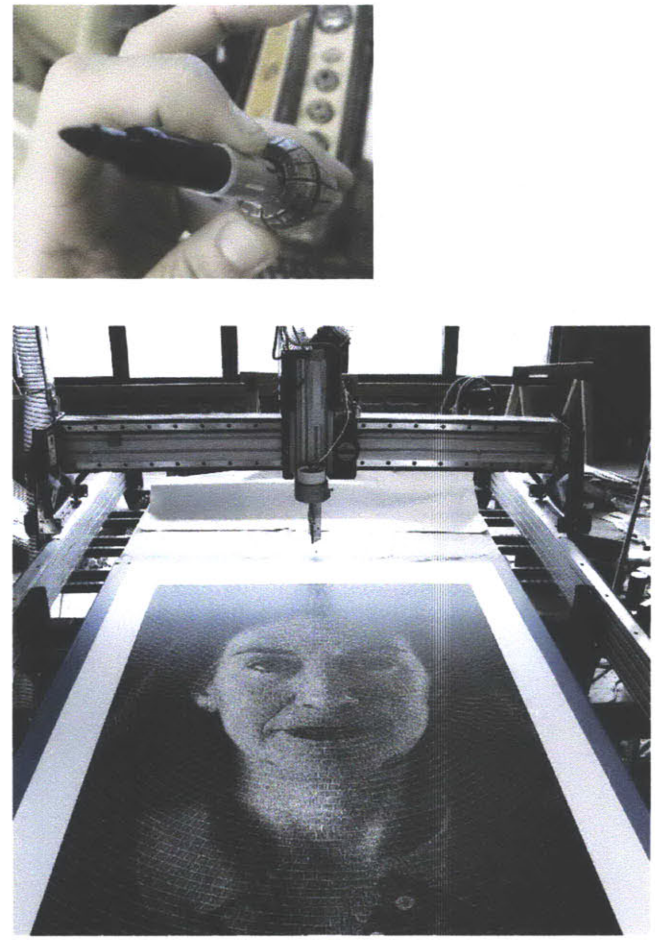


Figure 42

Figure 42: Mike Lyon pen plotted portrait.

PART FOUR

"Hack your house"

Housing flexibility and variation powered by a DIY fab community

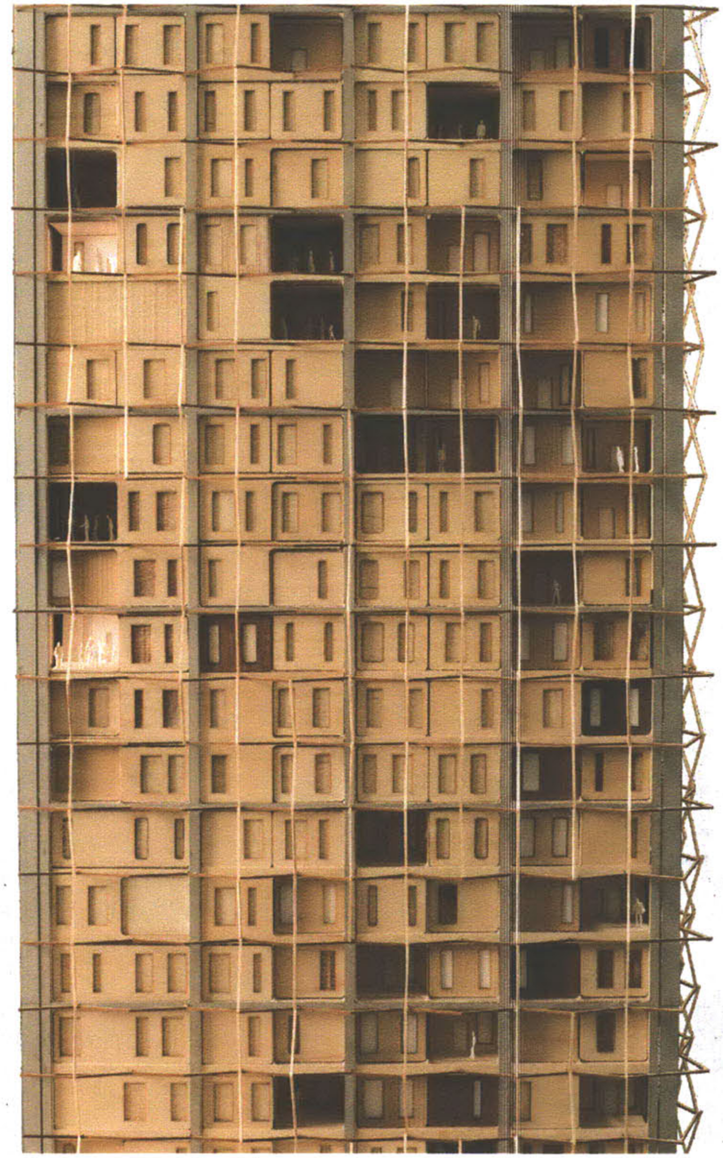
SECTION 4.01

Timber Tower: South Street Seaport , NYC

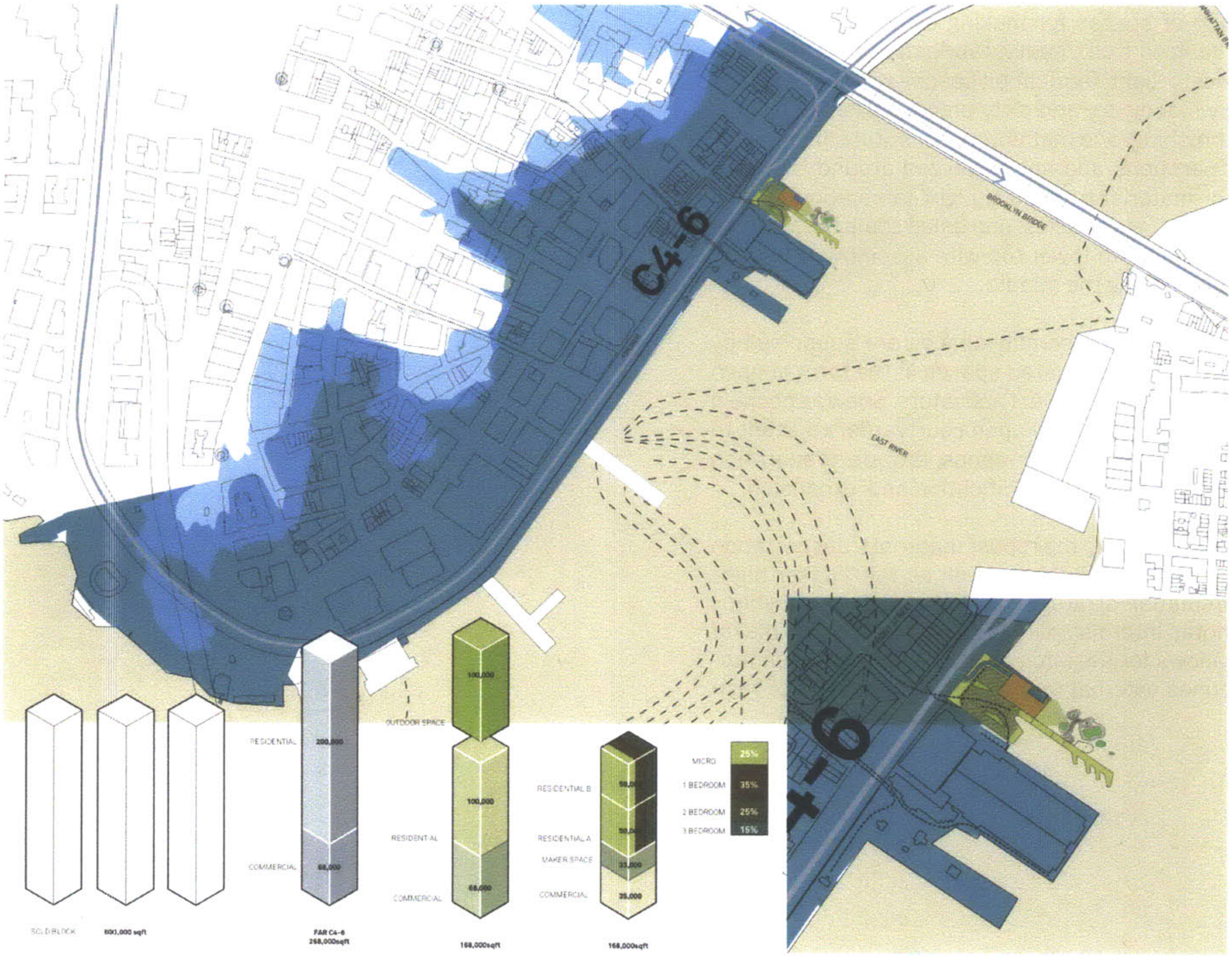
A Boeing 737 can be assembled in 11 days and contains over 1,000,000 parts. A house typically is composed of a ~10,000 and takes 3-4 months to complete and once finished cannot fly. Both the aircraft and automobile industry have produced higher performing more sophisticated projects over the last 60 years which continue to drop in price. Architecture meanwhile continues to have longer lead times, lower performance, and higher costs. In order to adjust this trend we must embrace a level of standardization and take on the project of prefabricated housing with modern techniques and tools.

Situated in the South Street Seaport of New York City, the Timber Tower combines a series of small scale fabrication facilities (makerspaces) with 213 flexible housing units that allow for rapid reconfiguration. In a city saturated with creative capital, the tower is poised to reinvent the housing tower through the strategic link between off-site prefabricated wooden structural components with onsite customization. A robust triple height reinforced concrete and steel frame provide the framework for 3 story interventions that allow for the reconfiguration of housing units. Partitioning, unit recombination, and even facade transformations are possible in the Timber Tower; all produced within a highly flexible yet highly orchestrated organizational framework.

The Seaport and it's history as a center of material exchange is perfectly suited for a tower of makers and for the dissemination of both material goods and creative capital.



Tower rendering looking west from East River
Tower model south facade



Site map and zoning strategy

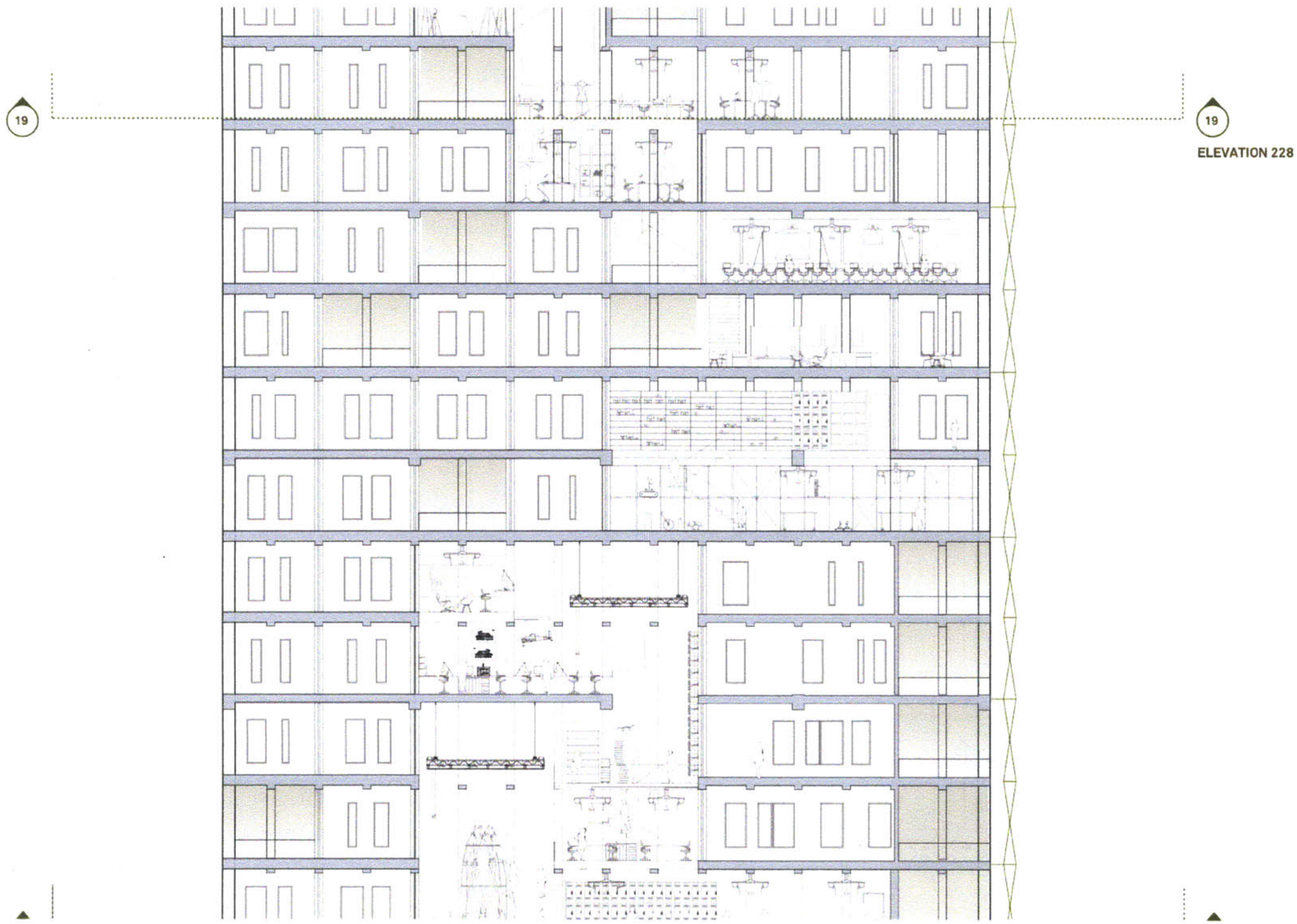
A collection of spaces for making exist throughout the tower, organized from 'heavy' fabrication near the base of the tower to 'light' fabrication spaces situated near the top. Heavy machinery and dirty process such as milling, sanding, finishing, and metal work constitute 'heavy' fabrication operations and are organized around the base for ease of material transport. Light fabrication spaces such as textiles, electronics, and small scale fab projects are collected near to tower top with assembly, and project storage bridging the middle.

Formal making and assembly spaces are supported by a network of informal shared spaces in the form of open courtyards that act as project activators. Show as poche'd areas in the section, these open courtyards, adjacent to living spaces and fabrication zones, provide preparation space that supports unit modification and expansion.

The section illustrates the robust material transportation system within the building as well as the "maker highway" a circulation strategy that links each of the shops and promotes interdisciplinary collaboration. The maker highway allows for the informal circulation between fabrication zones external to the formal circulation of residents.

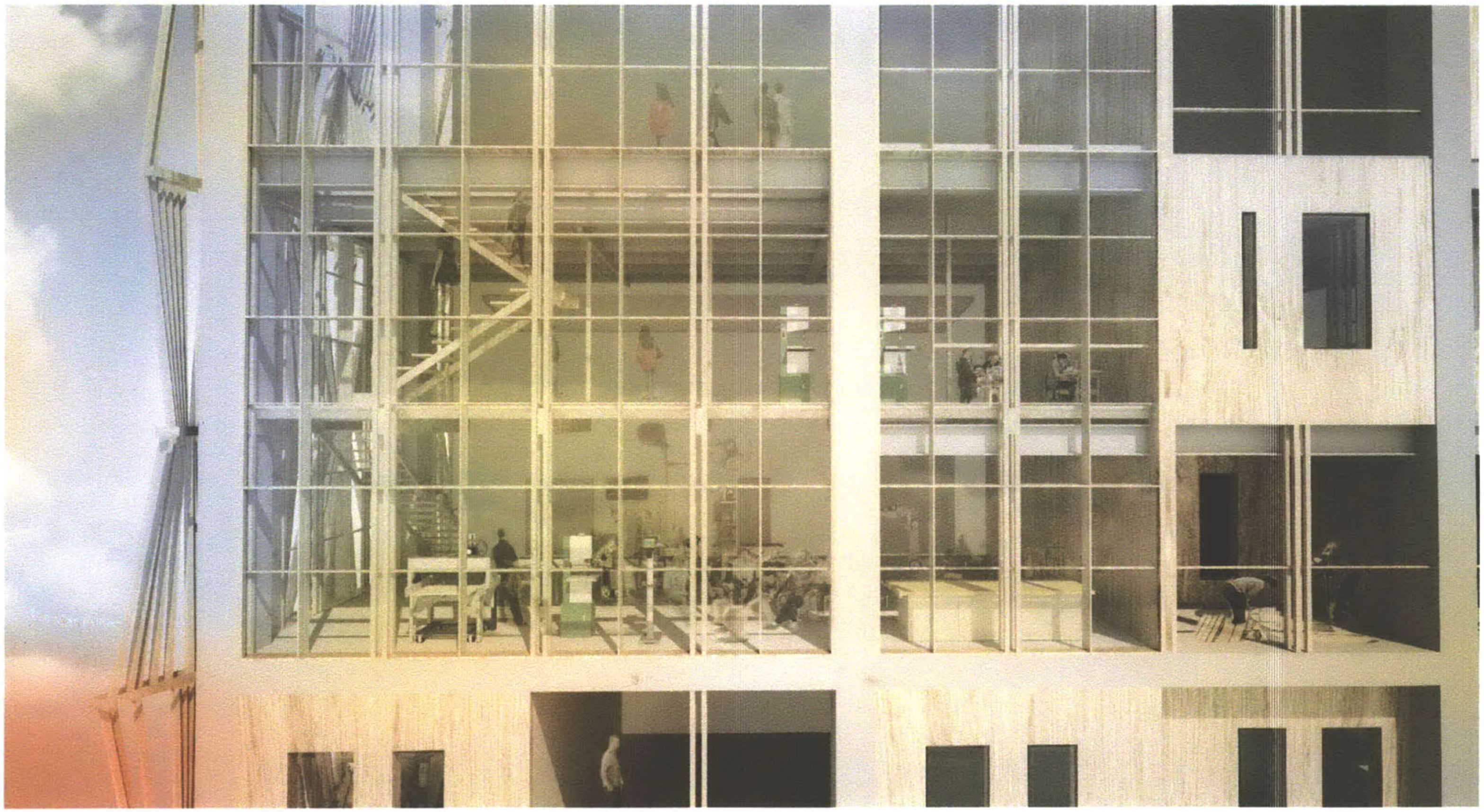
Tower section A

Tower section A (BASE)



Tower section A (MID)

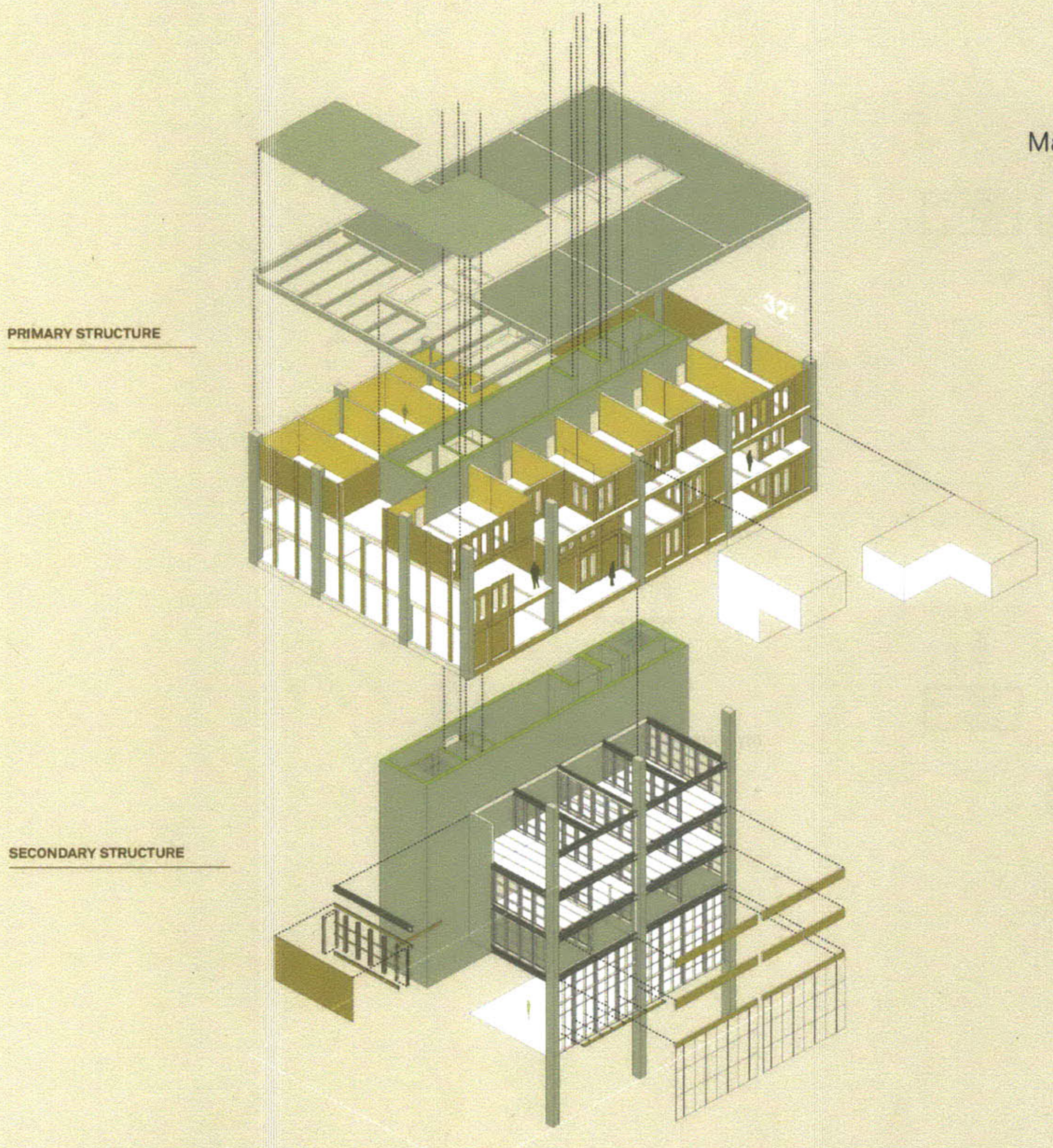
Tower section A (TOP)



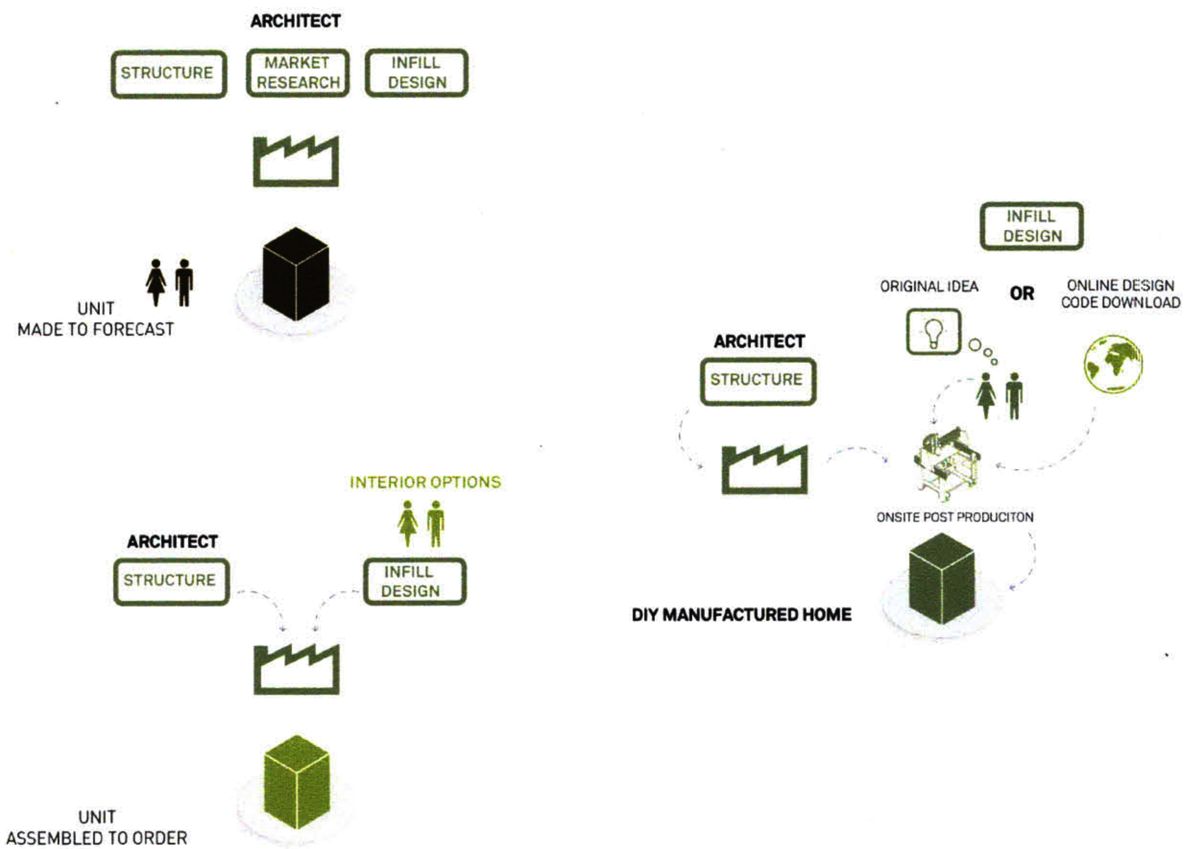
Rendering of heavy shop space and shared courtyard spaces

Rules of the game

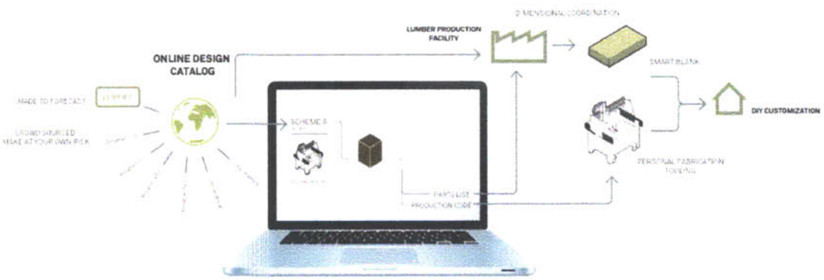
Margins, zones, dimensional coordination.



Exploded Axon of structural system



Methods of unit production



Unit types

A DIY manufactured unit within the Timber tower allows for the user to completely personalize the space within the structural framework provided. This is the extreme example of a maker taking charge of the entire fit out process, and the space is delivered to the user as a shell. This is one of three delivery options available within the tower, and hybridizations of these three are possible.

1. Total fit out:

   The occupant takes total charge of the fit-out of the space working within the organizing framework set up by the structure and infrastructure.

2. Assembled to order:

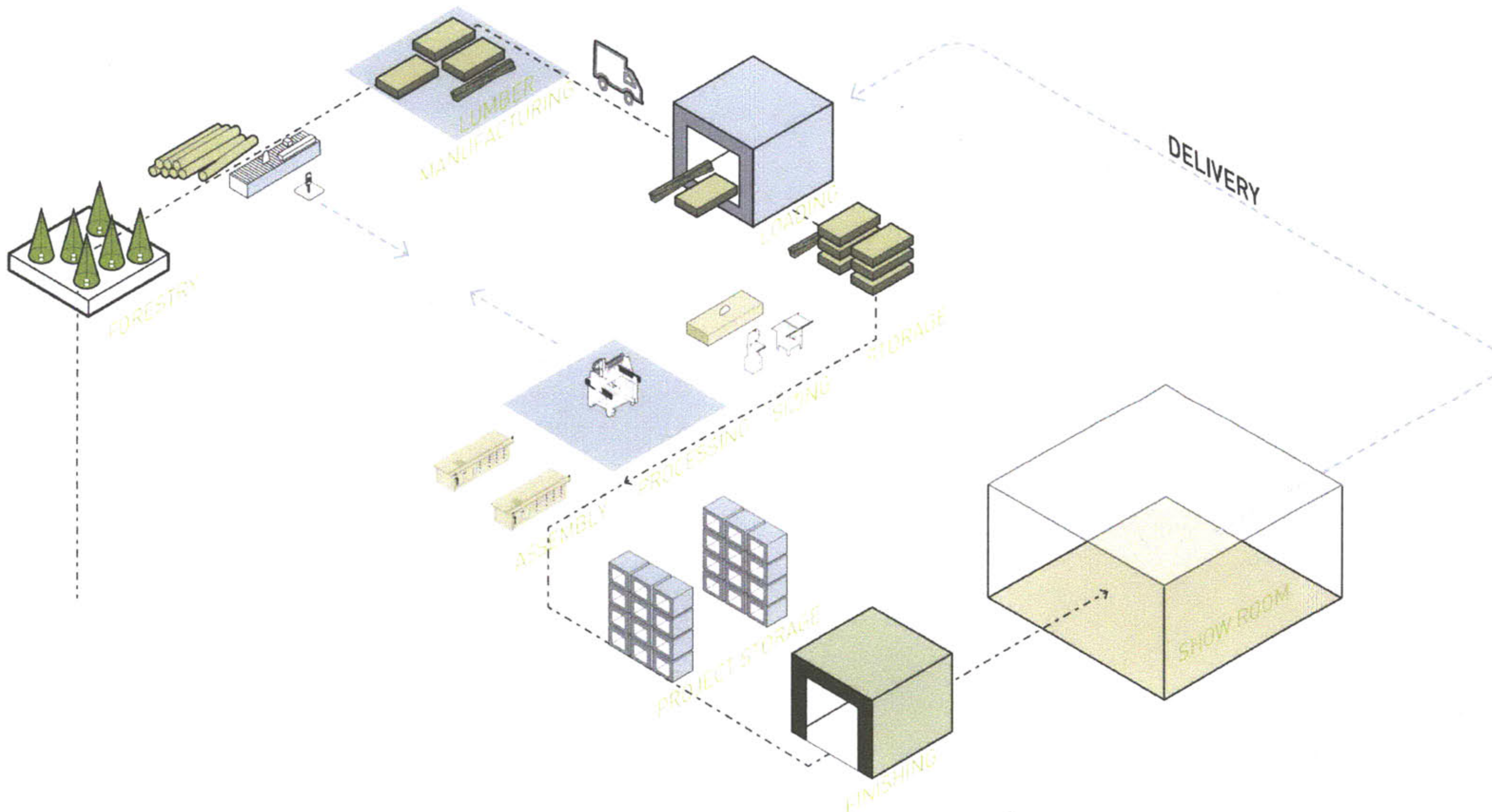
   This unit type is much like current developer products where a customer can specify certain elements of their unit by choosing from available options.

3. Made to forecast

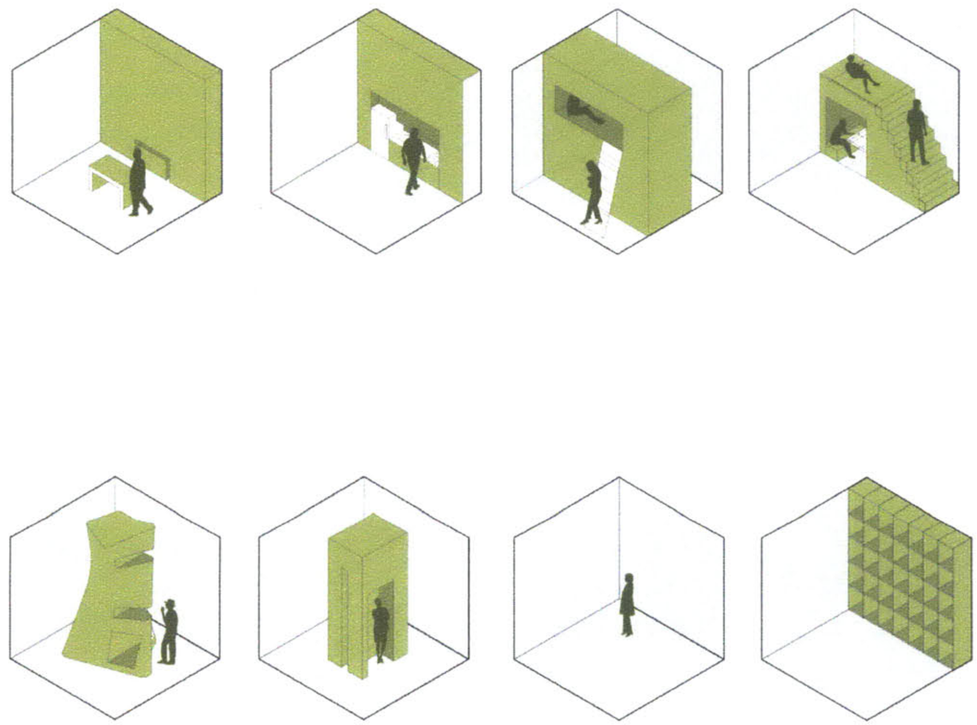
   This unit type is designed and delivered by the architect and is no different that a typical housing project.

The 3 unit types ensure that the tower is inclusive of differing user groups and funding streams. As units morph and change, unit 2 available fit outs can reflect the successes and failures seen in the total fit-out units.

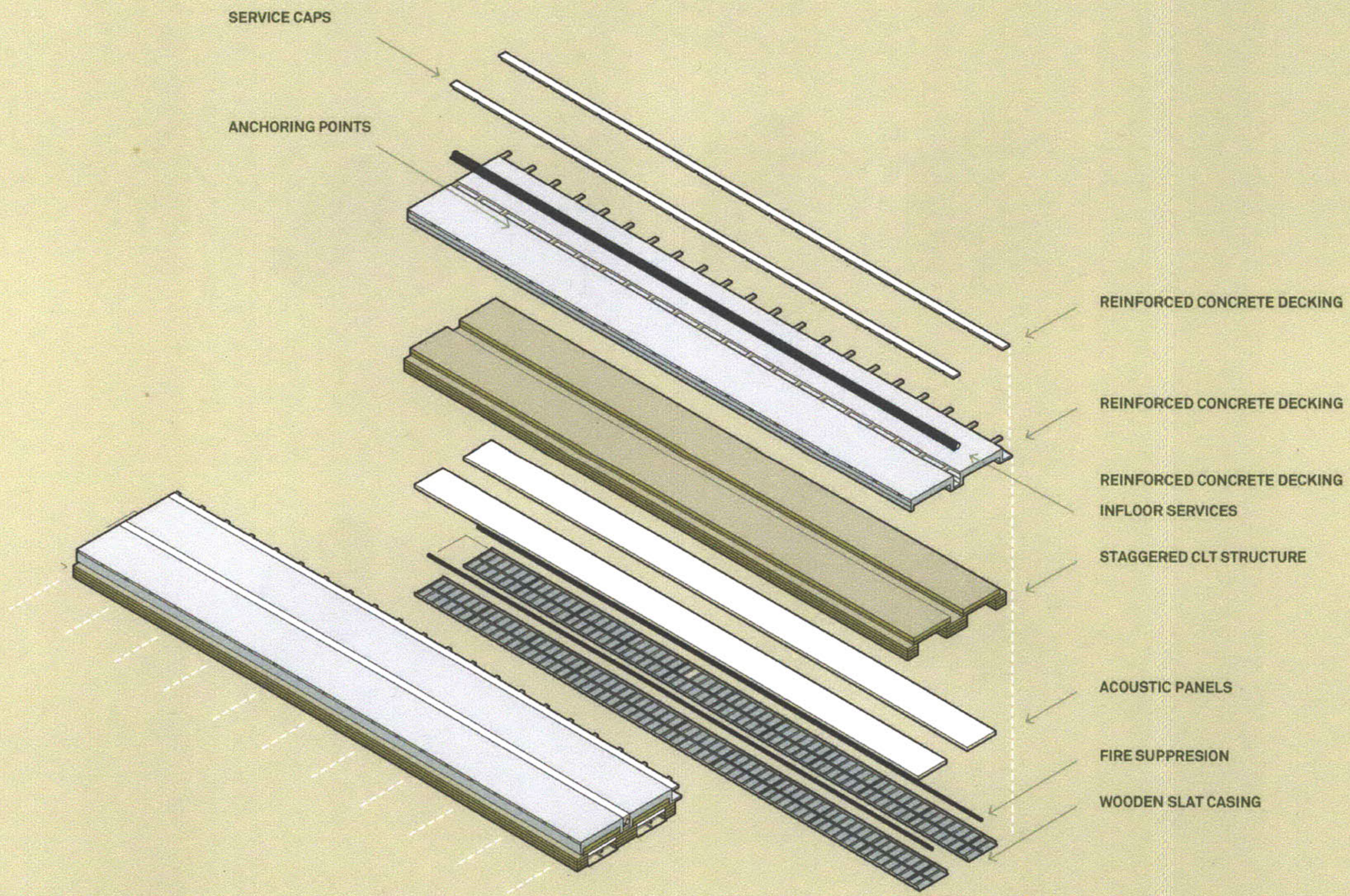
Total fit-outs do not necessarily need to be directed by the occupant but instead can be "downloaded" from a designer of their choosing and implemented with the available tooling within the tower.



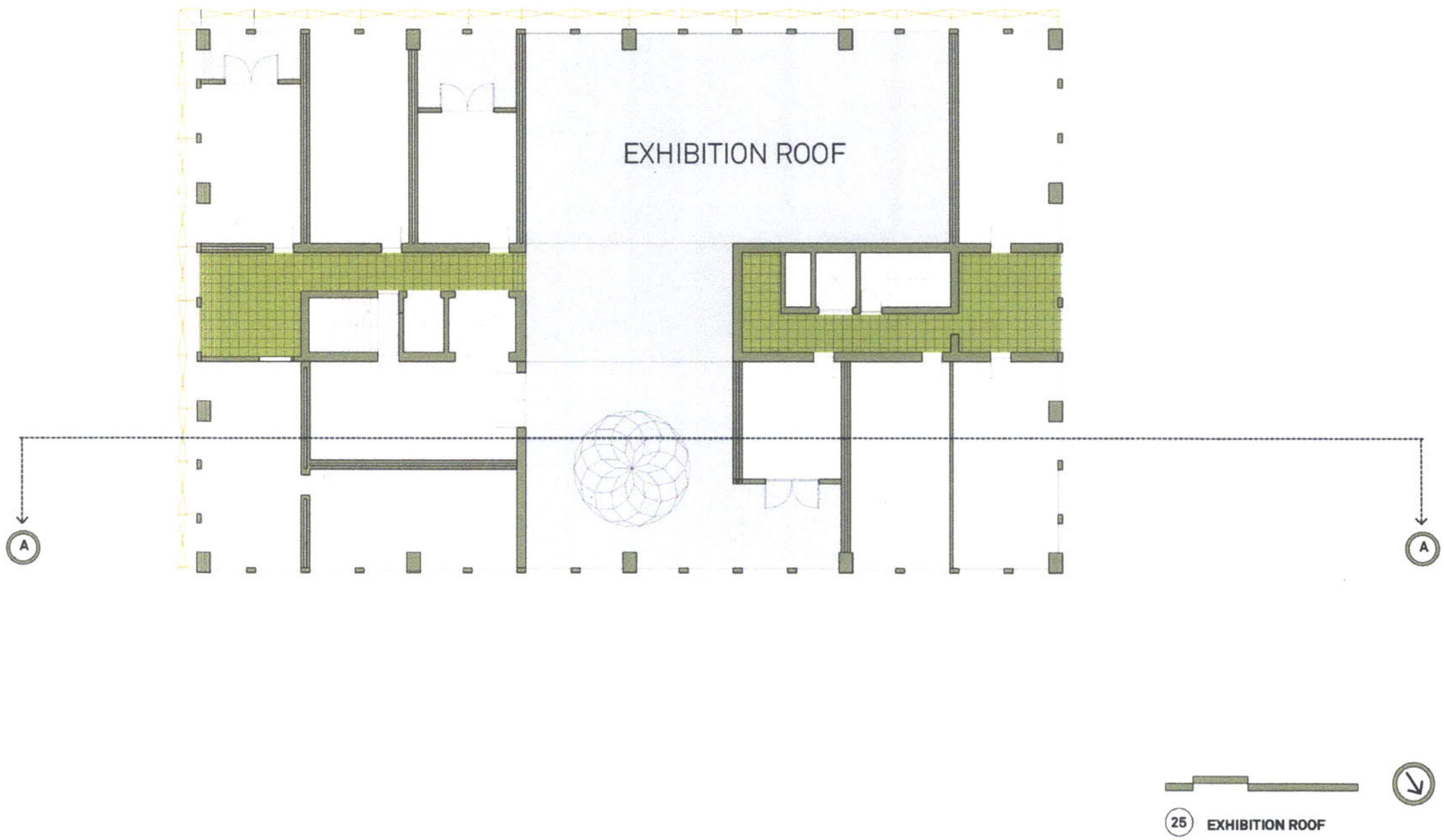
Production cycle for tower components demonstrating information exchange between pre and post production.



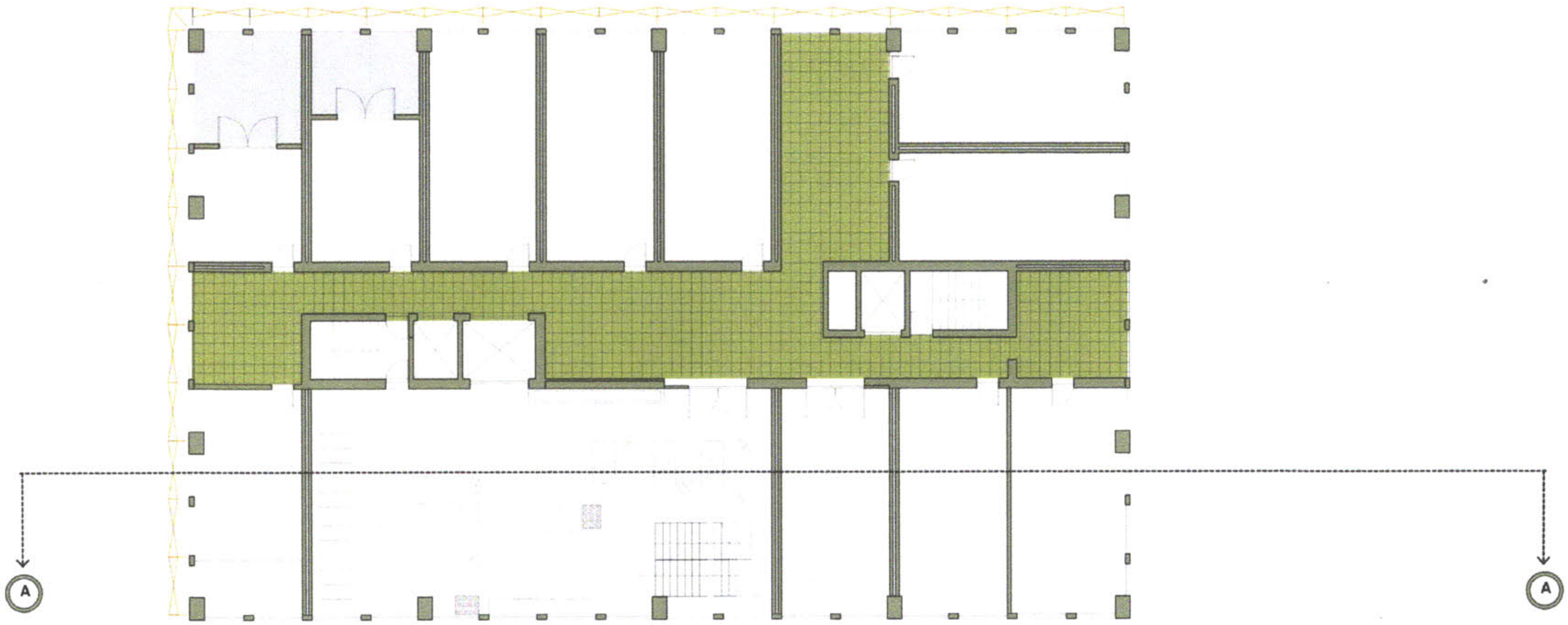
Potential spatial interventions "super furniture"



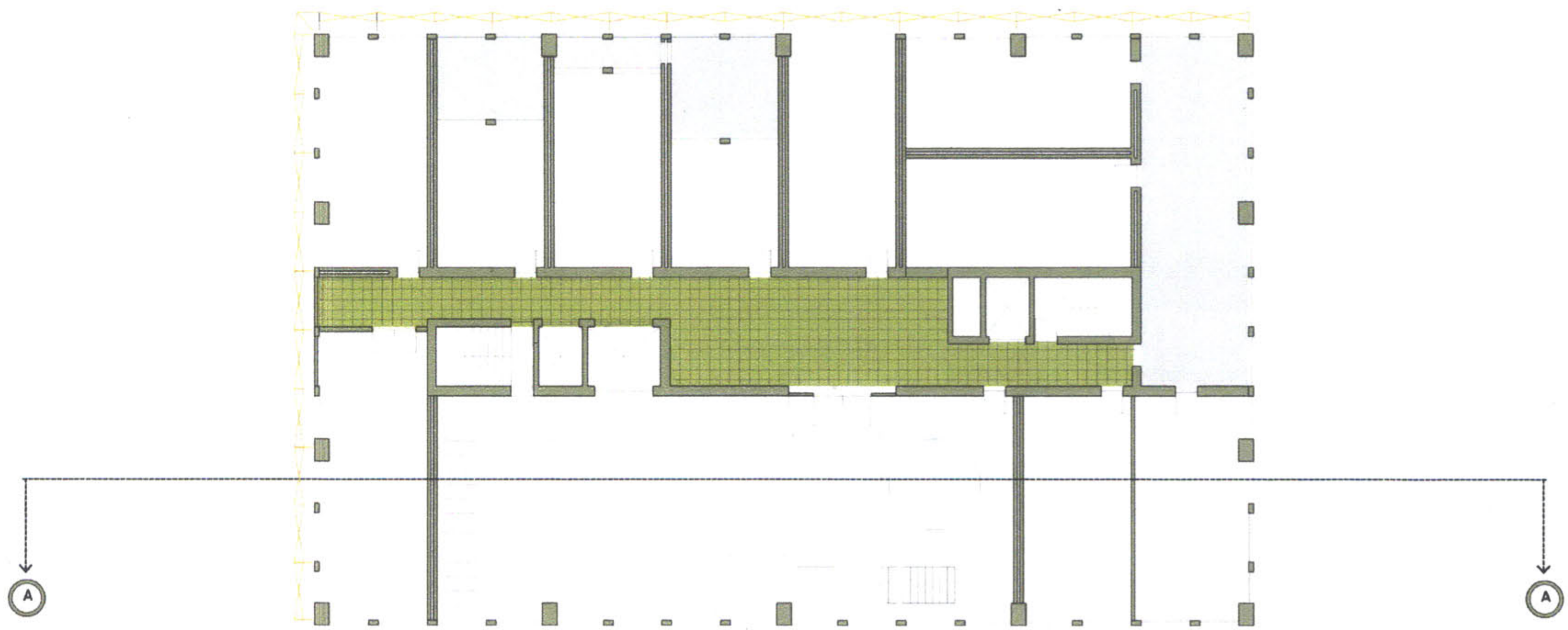
Flooring and infrastructural strategy



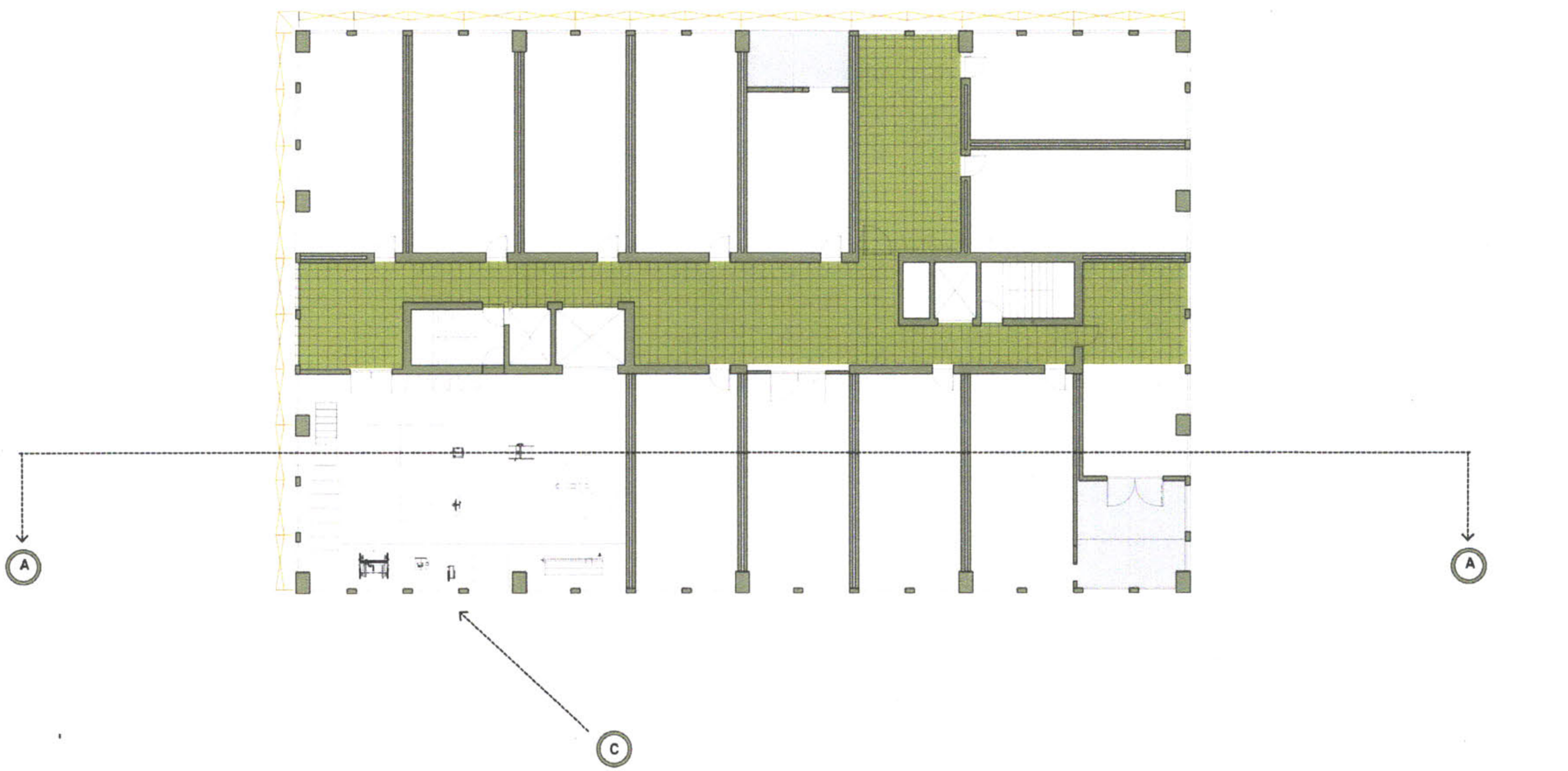
EXHIBITION ROOF
A
A
25
EXHIBITION ROOF



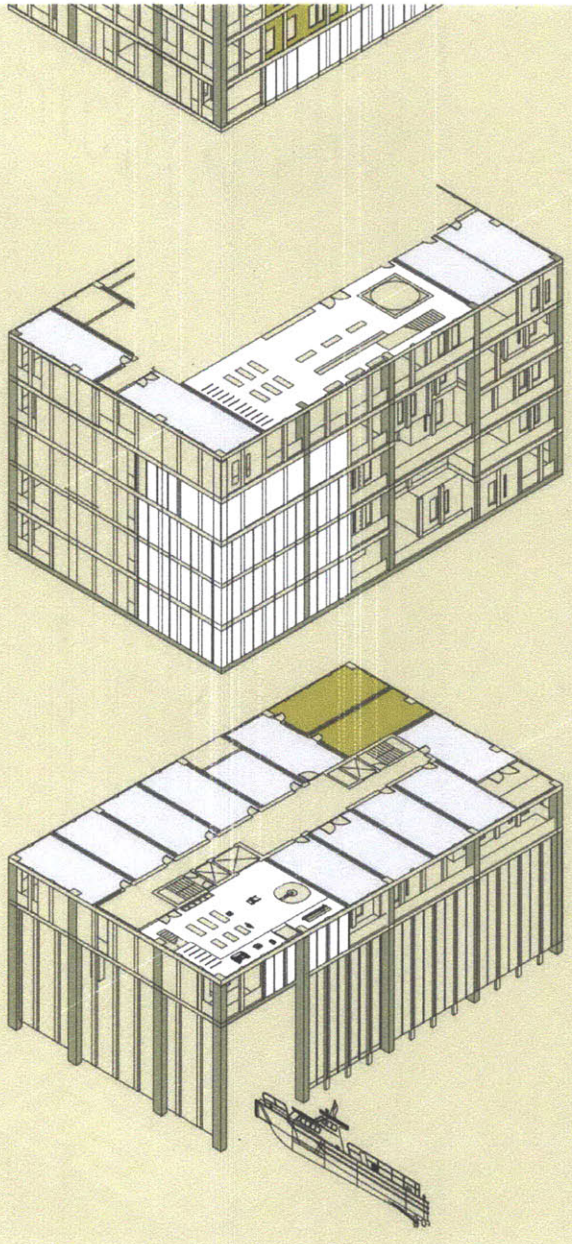
19 LIGHT FAB: TEXTILES STUDIO



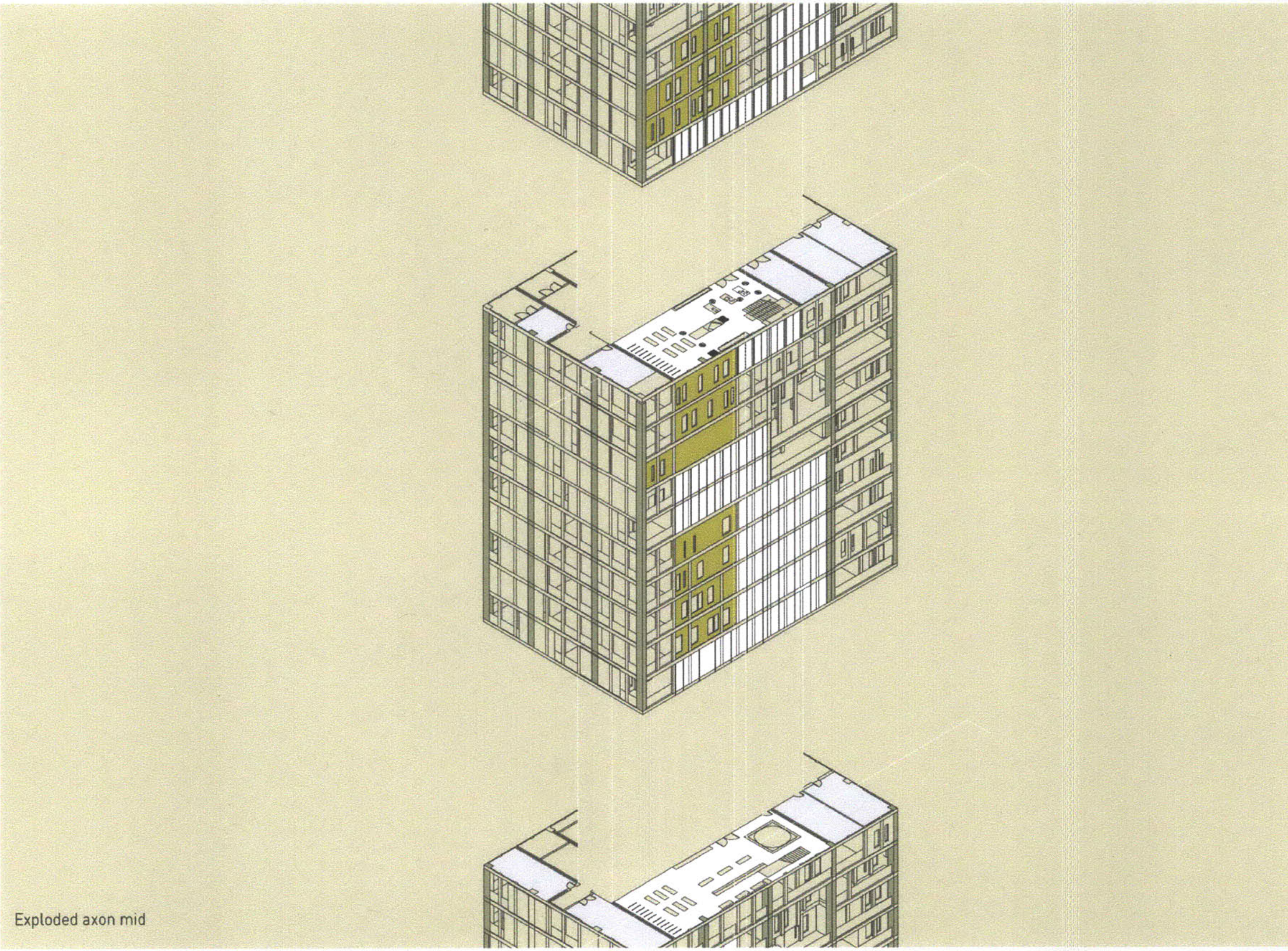
9 POST FAB: ASSEMBLY AND PROJECT STORAGE



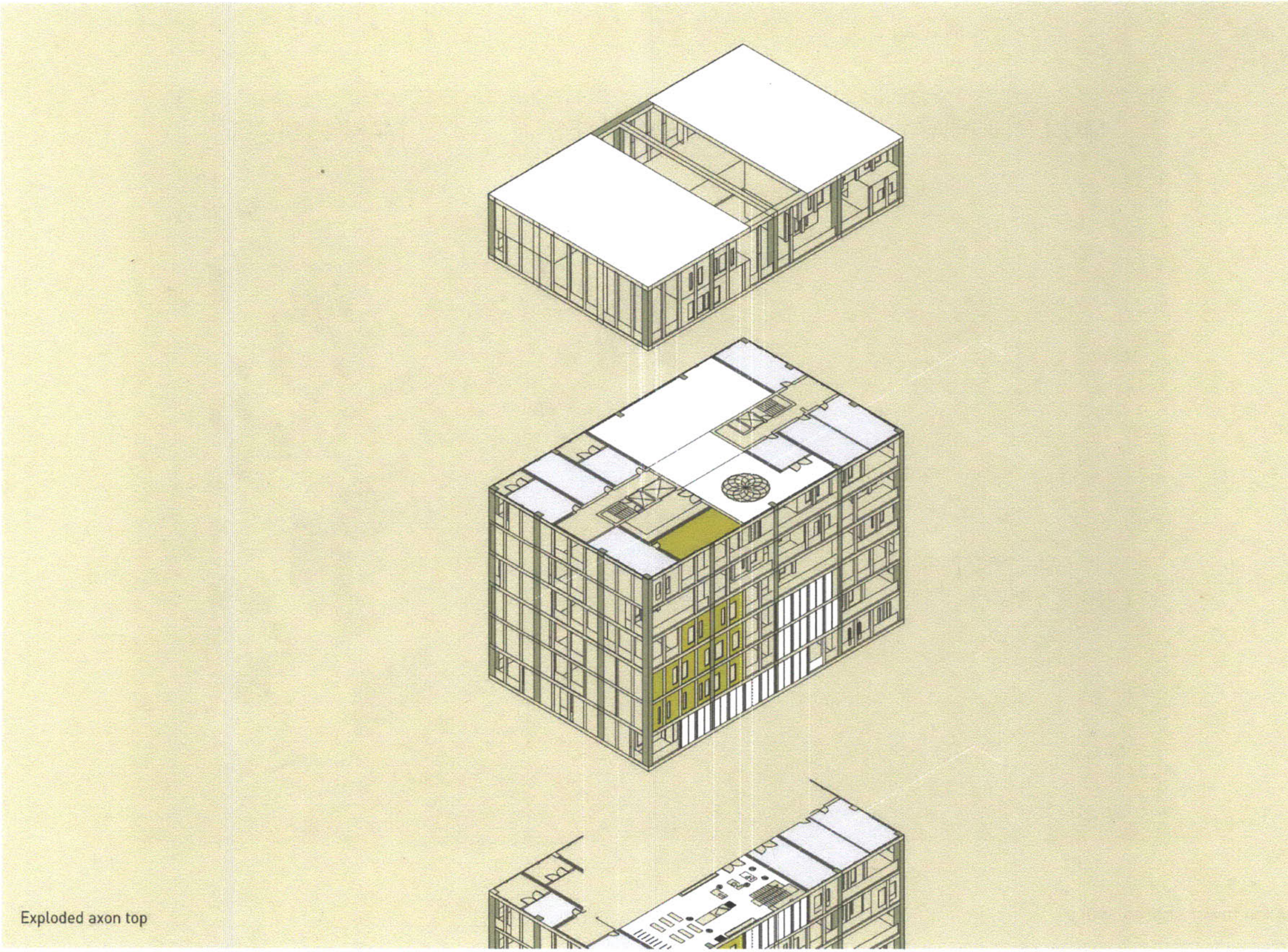
4 HEAVY FAB: FABRICATION SHOP



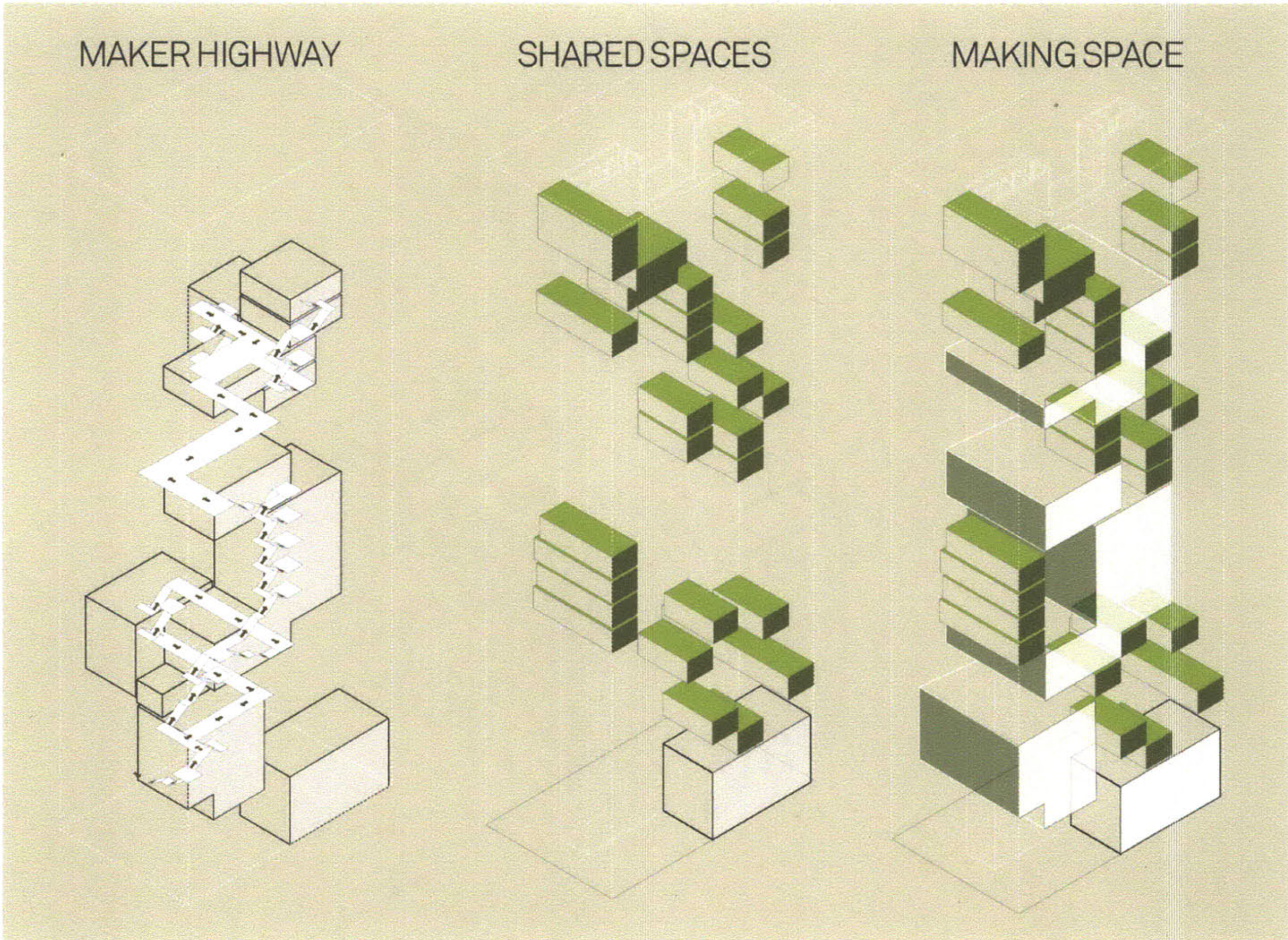
Exploded axon base



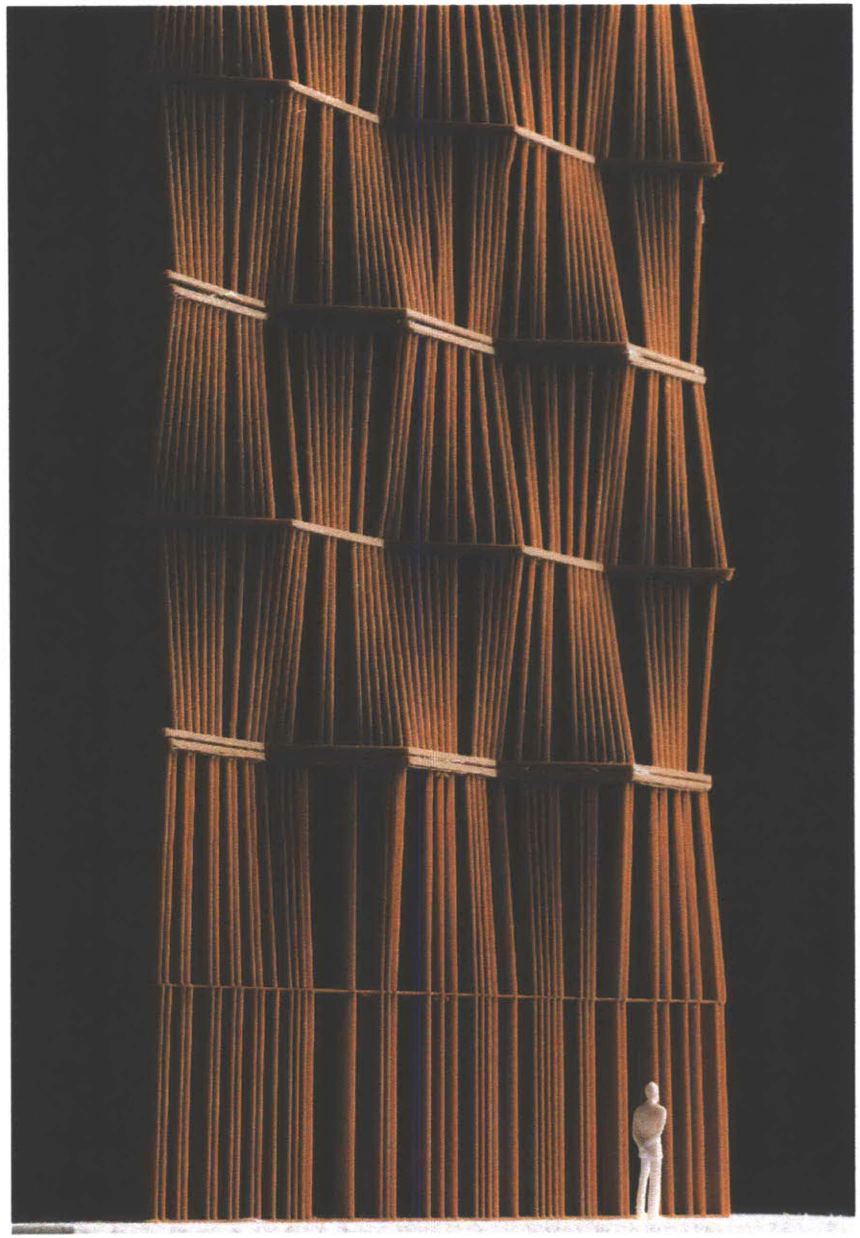
Exploded axon mid



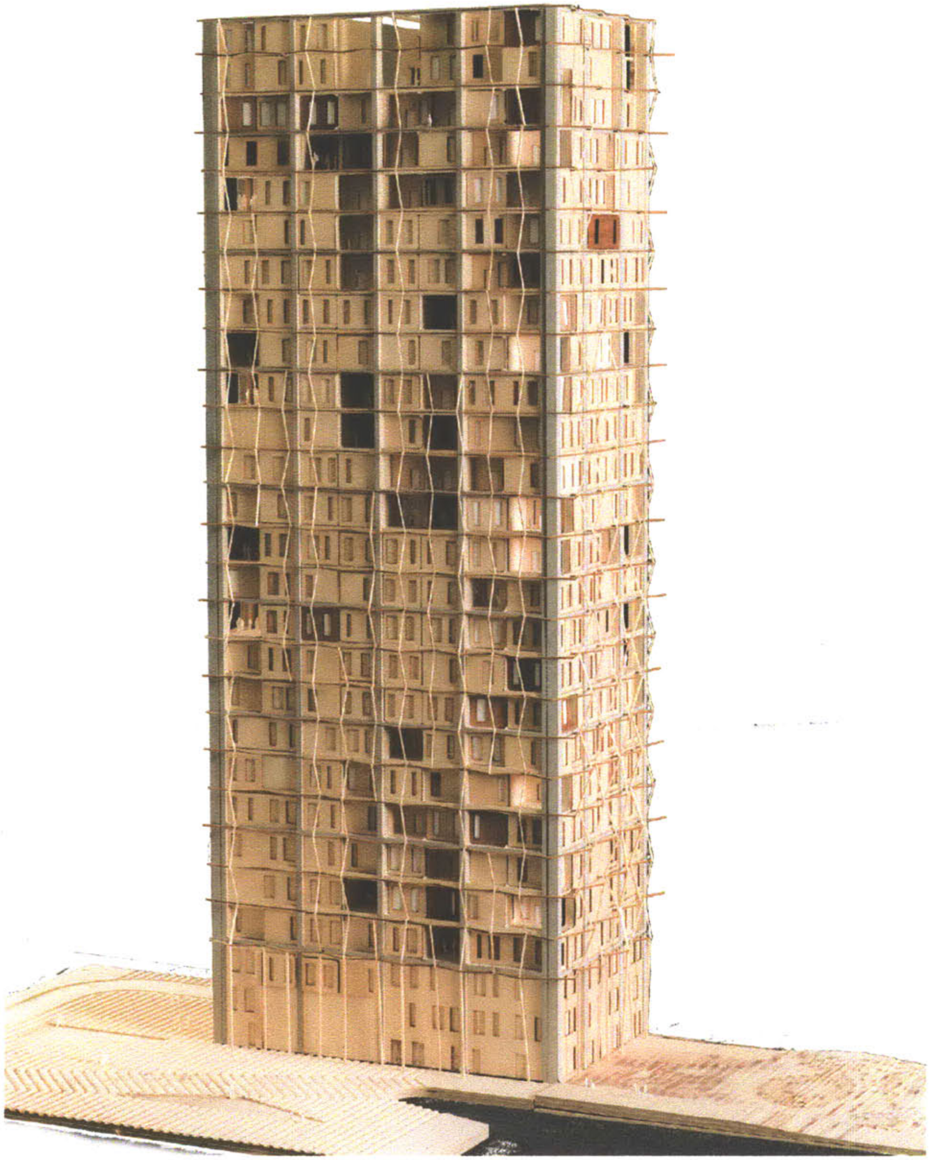
Exploded axon top



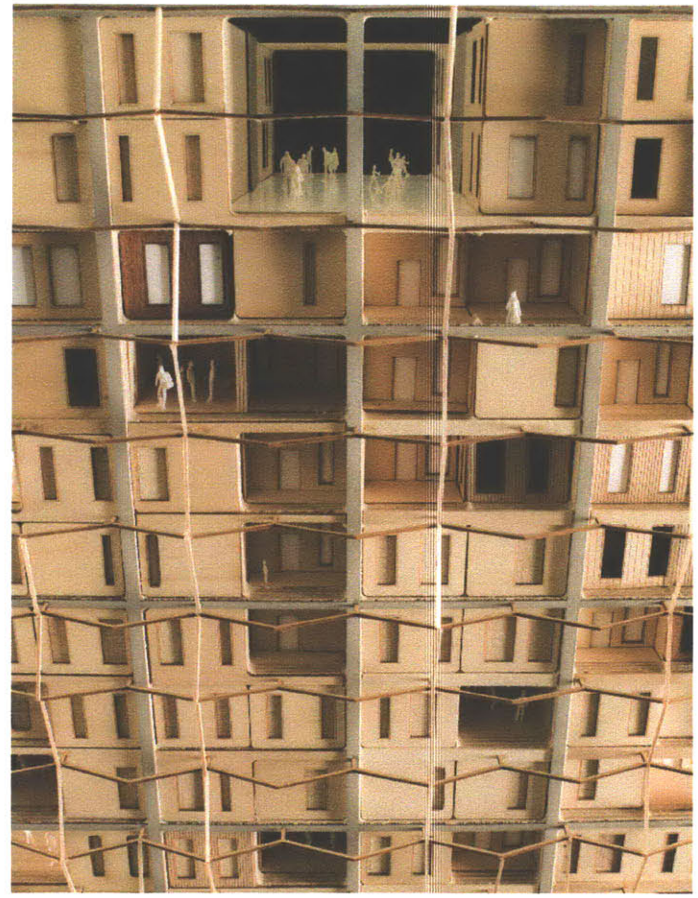
Axon tower shared space



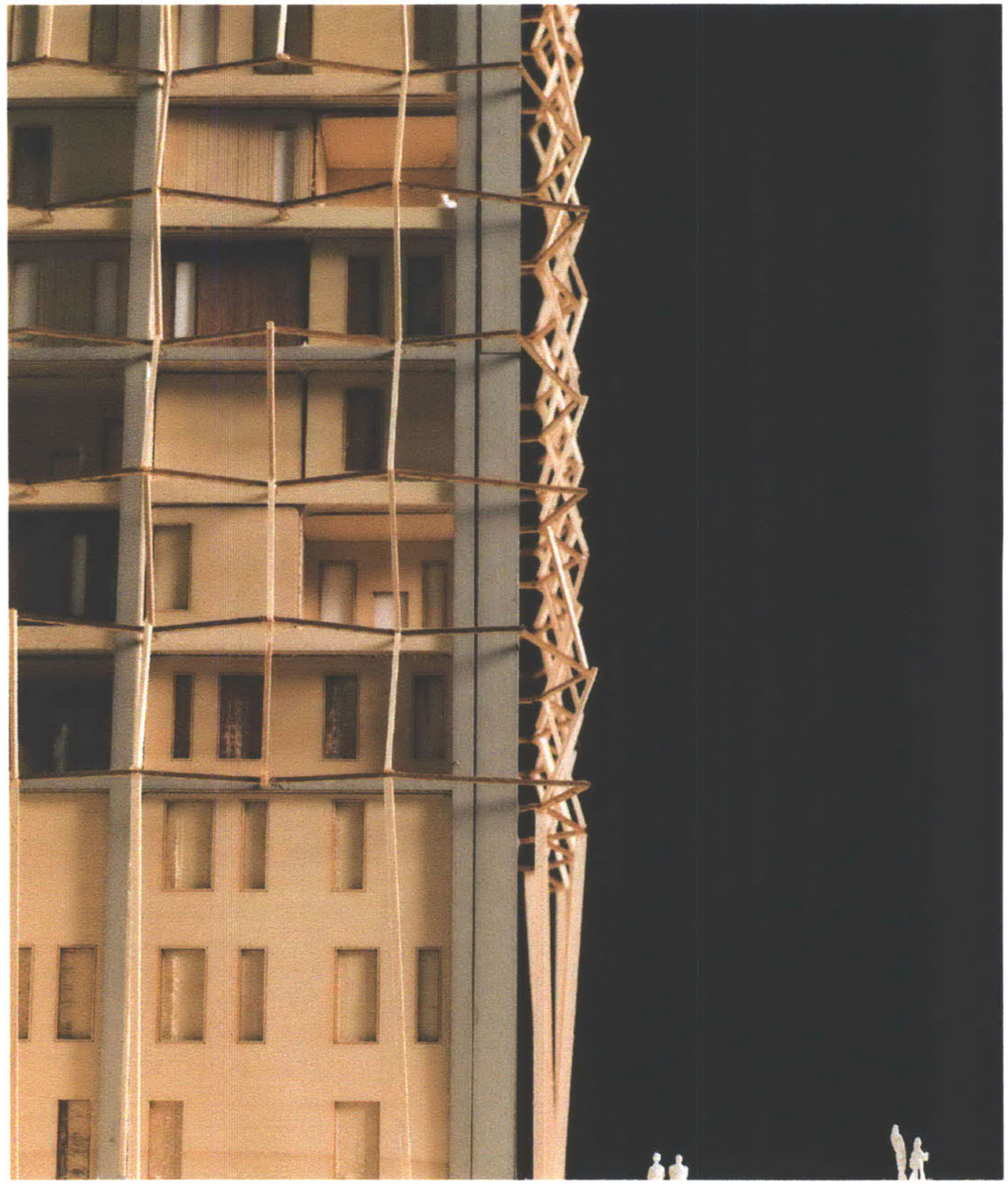
Tower screen model 1/4" = 1'



Tower model South East perspective



Model view of tower top exhibition terrace



Tower model base

PART FIVE

Machines that make

Tools for design vs tools for production

All machine work done in collaboration with Nadya Peek

SECTION 5.01

Out of the box: digital fabrication beyond 3d printing

Just a small portion of the expanding marker of 3d printers

Flexible tooling

The primary motivation for this research is a deep and vested interest in the physical act of making. Interaction with digital fabrication tooling provides designers with a fluidity between idea and actualization. During the physicallization of projects the maker is made keenly aware of material properties, geometric relationships, spatial effect, and often times in my case all the aspects that could be done better with the next revision!

Recently the design community has become enamored with 6 axis industrial robot arms and has utilized them in a number of creative manners. I attribute part of this interest in robotic pursuits to the relationship of designer and fabrication machine. Unlike more conventional fabrication equipment (laser cutters, 3d printers, CNC routers, etc) which have a predictable results due to their specified operation, the robotic arm is an open platform that can take on a number of functions. By simply modifying the end effector (tool head) the operation is drastically changed. To make an comparison with printing, the designer is no longer pressing print and waiting for the document, they are determining the printers functionality and choreographing how the material transformation happens. In this scenario designers are not limited by the what a machine can do, but are instead asking how a machine must work to accomplish the desired task. The robotic arm provides a motion platform from which a designer may innovate because it removes the high barrier of entry associated with motion control.

So is everyone buying a robot the answer? No. Robots are expensive, HIGHLY engineered machines that are both out of reach for many designers and often overkill for many types of fabrication applications. Is there a way to similarly enable designers with a robust motion platform that is inexpensive and highly accessible? This thesis probes the intersection between design and fabrication with the goal of creating a reconfigurable motion platform for the creation of bespoke digital fabrication techniques.

The insurgence of low cost "machines that make' in the form of 3d printers and desktop CNC mills has had a two pronged effect; cheaper more readily available machine parts (steppers, shafts, control systems) and the development of generation of makers/tinkerers. Utilizing the momentum of these trends the this project aims to develop a non specific tool set for the rapid development of novel fabrication tooling.

> "We can separate the design of a product from its manufacture for the first time in history, because all of the information necessary to print that object is built into the design." (Carl Bass)

It is a mistake to think digital fabrication separates design from manufacturing, in many ways it conflates them. The design is intricately related to the method of fabrication and within it is the potential for new exciting and disruptive ways of making.

1 Carl Bass. The Washington Post 'The past present, and future of 3-D printing 09.24.2011

A high barrier of entry: DIY 5 axis router

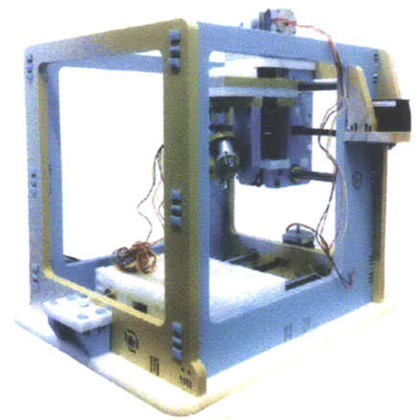
What is stopping people from creating their own fabrication tools?

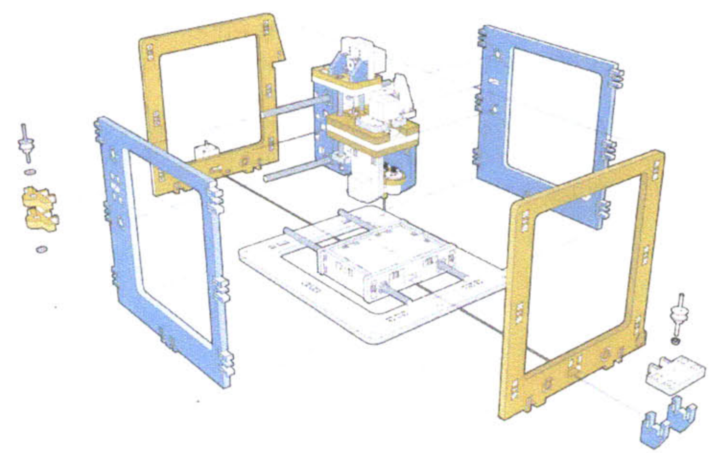
'How to make something that makes almost anything"

Neil Gershenfeld's follow up class to "How to make (almost) anything" is illustrative of the challenges faced by an individual interested in creating a machine that makes.

Machines are hard to make! In this class I created a belt driven 5 axis router that could be entirely fabricated on a Shopbot router for under $500. During this process I encountered numerous hurdles in mechanical assembly, motor control, software integration, and hardware sourcing. Each of these hurdles is independent of the actual function of the router and the creative potential associated with said functionality. The barrier of entry is high for the ground up development of a fabrication machine. For a designer interested primarily in the output of the router, overcoming such hurdles is out of reach.

This machine was a 3 + 2 axis (5 total axes) which means it is a 3 axis system with a 2 axis articulating tool. The decoupling of the 5 axis motion simplified the overall construction. This principle of decomposing complex motion into component parts is explored in later sections as a means of creating complex tools with simple parts.





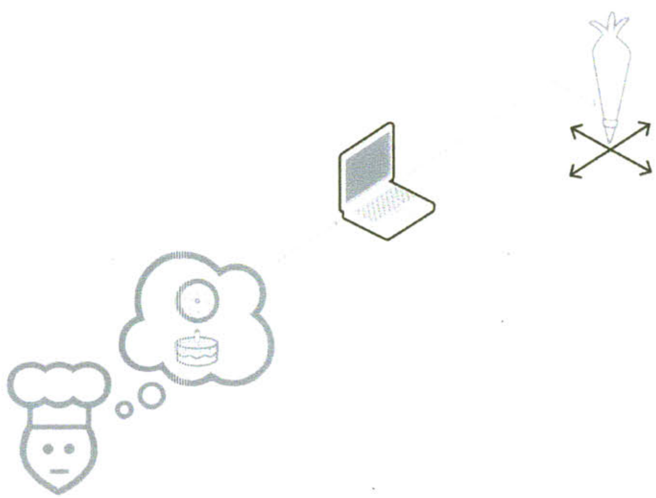
SECTION 5.02

The cake decorator

To illustrate how the barrier of entry I described might prevent the creation of personal fabrication tools let us look at the task of CNC cake decorating. Computer controlled frosting deposition on the surface seems like a simple task, little payload, simple 2 axis motion, and speed is of little consequence for the hobbyist. A ground up build of such a system is far more than an average person is interested in taking on, especially when the decoration and composition of the cake is really their primary goal.

How can we remedy this situation? The user whom may have the most interesting ideas and vested interest in the decorating of cakes is blocked from participation.

By breaking down this system into pieces we are able to see where barriers exist and where the machine design process can be "short circuited" allowing for wider participation. With a wider community participating, a diversity in tooling is inevitable.



A seemingly simple machine

As the diagram on the following page shows, the process of designing a CNC froster quickly becomes complex and requires a vast skill set. Knowledge of mechanical engineering, electrical engineering, and software are imperative for a this type of project.

The next thing to observe in the diagram is the splitting of end effector and motion platform. The motion platform is similar in design to any number of 2 axis machines and each requires similar/identical componentry. If a motion platform were provided, this method of working would resemble the way in which designers interact with industrial robot arms, adapting an existing infrastructure to suit their needs.

The following sections investigate how this decoupling of machine design elements can engage a larger community of potential DIY CNC enthusiasts.

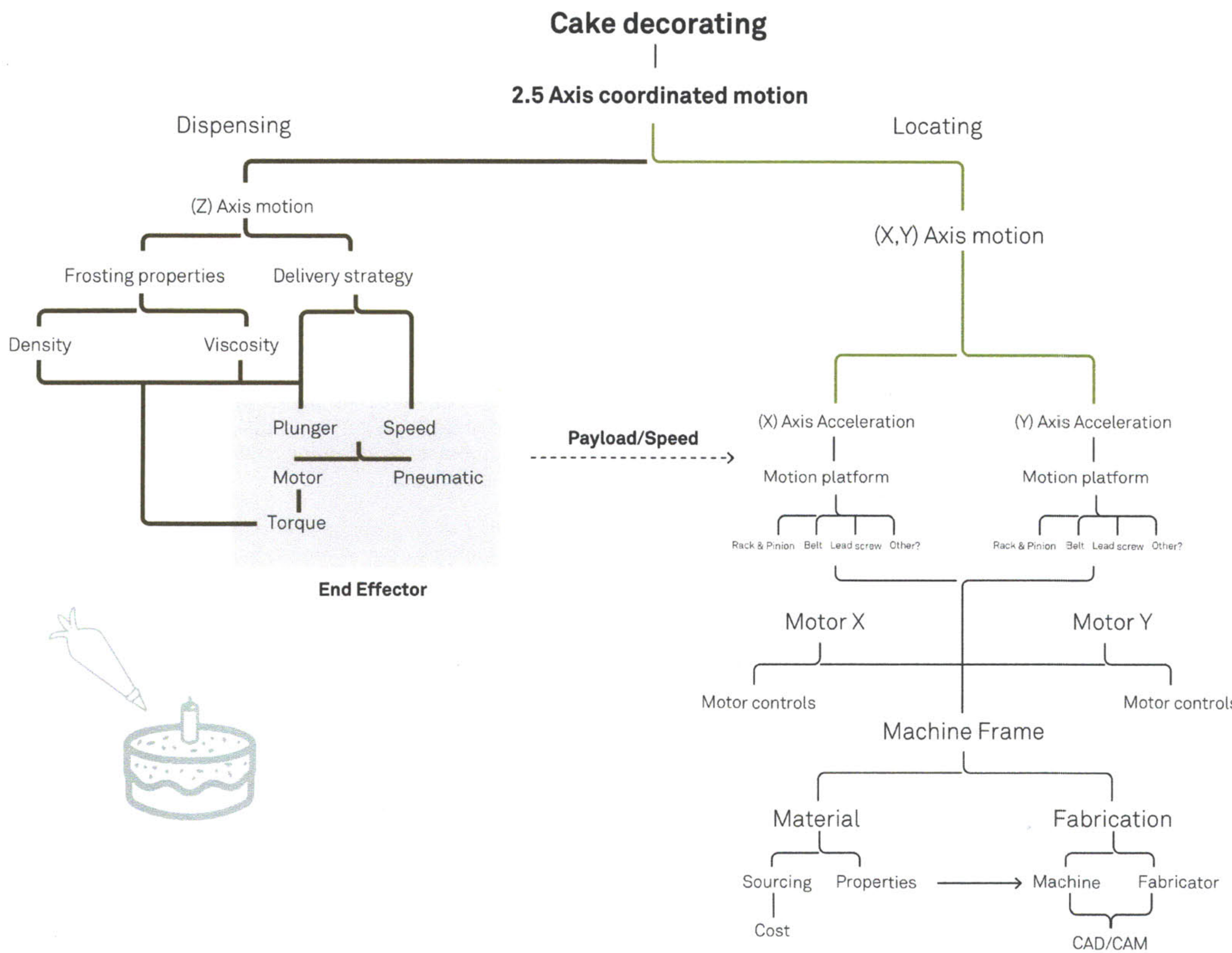


Diagram describing the rapidly increasing complexity of machine design

SECTION 5.03
Enabling design: Rapid tool design

Task specific machines require thorough engineering and do not lend themselves well to alternative/non specified uses. This becomes particularly apparent when production goals change and the machine is incapable of achieving the adapted/new operation. Multiple fields of research address this issue including multi purpose tooling and component based machinery that provide flexibility of operation. While this approach has been proved successful in slowing machine obsolescence, alterations to the machines are often difficult and still confined to specific tasks.

So what happens when the desired task is not known? How are new fabrication methods prototyped and explored by designers?

The following series of components aim to make the machine prototyping process extremely streamlined, revolutionizing how designers work with, imagine, and fabricate their ideas. By providing a non specific machine "framework" users are able to explore personal methods of making, leaving room for surprise, in what I deem orchestrated invention.

Instead of designers and engineers designing within existing machine constraints, in this scenario machines are created to manufacture the initial idea. This allows for the more fluid transfer of design intent from idea to actualization. This process would continually re-examine our current means and methods of making.

The following section describes how the combination of a universal control network with decoupled motion axes allows for the creation of unique CNC operations.

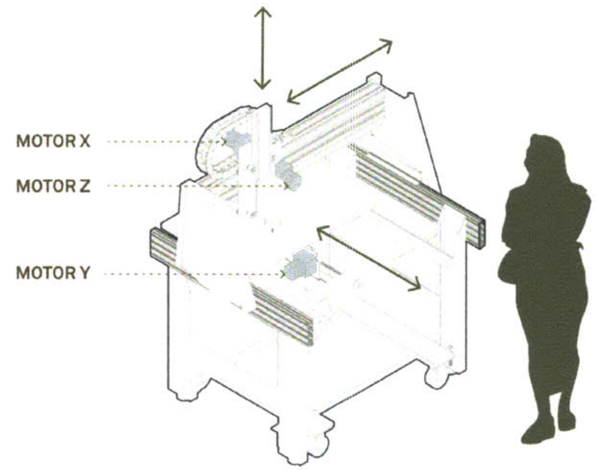
CNC breakdown

The majority of digital fabrication tooling operates within a Cartesian motion framework. Like the milling machines of the past, by combining values of 'X','Y', and 'Z' one can quantify a point in space respective to an origin location.

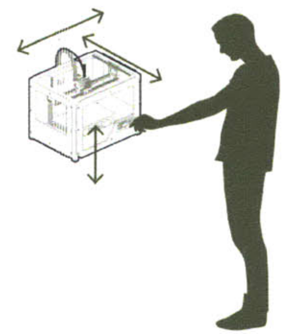
Though seemingly complex on the surface, either of the machines shown here can be broken down into:

- a series of coordinated motors
- motion transmission
- directional guides
- end effector (payload) or tool

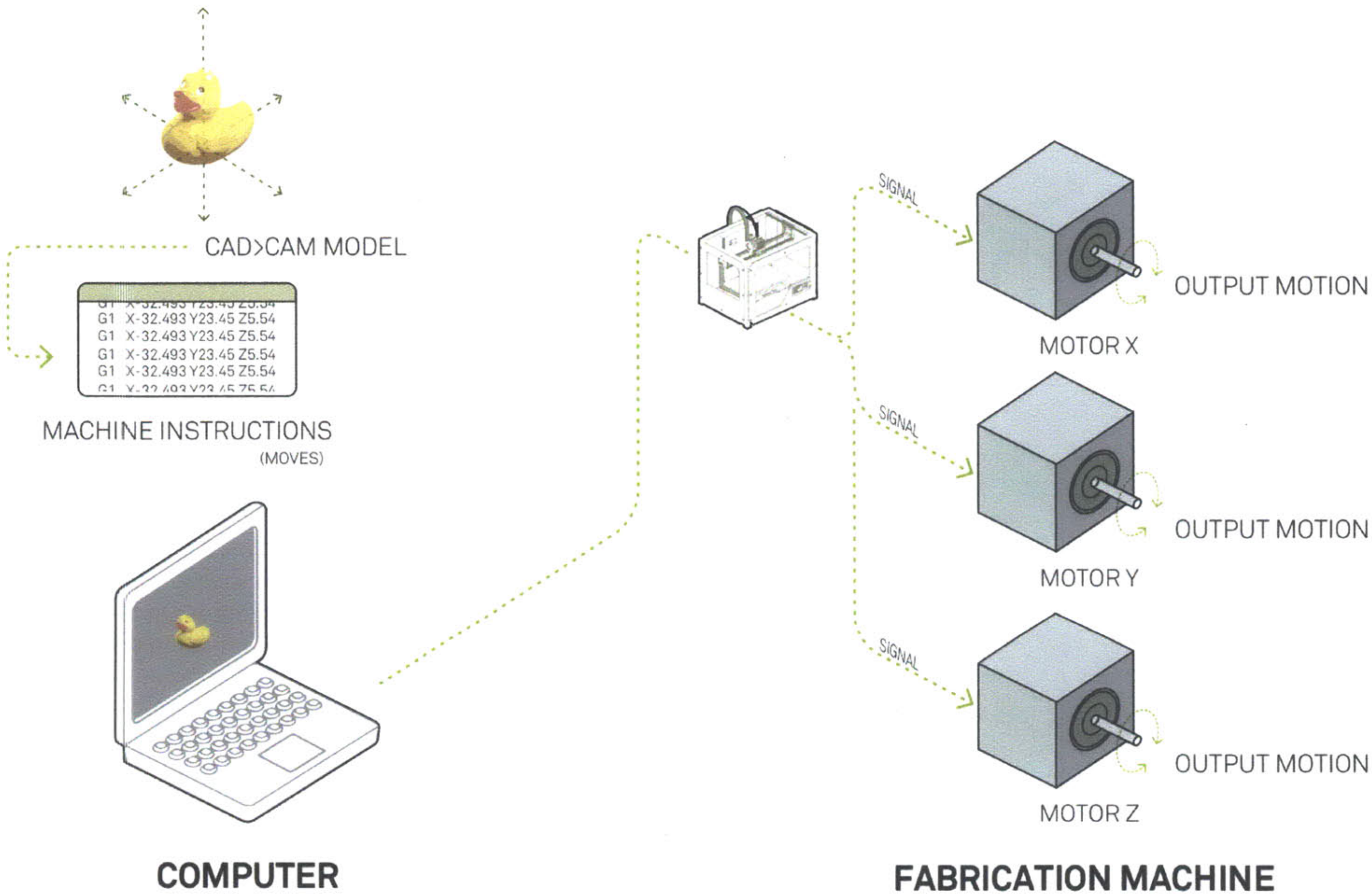
By linking axis position values to independent motors, they can be varied precisely, in turn covering a 3 dimensional volume. For operations that only require the varying of one or two values, such as writing, the motion can be accomplished by 2 motors. Routers exhibit one additional degree of freedom, translation in Z, which allows for any motion within a 3 dimensional volume. 3d printers like the Makerbot Replicator require an additional motor (4 total) for the controlled deposition of plastic.



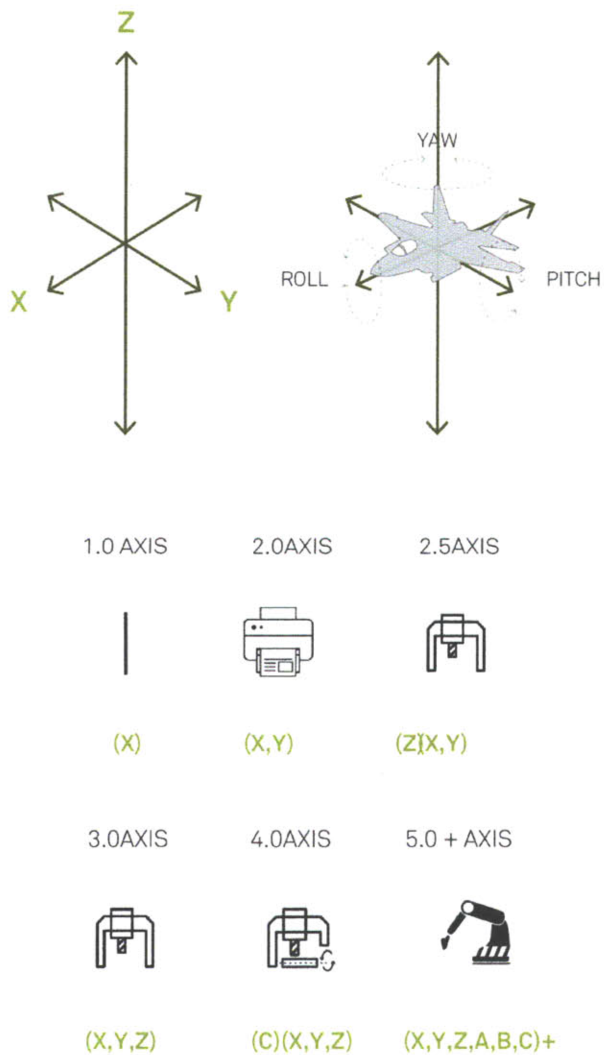
SHOPBOT BUDDY



MAKERBOT REPLICATOR 2



Machine control simplified diagram

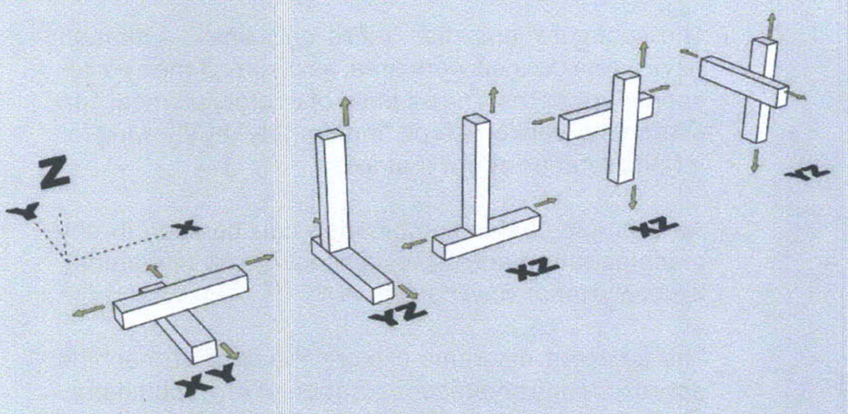


It is useful to evaluate the current methods of describing CNC motion mathematically in order to gain an understanding of the component parts of a fabrication machine. All fabrication machines must be provided with a set of instructions in order for it to move in a specified manner. These instructions are typically generated within a CAM (computer aided manufacturing) software that takes the mathematical representation of an object inside of a CAD (computer aided design) and converts it into a series of move commands often referred to as 'G Code'.

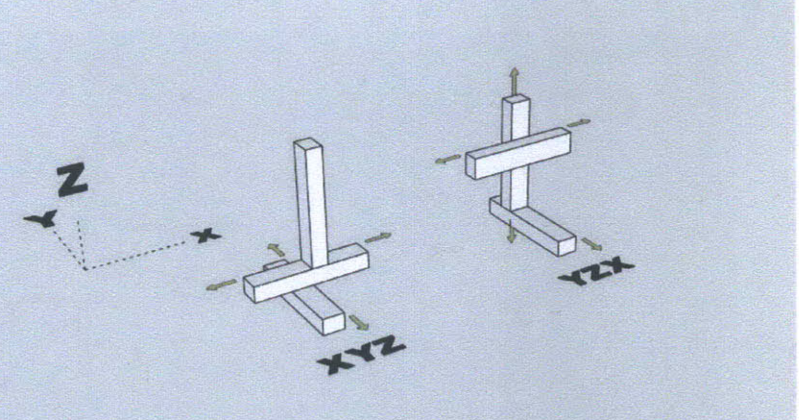
Depending on machine capabilities and the complexity of the desired motion, more or less instructional variables are required. For instance and printer manipulates a print head in 2 axes and requires 2 variables (X,Y) to describe its location in 2 dimensional space.

As the system becomes more complex, more and more variables are required to coordinate the motion of each of the actuators. These values can represent distance from the origin (X,Y,Z), or angular values when describing rotations in 3 dimensional space. The kinematics associated with different motions will be described later, but it is important to note there are 2 primary ways of instructing a fabrication machine; linearly and rotationally.

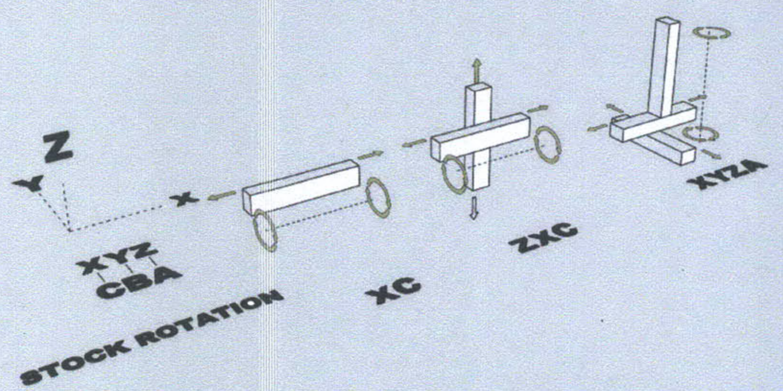
The following set of diagrams speculate around machine configurations possible with a combination of linear and rotary actuators.



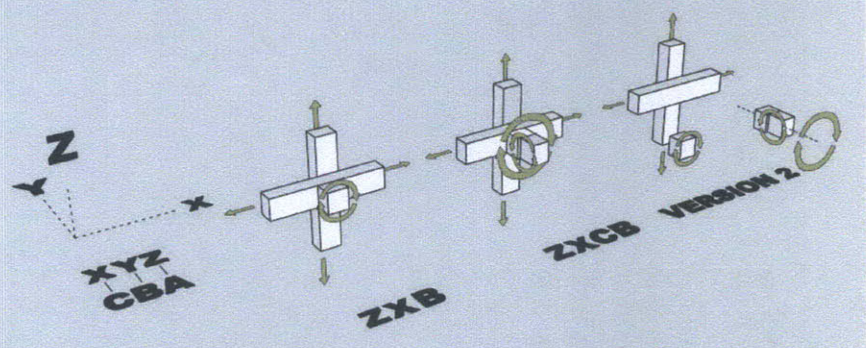
2 AXIS CONFIGURATIONS
LINEAR STAGE ONLY



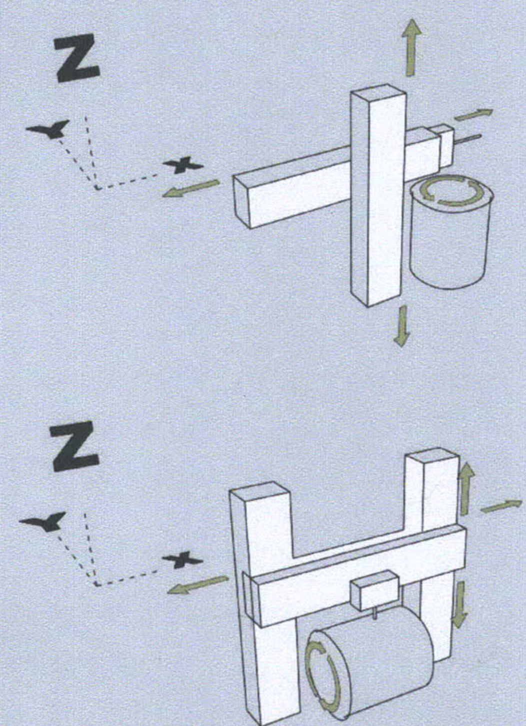
3 AXIS CONFIGURATIONS
LINEAR STAGE ONLY



MULTI AXIS CONFIGURATIONS
LINEAR AND RADIAL COMPONENTS



MULTI AXIS CONFIGURATIONS
LINEAR AND RADIAL COMPONENTS



MULTI AXIS CONFIGURATIONS
SPECTULATIVE ARRANGMENTS

The configurations that utilize only linear actuation have a very defined work area, as a sum of their corresponding lengths. The addition of a rotary element can extend the work envelope "indefinitely" by allowing for infinite rotation about that axis.

An example of this combination can be seen in any machine that manipulates a spool or roll of material, like a plotter or vinyl cutter.

The adjacent diagrams explore the idea of machine approximation and reconfiguration. With a robust precision linear stage and rotary platform bespoke fabrication tooling can be quickly prototyped.

SECTION 5.04

Design strategy of a non specific machine

The notion of a non specific machine is inherently non intuitive because we typically understand machines as being purpose driven and designed to meet a set of specifications. This is evident in the Merriman definition of a machine:

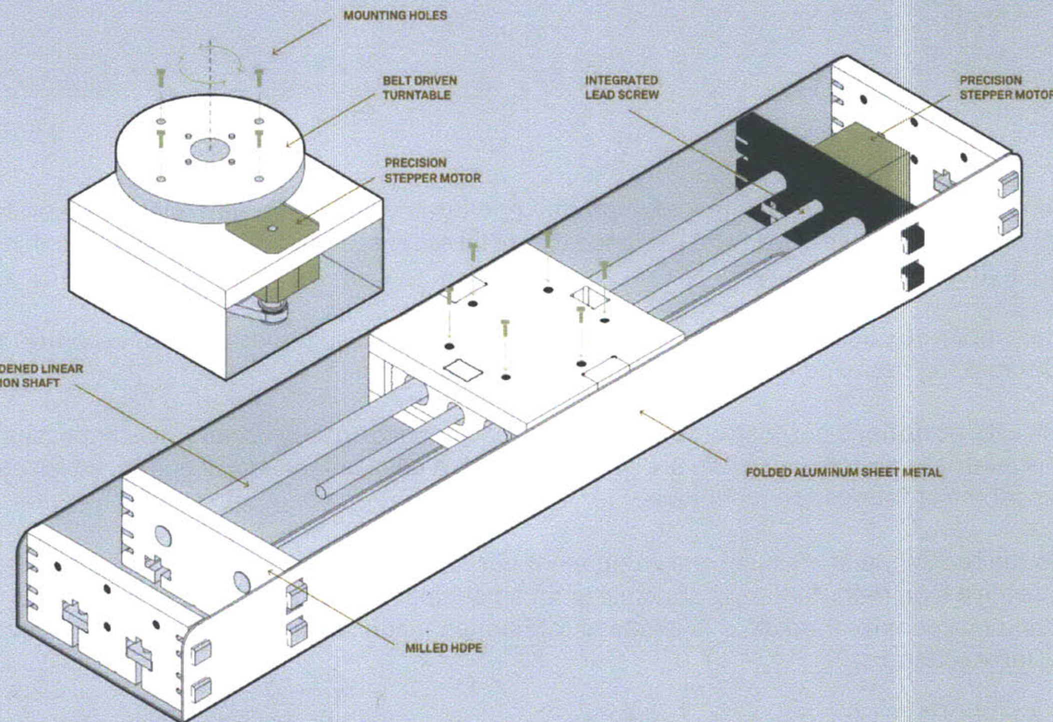
> "an apparatus using or applying mechanical power and having several parts, each with a definite function and together performing a particular task."

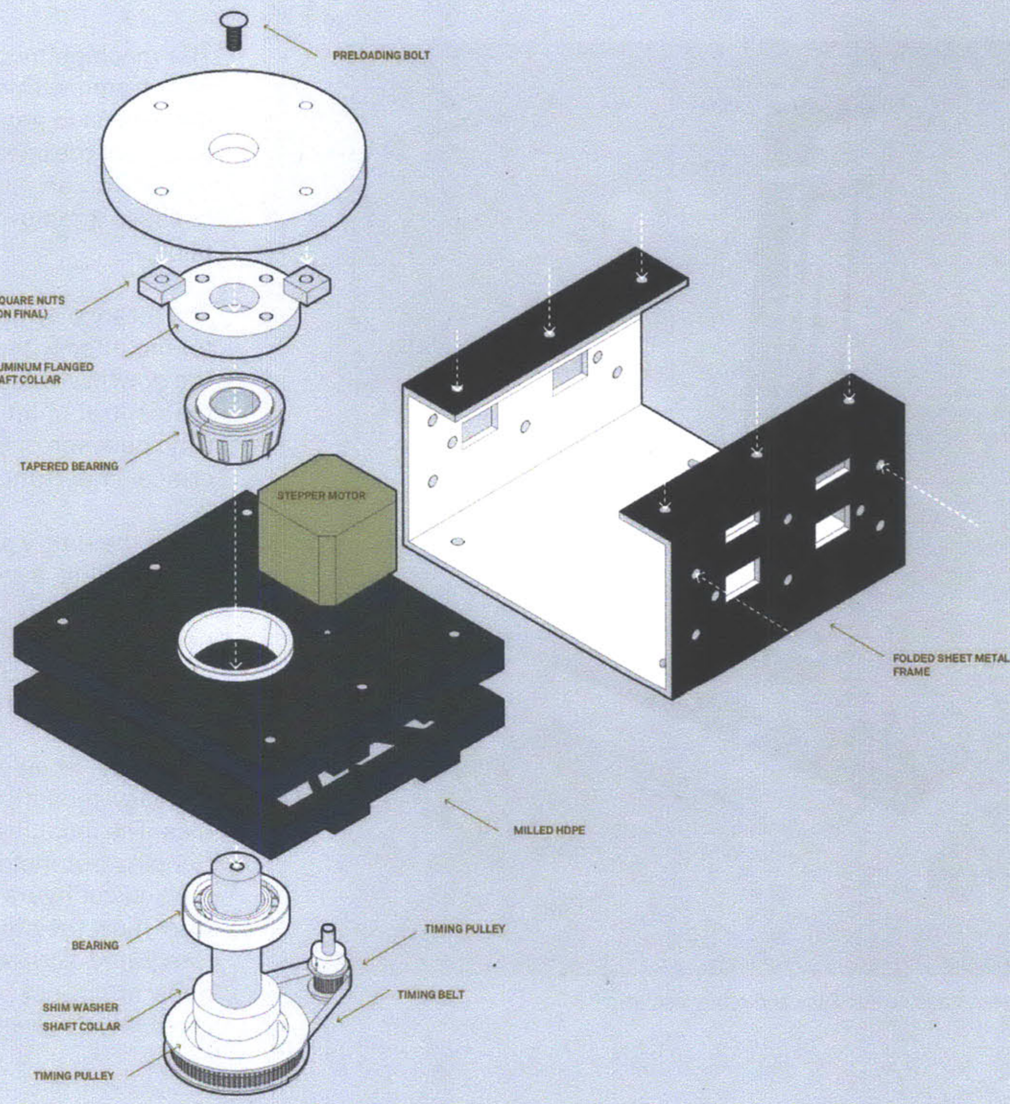
A machine with no defined purpose or function is a difficult one to specify because it is impossible to quantify or evaluate performance. We are presented with a chicken and egg scenario, which came first the machine or fabrication technique.

Similar to the technique of 'misuse', the component based strategy deploys 'quick and dirty' prototypes, utilizing a lean manufacturing principle of minimal input for maximum learning. By providing a robust and inexpensive module, a diversity of fabrication machines can be quickly tested, evaluated, and later refined.

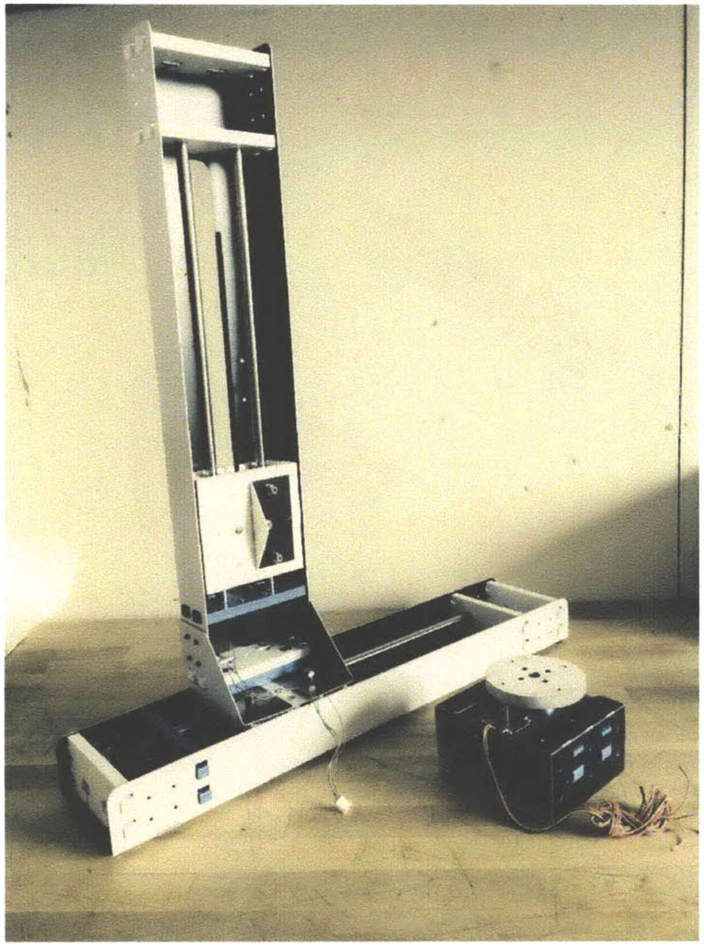
ROTARY POSITIONER

LINEAR STAGE





ROTARY MODULE COMPONENTS


Linear stage combination and rotary platform

The machine modules are composed of a folded aluminum frame with milled HDPE components that position the precision ground shafts and support the motor. The motion of the linear stage is driven by a precision stepper motor with an integrated lead screw. This is convenient because it removes the need for a shaft-lead-screw coupling.

The rotary platform also utilizes a precision stepper motor mounted with the shaft facing downward. Attached to the downward facing shaft is a timing pulley that rotates the central shaft via a urethane timing belt. The pulley ratio between drive pulley and shaft pulley (1/4) and is of critical importance for the translation of torque.

Since the rotary platform can experience both radial and axial loading, a tapered bearing was used at the base of the platform. To provide the required preloading force necessary with the tapered bearing, a shaft with tapped ends was used to compress the bearing by forcing the aluminum platform downward onto the bearing.

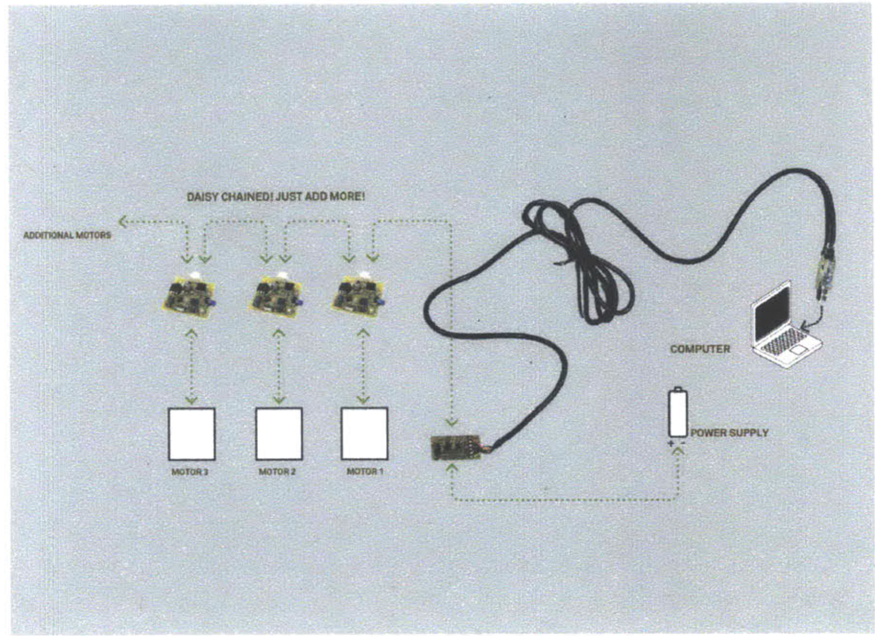
Additional holes were provided in the aluminum frame for easy reconfiguration and disassembly of the modules. The modules do not contain any preconceived functionality but instead prompt the user to invent the tooling and configuration to suit their needs. To support this work-flow the stage platforms have mounting holes with integrated square nuts for the easy attachment of any apparatus. Just bolt it on and let it rip, precision control is achieved in seconds.

Once a configuration has been assembled we now require a method for precisely controlling the motors in the network. The control system of a fabrication machine is often one of the more daunting tasks because it requires a wide array of skills and knowledge.

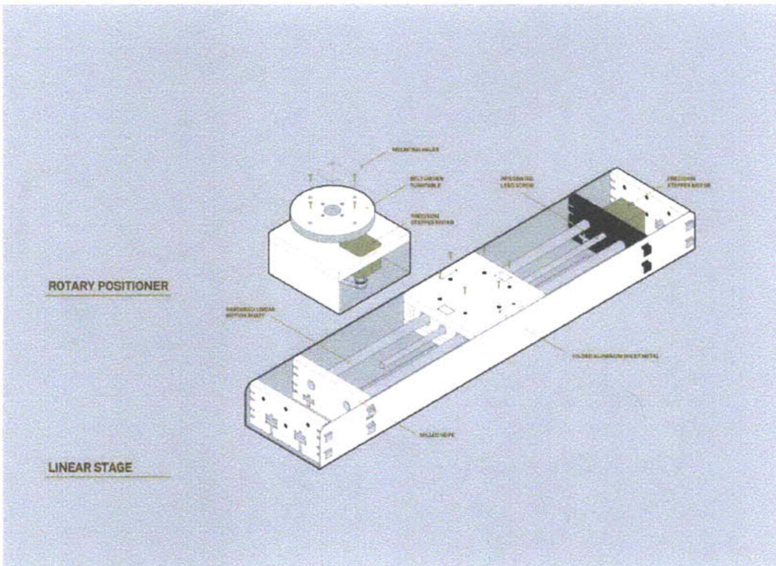
If the seamless reconfiguration of modules is to work as planned the control framework must be equally as modular and reconfigurable. This is a pivotal aspect of the project and without it there would be little chance a user would find the reconfigurability of the stages useful. The system implemented here is outlined in Ilan Moyer's Masters Thesis "A Gestalt Framework for Virtual Machine Control of Automated Tools" and described by Moyer as:

> "Gestalt is an accessible and flexible control framework which aims to augment the ability of individuals to create new automated tools, and to thus self-extend their abilities to create objects which would be too tedious or impossible to create by hand. This work will enable individuals to rapidly construct controllers and rich user interfaces for automated personal fabrication tools. "

The following diagram illustrates how the user can 'daisy chain' an arbitrary number of motors together, freeing the user from the requirement of creating a specialized control strategy for each configuration. Chain the motors together, identify the respective axes, and you're off to the races.



GESTALT



System components

Force calculations: Ambiguous loads

Without knowing the exact payloads, speeds, forces, or even orientation associated with the operation of the stages makes it difficult to prescribe part sizes and overall stiffness. Using the motor as a base metric to size the rest of the components was the strategy implemented here because it directly corresponds to payloads, accelerations, and available thrust force.

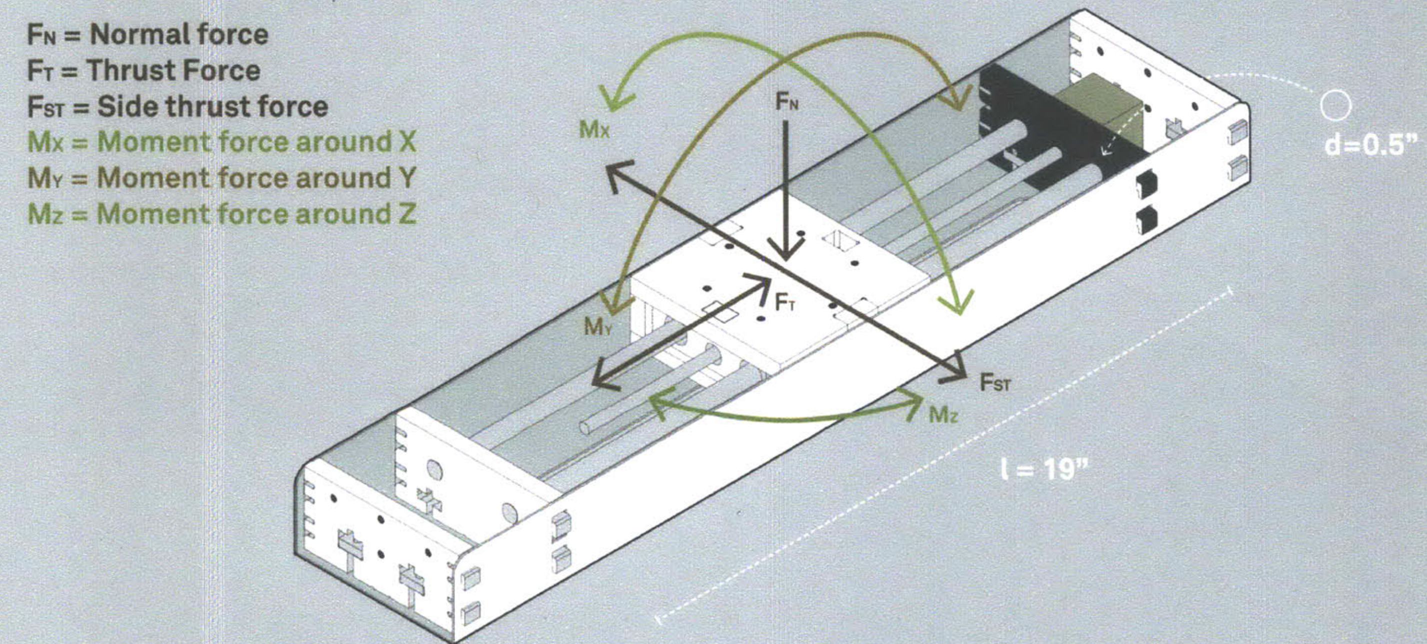
The following diagrams and formulas demonstrate the general loading conditions of the stage.

The thrust force (FT) is controlled by the capacity of the leadscrew lead nut assembly as well as the available motor torque.

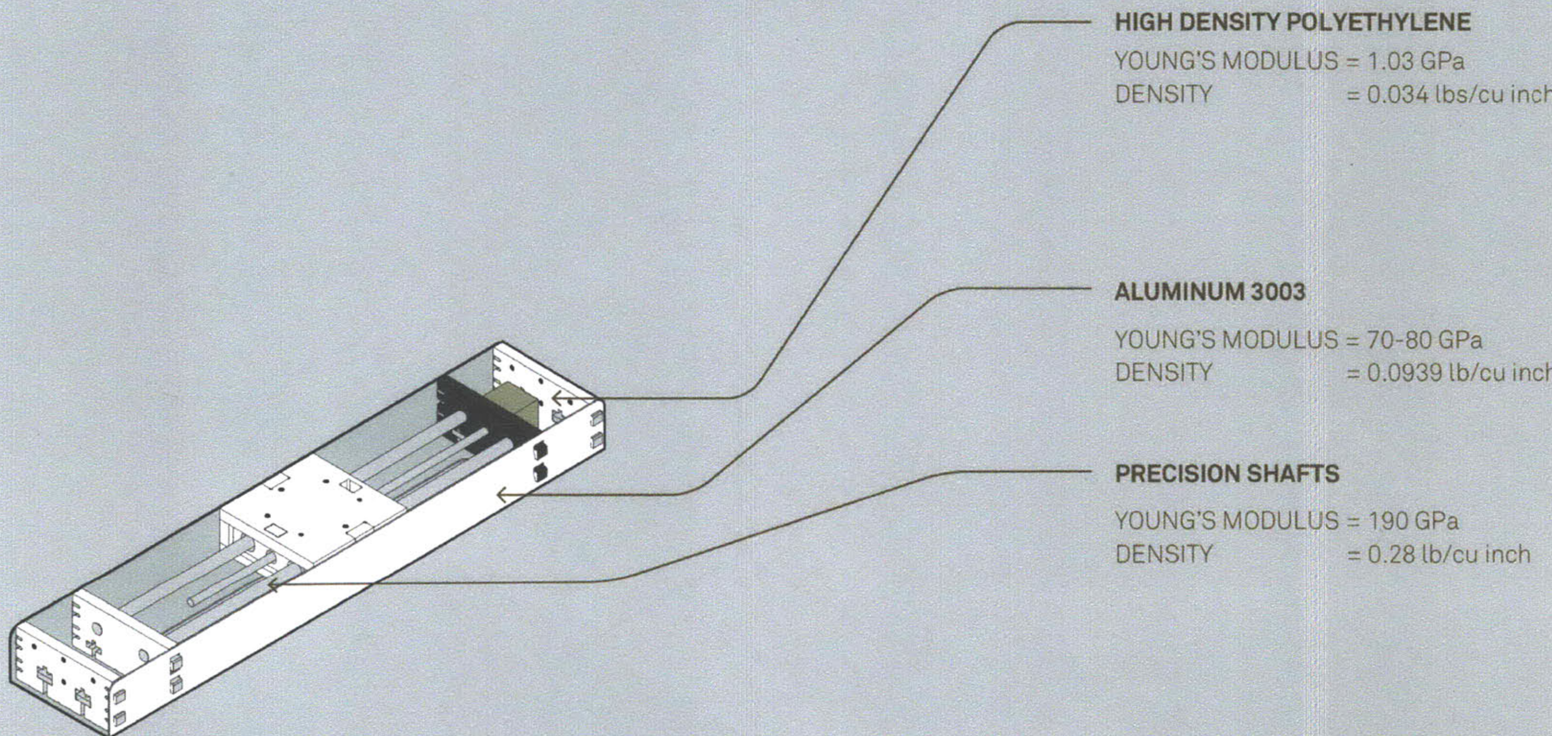
The Normal force and estimated payload were not significant contributors because any force that exceeds the capacity of the precision shafts would undoubtedly exceed the motor stall torque.

Any or all of the moment forces may exist during operation of the stage and are exaggerated by the distance away from center of the platform. These forces were estimated using a cantilevered beam equation. These forces can increase greatly during acceleration/deceleration of the platform.

As the configurations change the modules will experience a variety of forces and intensities. Performance, accuracy, and success of the operation will vary along with these forces. This is the curse of a non specific machine, it will be good at a number of things, but not great at any one.



Primary force diagram



Axis Stiffness $K = \frac{P}{\Delta} = 3\pi E \left(\frac{d^4}{l^3} \right)$

Beam deflection $\Delta = \frac{(P * l^3)}{48 * E * I}$ $MI = \frac{(\pi (d^4))}{64}$

Euler's Column Formula $P = \frac{(n * \pi E * I)}{L^2}$ $I = \frac{(bh^3)}{12}$

Image of drawing machine configuration

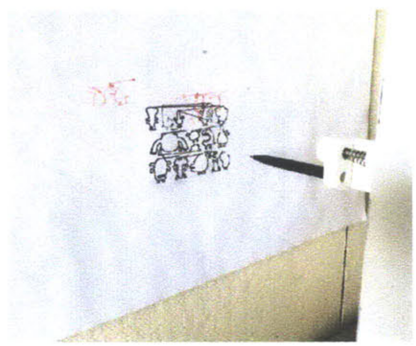
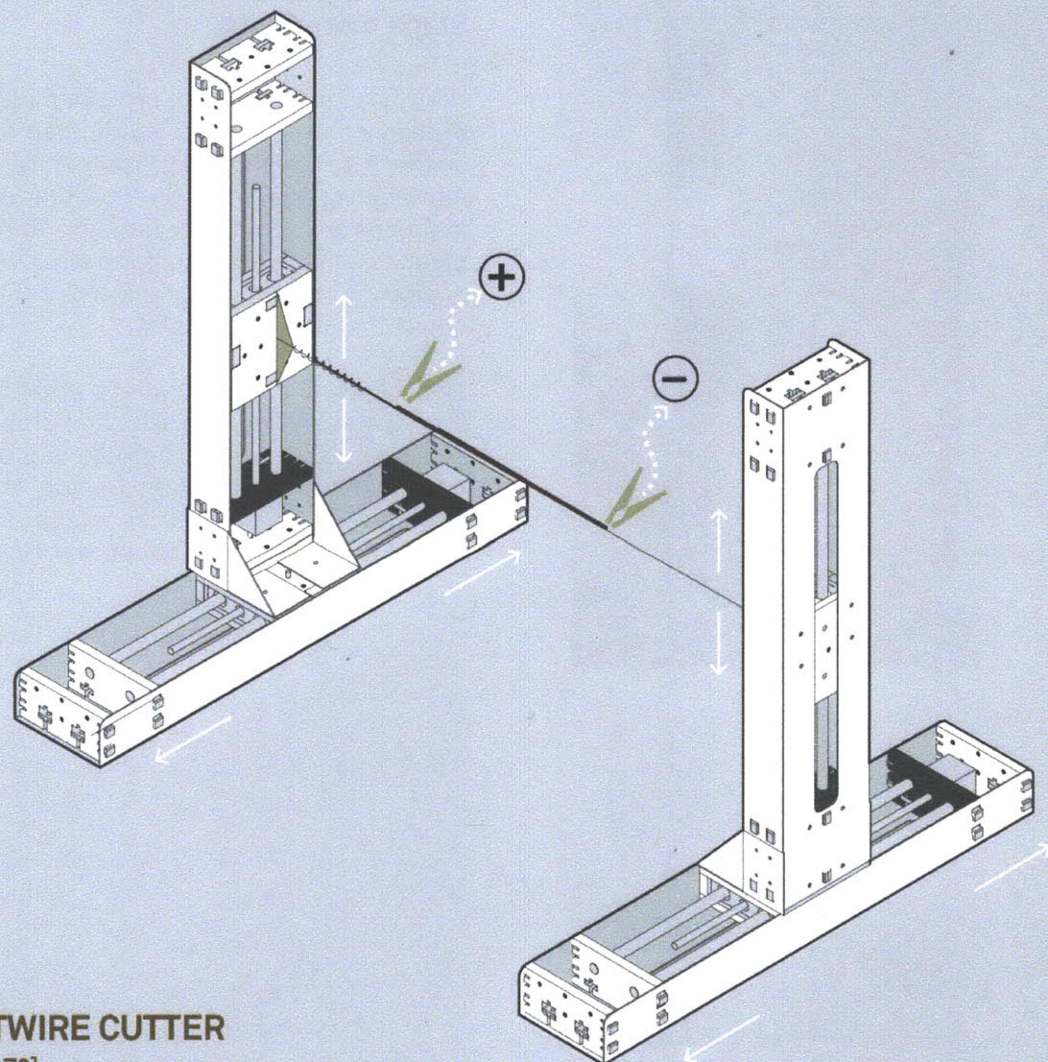


Image of drawing and end effector

Stage materiality

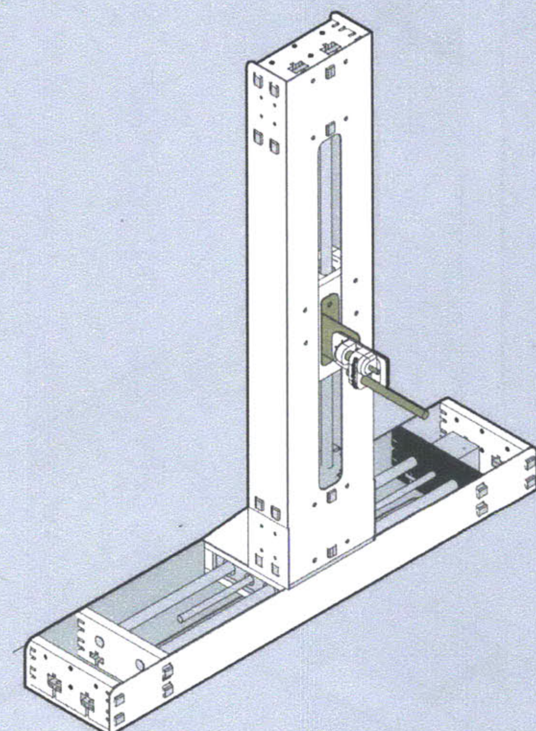
HDPE was selected as a primary material for a number of reasons including but not limited to; ease of tooling, strength to weight ratio, availability, and recyclability. Allowing the stages to be 'non-precious' removes user inhibition and promotes rampant experimentation. The plastic components transform what would be a very intimidating object out of metal into a friendly user-centric object that encourages play.

The following pages illustrate potential configurations for hotwire cutting, drawing, and 3d printing. These assemblies demonstrate the potential of 2, 3, and 4 axis coordination. These are well established machines/operations and are useful case studies for gauging performance under a variety of applications.



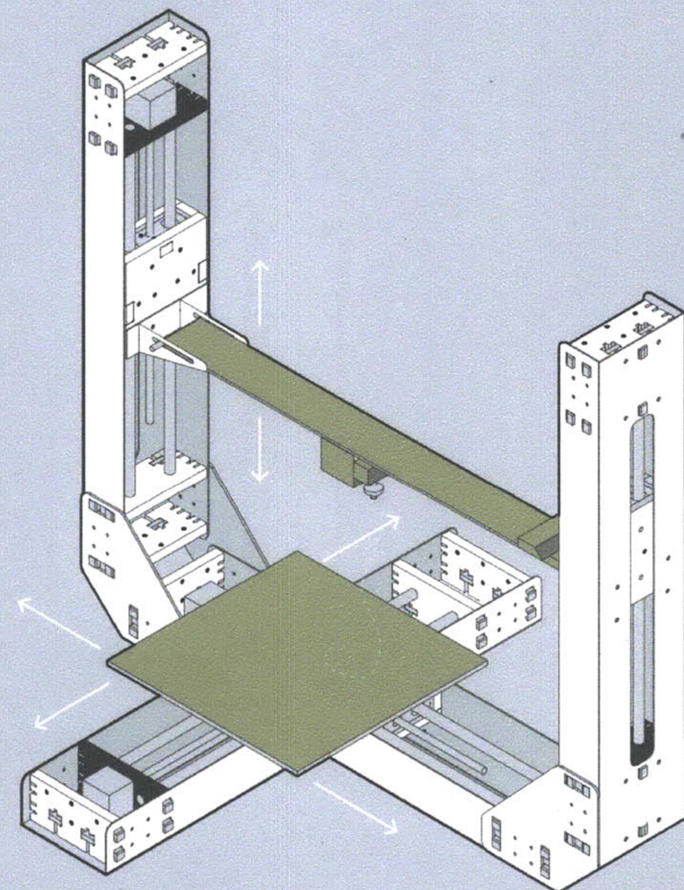
4 AXIS HOTWIRE CUTTER

[X1,Z1] [X2,Z2]



DRAWING MACHINE

[X,Z]



FDM 3D PRINTER

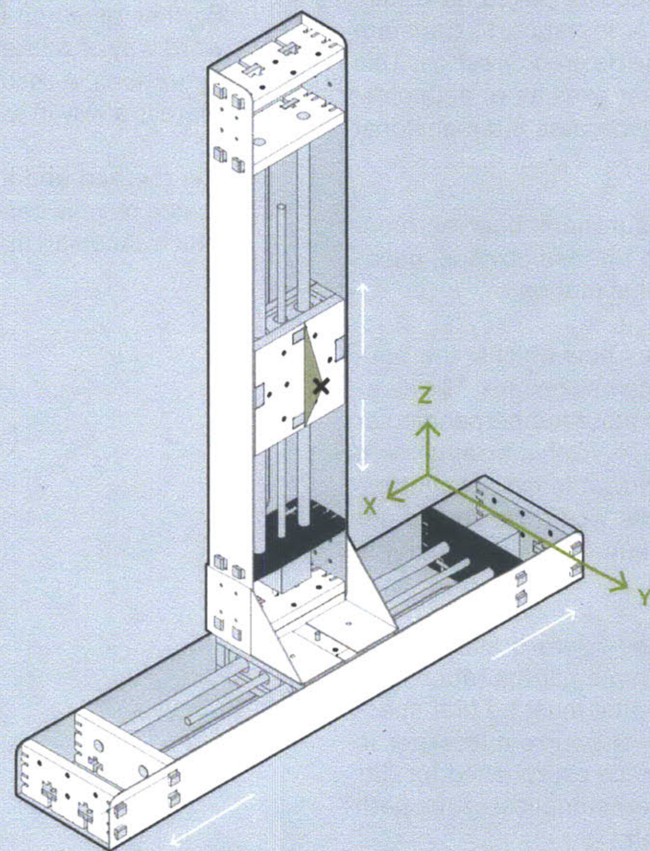
[X,Y,Z1,Z2]

END EFFECTOR POSITION = $\begin{pmatrix} X_E \\ Z_E \end{pmatrix}$

SERIAL KINEMATICS

$\Delta X = X_{desired} - X_{current}$

$\Delta Z = Z_{desired} - Z_{current}$



Kinematic strategies

The 3 configurations on the preceding pages have fairly straightforward kinematics. For instance, to translate in X, move the X axis motor in the desired direction. This remains true for each of the other axes as well. Coordinating moves in all three axes generates 3 dimensional motion.

As you might imagine, as configurations become more complex the kinematics become far less obvious, especially with the addition of rotational motion.

The following page demonstrates how quickly the path planning and kinematics can become complex. The illustration shows 2 rotary platforms mounted perpendicular to one another atop a linear stage. In this arrangement there exists kinematic redundancy. It is not straightforward what combination of moves would reach the desired end effector position because there are multiple solutions.

The calculations outline both the forward and reverse kinematics of this seemingly simple configuration. Because of the redundancy a (dx) value must be first specified for positions out of reach of the current location. In practice a ideal work 'offset' can be established for different operations, but this severely complicates the path planning and control of the system.

From the kinematics we can find the Jacobian matrix for this configuration which is a convenient way for identifying joint angles, torques, and velocities.
Further research is needed to determine a straightforward way of addressing increasingly more complex configurations. A reconfigurable machine is only valuable if there is a way in which to control it!

The method and kinematic model described on the following page is based on robot kinematic strategies from which Jacobian matrices are prevalent.

END EFFECTOR POSITION = $\begin{pmatrix} x_E \\ y_E \\ z_E \end{pmatrix}$

FORWARD KINEMATICS

$$x_E = (l_2 * \cos\theta_2)\cos\theta_1 + dx$$

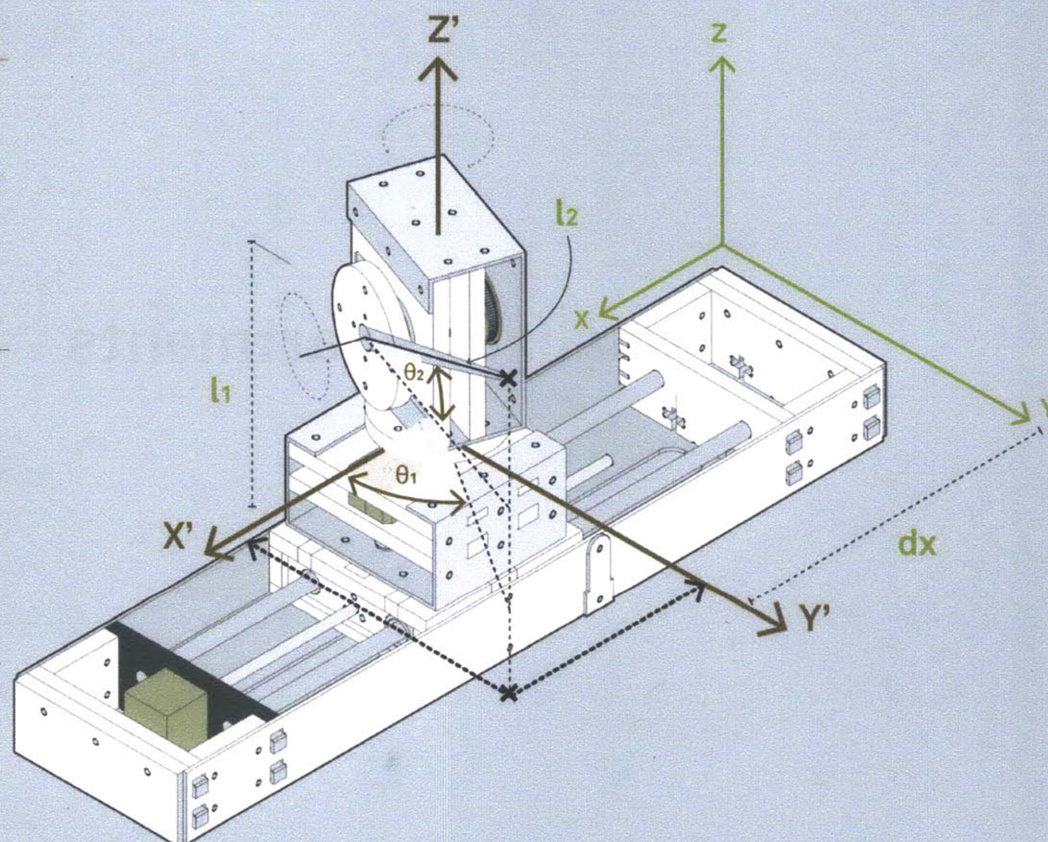
$$y_E = (l_2 * \cos\theta_2)\sin\theta_1$$

$$z_E = (l_2 * \sin\theta_2) + l_1$$

INVERSE KINEMATICS

$$\theta_1 = \tan^{-1}\left(\frac{y_E}{x_E + dx}\right)$$

$$\theta_2 = \tan^{-1}\left(\frac{(z_E - l_1)^2}{\sqrt{(l_2)^2 - (z_E - l_1)^2}}\right)$$



PART SIX

Personalized apartments

Power to the occupant

SECTION 6.01
Enabling reconfiguration

"New York's ability to adapt with changing times is what made us the world's greatest city – and it's going to be what keeps us strong in the 21st Century," said Mayor Bloomberg. "The growth rate for one- and two-person households greatly exceeds that of households with three or more people, and addressing that housing challenge requires us to think creatively and beyond our current regulations."

adAPT NYC is a pilot program that was launched in July 2012 through a Request for Proposals to develop a new model of housing – micro-units. The proposals were evaluated on several criteria, including innovative micro-unit layout and building design. The 'My Micro NY' proposal excelled in this category, with features like generous 9'-10" floor-to-ceiling heights and Juliette balconies that provide substantial access to light and air. The micro-units developed as part of this pilot will measure between 250 and 370 square feet.

Marc LaVorgna/Julie Wood NYC.gov

By constraining the square footage of the apartment modules to ~ 500 square feet, the spaces demand strategic thinking while space planning. Small living spaces must be efficient, clever, and often times transformable in order to accommodate a diversity of activities. In order to allow for quick retrofitting and customization of the space, a number of structural and organizational logics are put in place that take into account the readily accessible CNC fabrication equipment.

Example micro units and multipurpose spatial configurations

Figure 43

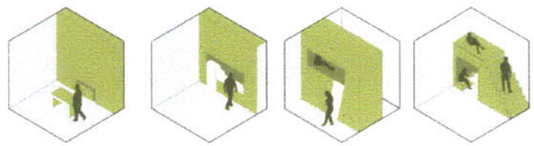
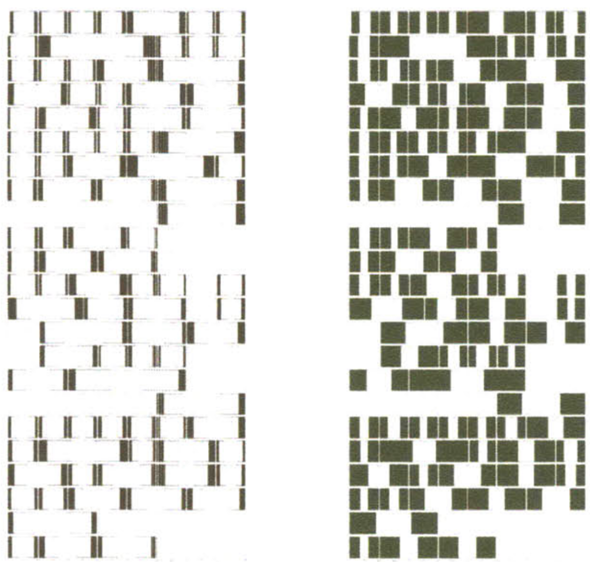


Figure 44



Reconfiguration of apartment space is enabled by a unique framing solution. Apartment walls are constructed of mass produced timber columns that come with pre drilled attachment holes for making quick connections. The wall footer and header are not load-bearing members, so the columns can be repositioned to suit the users needs. Simply unbolt, relocate, and re-bolt to alter internal configurations and even facade placement.

With access to CNC fabrication equipment, non planar connections are easily accommodated through 4 axis milling of the timber columns. The illustration on the following pages displays the connection strategy as well as the geometry required to make non planar connections to the timber columns.

The 'quick connect' strategy promotes the "thickening" of the walls to become either furniture or occupiable space. Figure 43 illustrates possible interventions possible when robust wall connection is available.

The ability for occupants to modify their ratio of indoor to outdoor space and in turn alter the building facade is an unprecedented flexibility in the tower typology.

Like the strategy of machine design discussed earlier, this connection detail orchestrates reconfiguration and provides users the ability to innovate within a framework that sponsors variation.

Figure 43: Sample occupant interventions and "thickening" of poche
Figure 44.: Building section describing the global effect of poche thickening, and how it might densify over time.

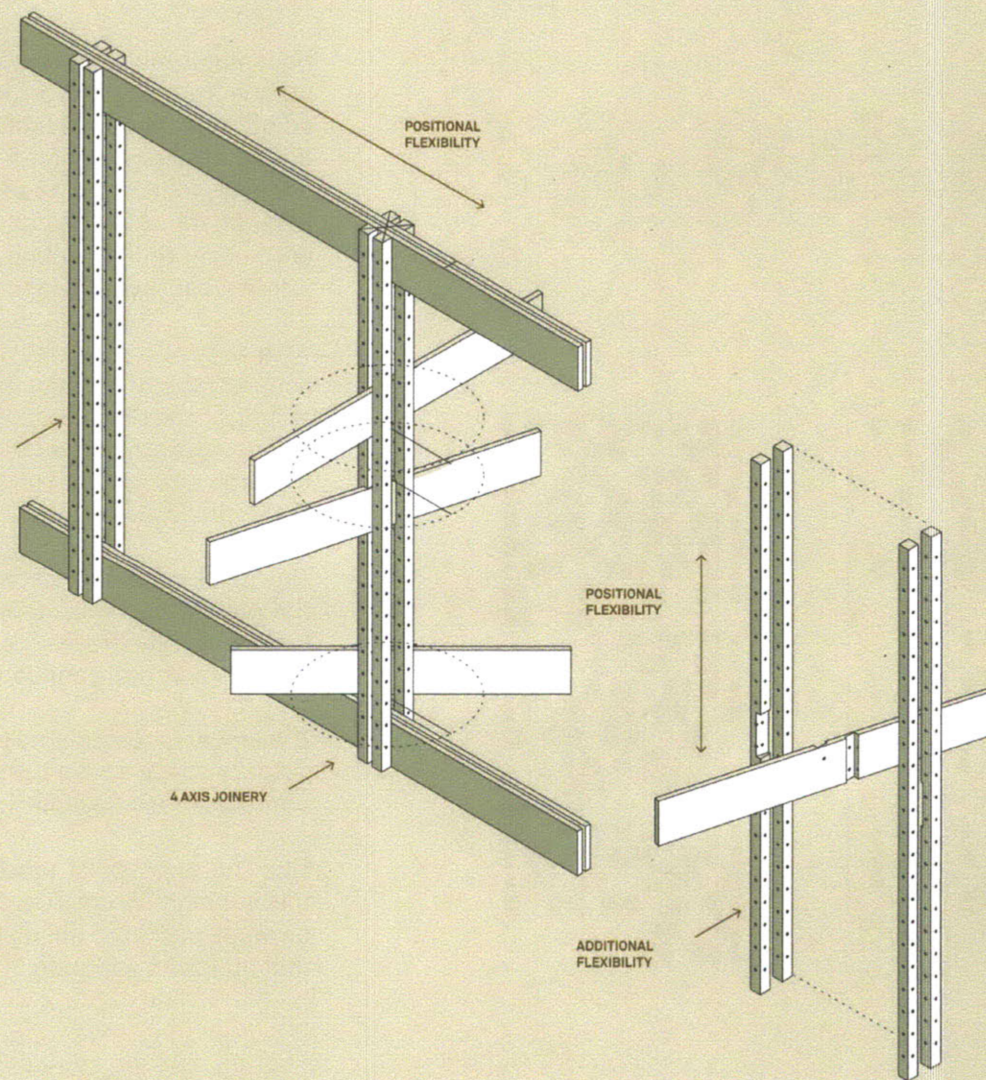
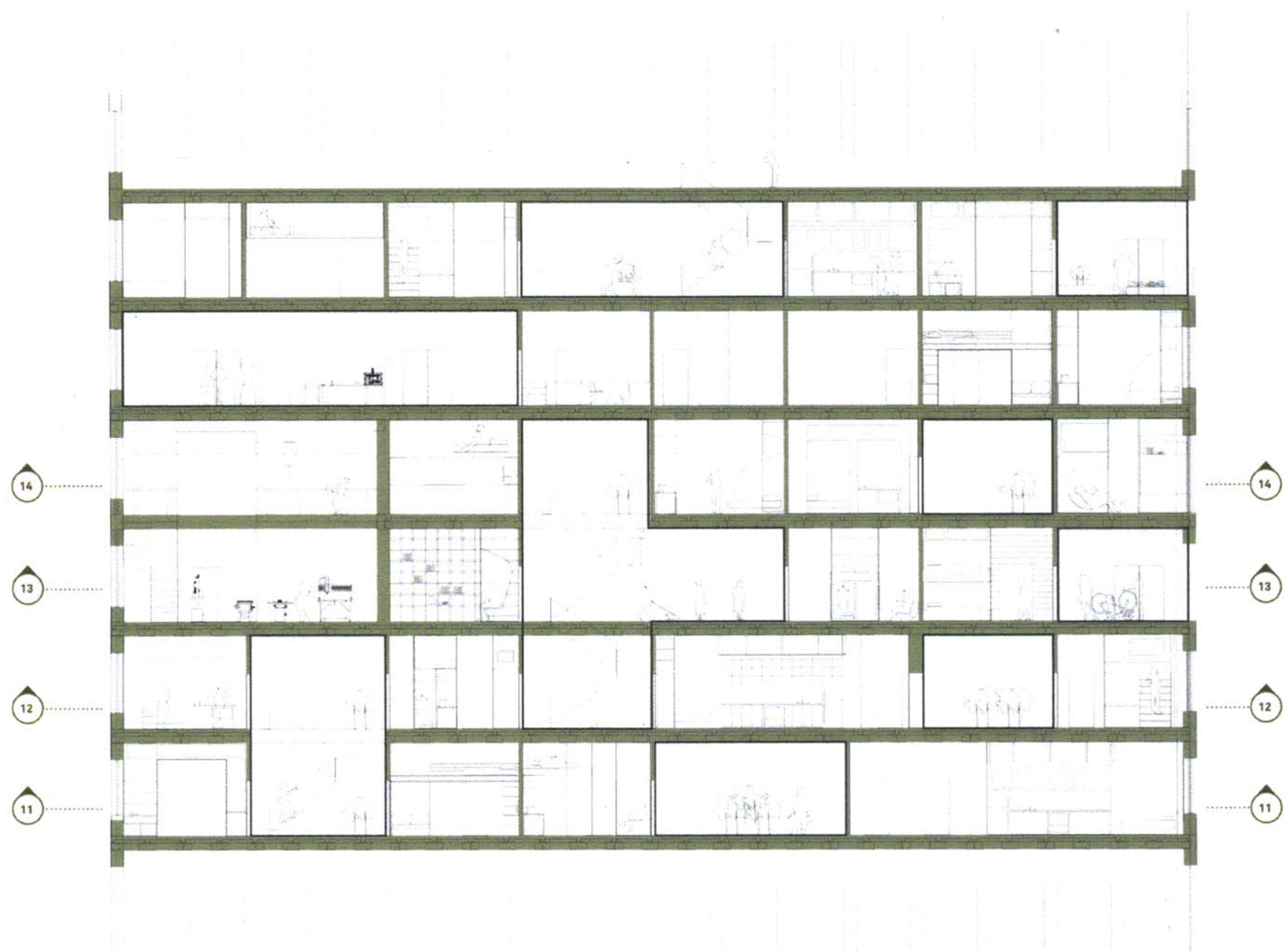


Figure 45: 'Quick connect" wall reconfiguration strategy.



Tower section illustrating a potential "thickening and subsequent occupation of the poche"

PART SEVEN

Machine building

how to make something that makes almost anything

SECTION 7.01

Fabricating fabrication machines

The initial prototype of the linear stage frame was constructed entirely of milled HDPE during a machine building working at MISIS University in Moscow. This design was eventually abandoned for a lighter and stiffer folded aluminum frame that could easily be stamped if mass produced.

Sheet metal folding is a much less precise operation than milling and special considerations were required during the fabrication and construction of the modules. One disadvantage of the folded sheet metal design is the requirement of a waterjet machine for the creation of a stage. Waterjet machines are much less prevalent than CNC routers (limiting the ability of others to replicate the work), but it was a necessary alteration for dramatically improved performance.

The following pages briefly describe the fabrication process and the special considerations taken to achieve simplicity of construction. As and open-source project, reproducibility and ease of dissemination was a primary goal.

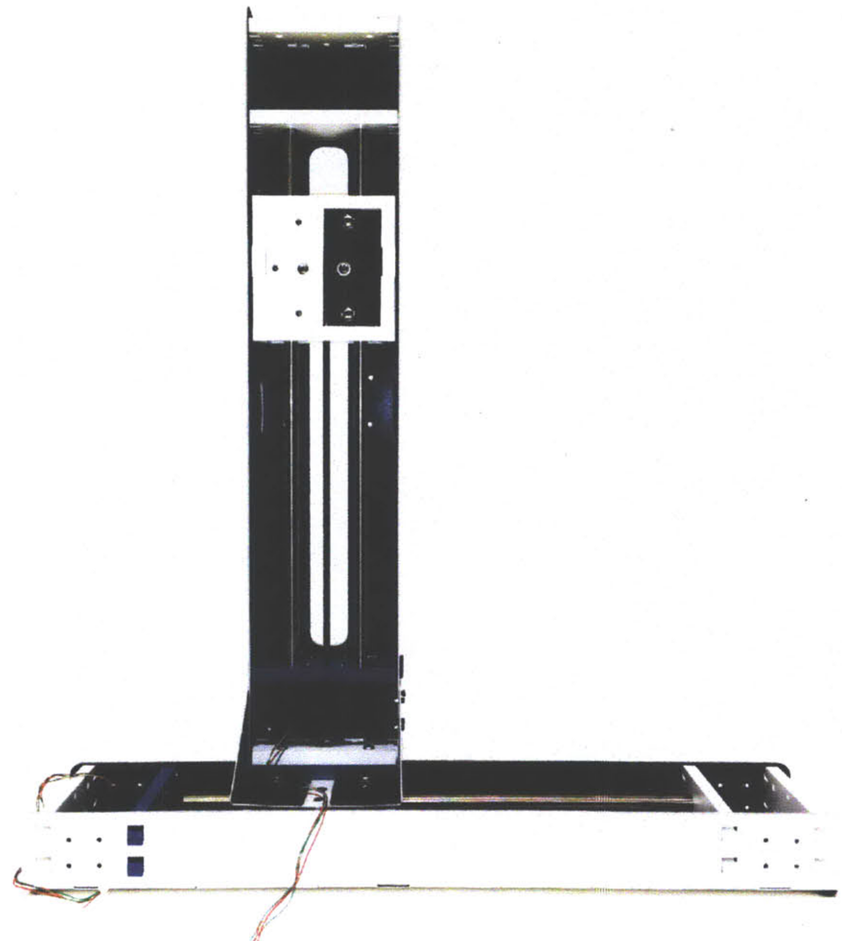
The primary materials of the stages as described previously are aluminum and HDPE.

The aluminum is has a thickness of .063" or 14 gauge. It was cut on an Omax waterjet and then folded on a hand-brake into its final configuration. Relief cuts were made along the folding centerline to improve accuracy and assist in alignment on the brake. The bend allowances and forces are described in the coming pages.

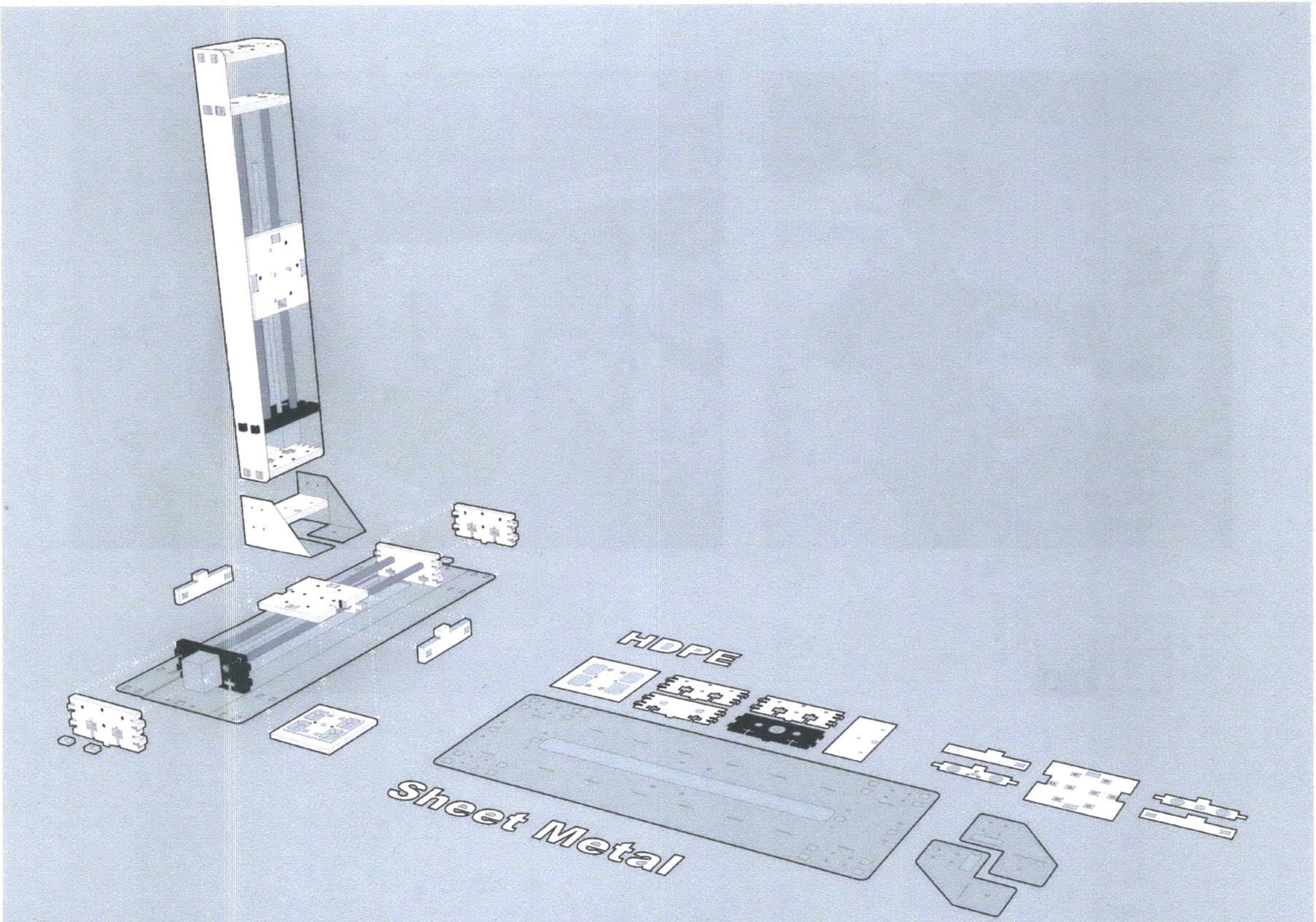
HDPE was used for the remaining components including the shaft supports, platform, and motor mount. The plastic was milled on a Shopbot router with a single flute soft plastic endmill. The cutting forces are considerably low with HDPE, using manufacturer recommended chip-loads the parts were cut at 3.5 in/sec. This makes for quick machining and negligible tool wear. The colored plastics has the added benefit being aesthetically pleasing and a refined appearance for a prototype.

Precision shafts, bushings, and hardware were sourced online, are readily available, and inexpensive.

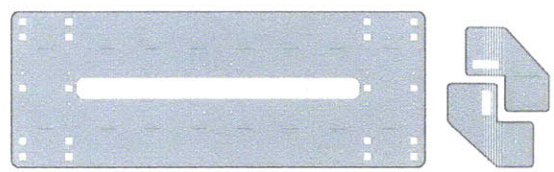
The following illustration shows the module assembly and cutsheets that were released as open-source files.



(Y,Z) machine configuration



(Y,Z) machine configuration exploded axon and cutsheet



HDPE components were milled using a CNC router and aluminum parts were fabricated using a Waterjet machine.

Sheet metal folding is an enticing operation because of the speed at which very rigid sections can be formed with relatively little material. This is the primary reason for the frame composition being aluminum sheet.

Knowing that this process is a notoriously low tolerance, special considerations were necessary for the connection between the machined HDPE parts and the folded sheet to ensure proper shaft alignment.

Based on Professor Slocum's 'General Dimensional tolerance for sheet metal formed parts' chart, it was apparent that there was a high likelihood the shafts could be misaligned vertically. To address this issue the additional tolerance was added to the slots that receive the HDPE parts. The HDPE was designed with hooks that could translate vertically to accommodate dimensional errors from the folding process. While the slots allowed vertical translation, they restricted movement parallel to the shafts. Translation in Z and perpendicular to the shafts was constrained by bolts anchoring the HDPE to the base of the aluminum channel.

This assembly as well as the sheet metal calculations are described in the following illustration.

GENERAL DIMENSIONAL TOLERANCES FOR SHEET METAL FORMED PARTS.

(UNLESS OTHERWISE SPECIFIED)

Dimension Range	Edge to edge, or hole to hole, or edge to hole. (NO BEND AREA) FLAT **Dimension A**	Edge or hole to bend* **Dimension B**	Bend to bend* **Dimension C**	Angular Tolerances **Dimension D**
0.25" or less (6.0mm or less)	± 0.005" (0.13mm)	± 0.01" (0.25mm)	± 0.01" (0.25mm)	± 2 degree
over 0.25" to 1" incl. (over 6mm to 25mm)	± 0.006" (0.15mm)	± 0.01" (0.25mm)	± 0.015" (0.38mm)	
over 1" to 5" incl. (over 25mm to 127mm)	± 0.007" (0.18mm)	± 0.01" (0.25mm)	± 0.015" (0.38mm)	
over 5" to 16" incl. (over 127mm to 406mm)	± 0.008" (0.20mm)	± 0.015" (0.38mm)	± 0.02" (0.51mm)	
over 16" to 40" incl. (over 406mm to 1016mm)	± 0.01" (0.25mm)	± 0.02" (0.51mm)	± 0.02" (0.51mm)	
over 40" to 90" incl. (over 1016mm to 2286mm)	± 0.02" (0.5mm)	± 0.025" (0.64mm)	± 0.05" (1.27mm)	

* Tolerance will increase if more than one bend (such as Dimension E)

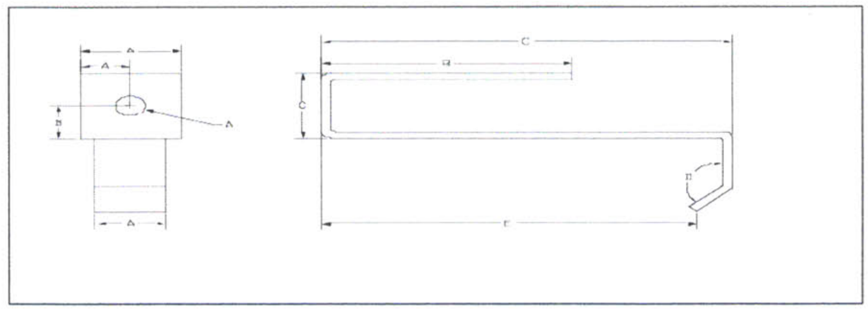


Figure 45

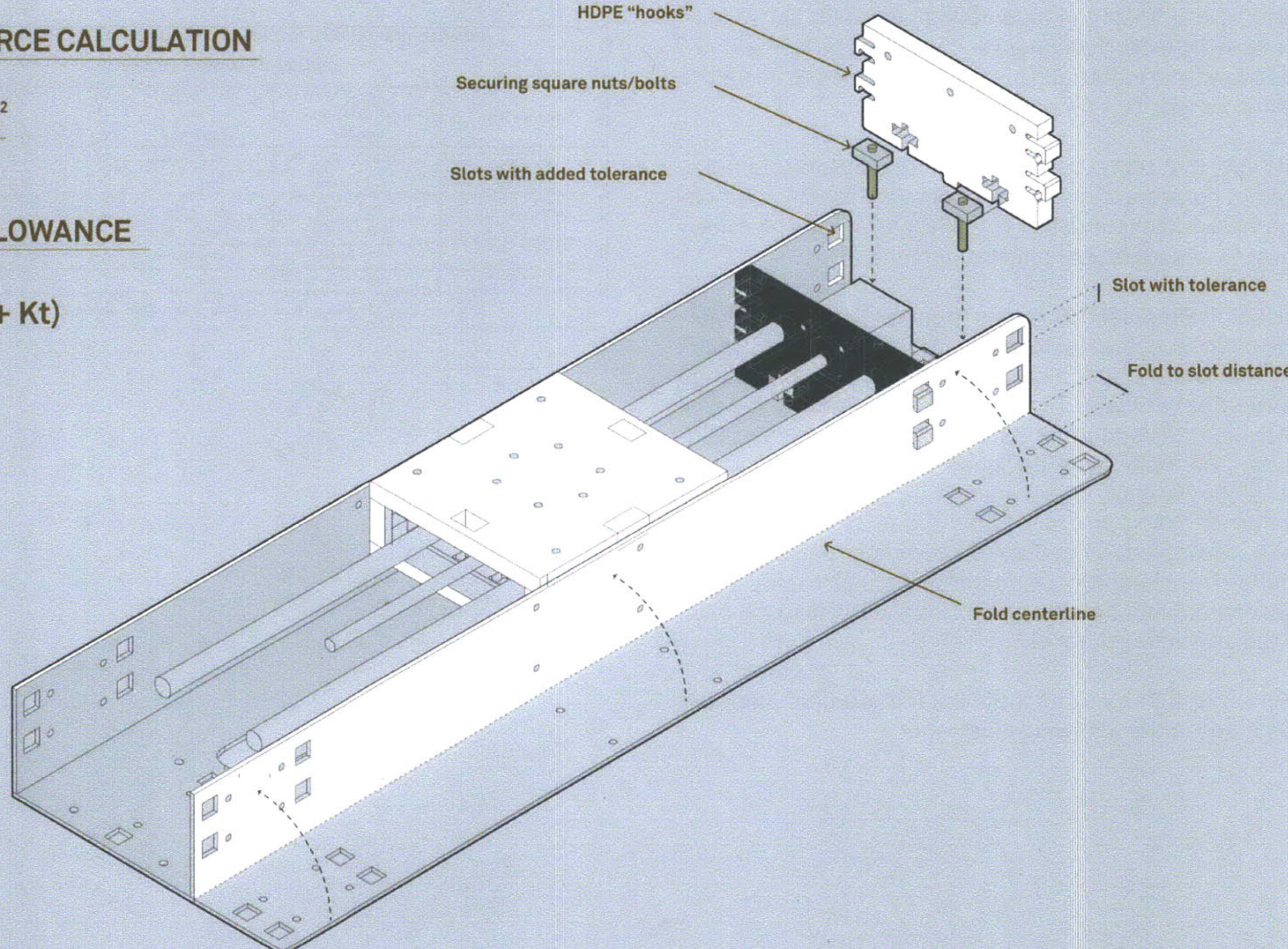
Figure 45: Professor Solucum's 'General Dimensional Tolerance for Sheet Metal Parts'

BENDING FORCE CALCULATION

$$F_b = \frac{KLst^2}{W}$$

BENDING ALLOWANCE

$$B = \alpha(R + Kt)$$



SECTION 7.02

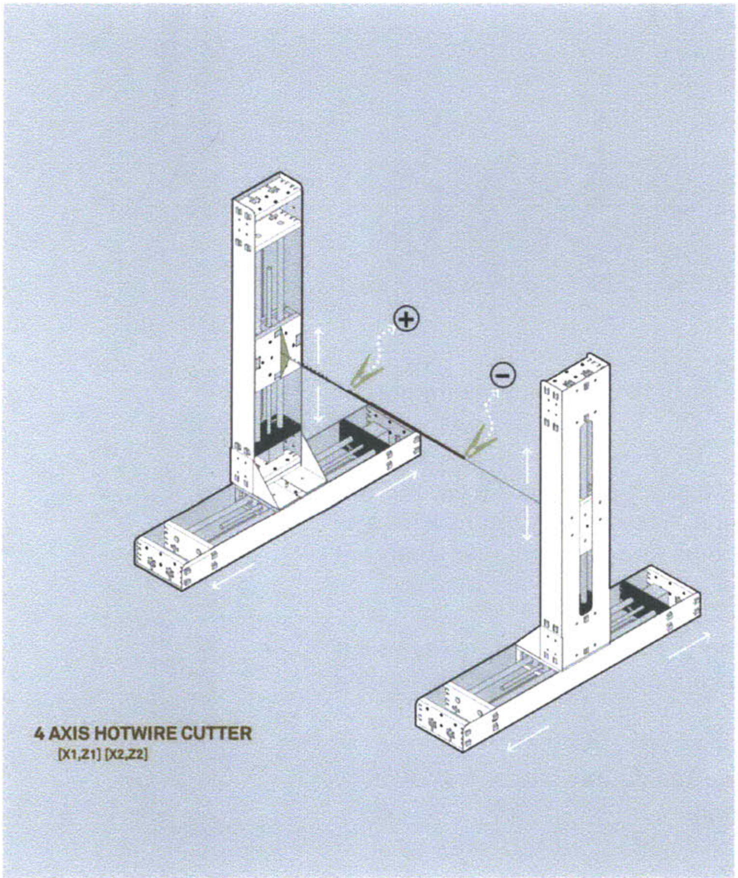
First implementation : SLASHBOT
4 Axis hotwire foam cutter

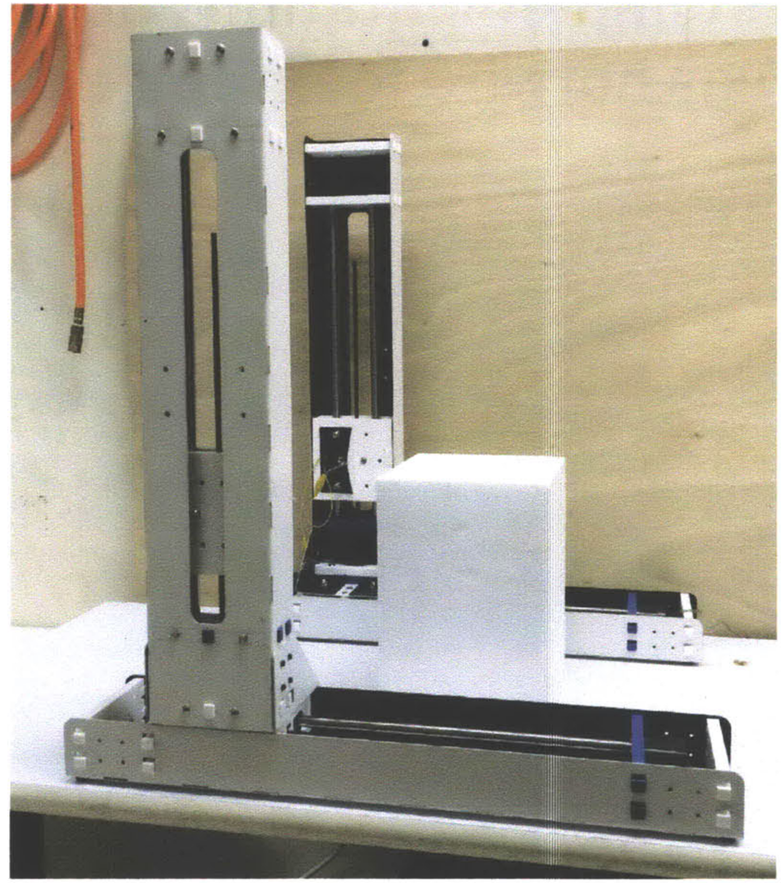
The first implementation of the modular machine components was in the form of a 4 axis hotwire cutter, affectionately named 'Slashbot'.

This configuration is made up of 4 linear stages, 2 oriented in the Y axis, and 2 oriented in the Z axis. The two assemblies where arranged opposite one another, mirrored along a centerline. A piece of nichrome wire was then strung between the Z stages with an extension spring to maintain tension and allow for displacement as the stages changed orientation.

Once the configuration was complete the nichrome wire was electrified and the machine was ready to cut foam. Foam cutting was an excellent first test because it is theoretically a zero force operation, giving us a chance to observe the module performance unloaded.

During this first test we successfully cut many complex ruled surfaces as well as doubly curved surfaces by extracting surface normals and taking multiple 'slices' of a single block of foam.





Hotwire machine configuration and machine implementation

To generate the tool paths the parametric plug-in Grasshopper for the software package Rhinoceros was used. The work-flow included specifying two guide rails that made up the bounding edges of the desired surface and a specified 'sampling level' (resolution) of the guide curves.

After sampling the reference curves the points were projected outward to the YZ planes of the corresponding stages. The projected point values are then collected and delivered via CSV (comma separated values) to the Gestalt control network in Python.

The following diagrams describe the path generation strategy for a complex ruled surface (zero Gaussian curvature).

The Grasshopper script not only provided a fluid method for the geometry and path generation but also a simulation of the machine motion during the cutting operation.

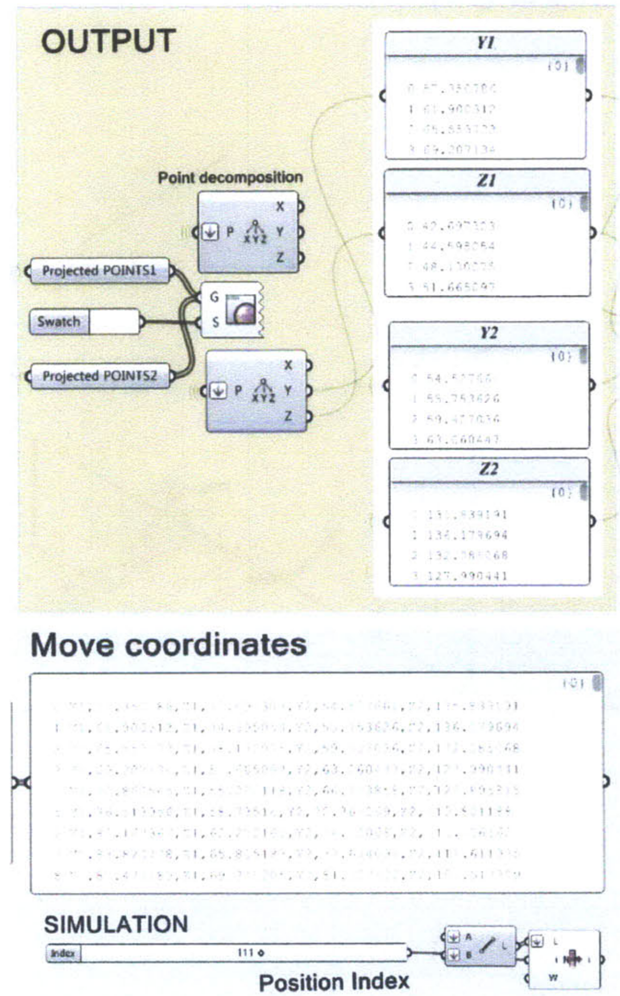


Figure 46

Figure 46: Screenshot of parametric control geometry creation

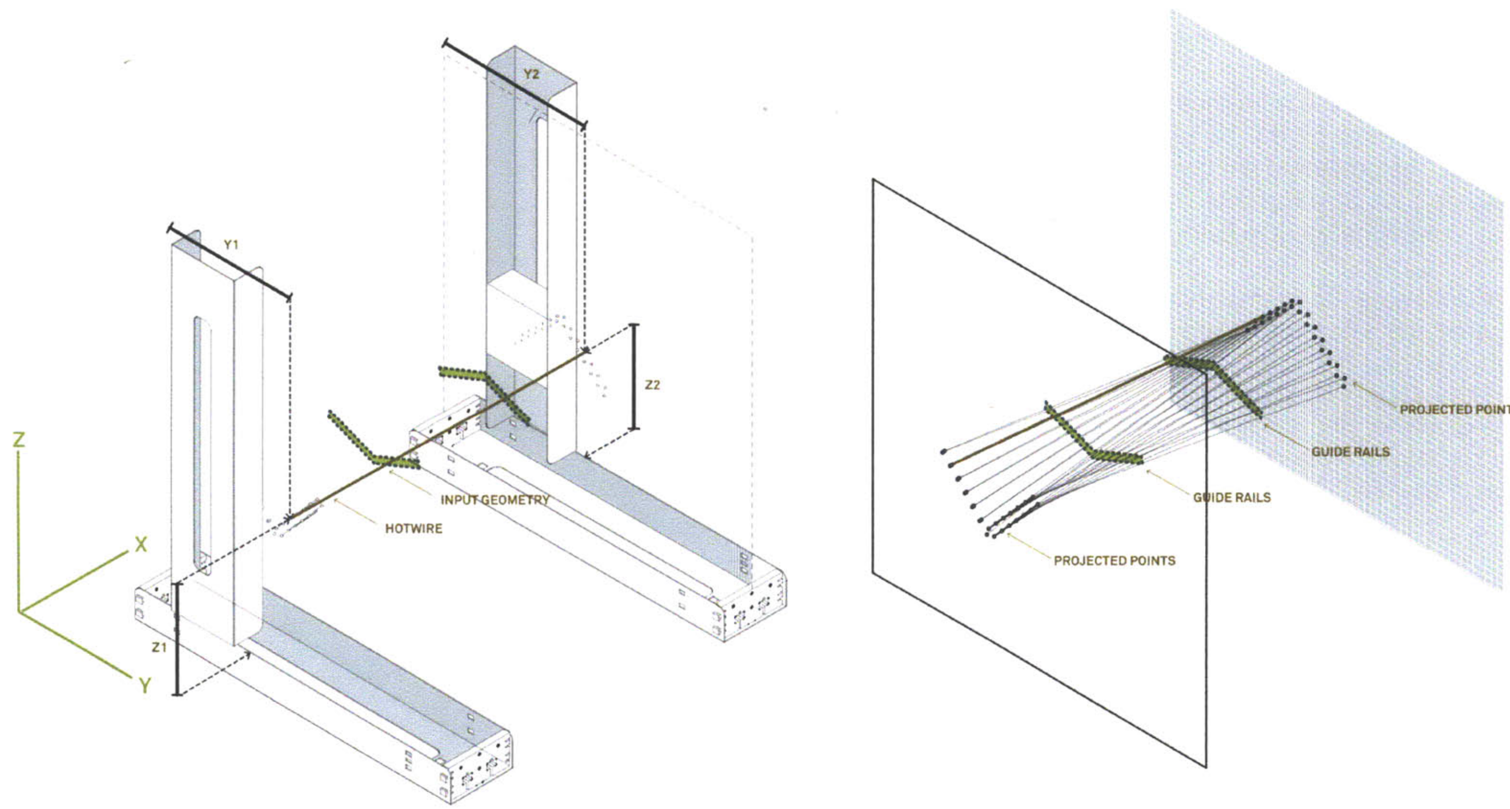
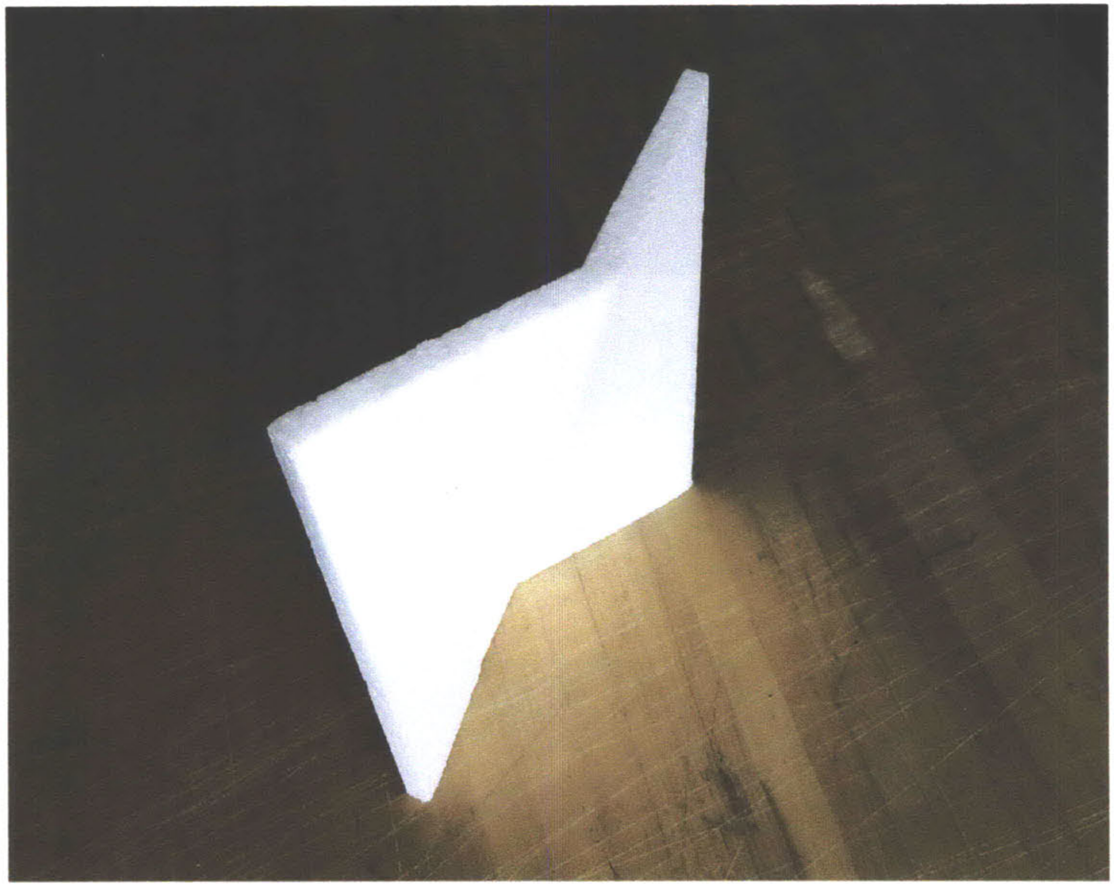
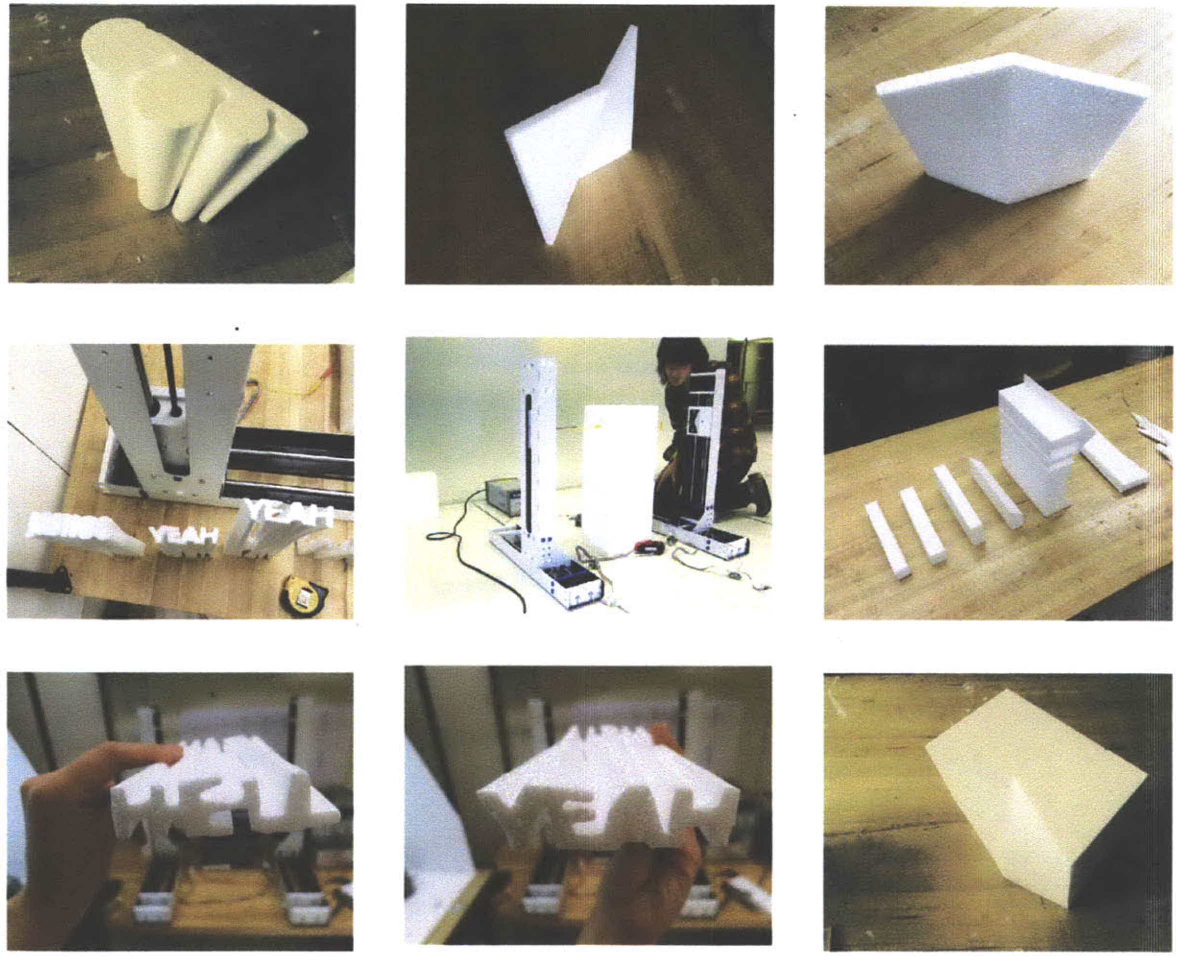


Illustration of control geometry, subsequent curve sampling and projection to machine (Y,Z) planes



Fabrication of complex foam surface. Part dimensions 6"x6"x .375"



Further results from foam cutting tests

Conclusions

With access and sophistication of digital fabrication tools increasing, we can readily execute complex projects previously deemed impossible. The generation and subsequent fabrication of custom goods by a consumer has become a relatively straightforward process. Yet despite developments in these technologies, the influence on architecture as a whole is still confined to isolated instantiations.

My research into the Timber Tower led me down a number of avenues related to the design and subsequent production of prefabricated housing. What became apparent is that architects need to deploy digital fabrication not through isolated experiments in craft, but as widespread investigations into production. Mass customization is only possible through a fluid integration with the current building industry where all parties benefit. DIY production and on site customization leverages the power of computation and digital information exchange to deeply impact the way in which we make and occupy space. This requires an operatively blurry distinction between designer and consumer. By providing a non specific "framework" users are able to explore personal methods of space making, leaving room for surprise, and invention.

The architectural questions addressed in this project can be distilled into 3 primary questions:

How can prefabricated housing be diverse and personal to the occupant while taking advantage of the economic and qualitative benefits of standardization and mass production?

What are the methods of housing modification currently available through digital fabrication that allow projects to be adaptive and change over time?

What are the unique applications of timber and engineered wood construction that enable architectural transformation and experimentation?

More work to follow, thanks for reading.

James

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