# *New Generics*

## ***Vol. 1***

*Blanchet / Sturt Studio*

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In January, 2019, twelve graduate students at the University of Michigan's Taubman College began work researching the topic of pre-fabricated architecture. These students undertook this work with guiding faculty Clement Blanchet and Jono Bentley Sturt, and in collaboration with representatives from Vinci Construction. The following serves as a summation of their initial findings.

The contents within range from the banal to the speculative, as the group tackles a number of often large and/or nebulous issues. For example, one might consider the question of "what counts" as pre-fab? If a brick is made in a factory, should a brick building be considered pre-fabricated?

Taken from another angle, what are the most salient logics and metrics by which to compare one system of construction to another? When should pre-fabrication be used as opposed to on-site construction? What materials should be used?

Or, given that global trends of automation, economies of scale. and climate-controlled environments appear to be making the production of goods more affordable and ubiquitous in nearly every other industry, why has architecture lagged behind? How has this history differed in France vs. the United States, and how might the contrast be explored productively?

The research document which follows serves as both a view into the thinking of these students and a document to be referenced as they move forward to design new, scalable systems of material assembly.

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architecture + urban planning
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and Vinci Construction for
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# The History of Pre-fabrication

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**ABSTRACT**

For all of modern architecture's ambitions to capitalize on industrialization and technology, architecture has resisted the kind of mass production that characterizes most other industries. Or so it appears. In fact, the history of Pre-fabrication shows that several Pre-fabrication techniques *have* been mass produced. Millions have benefited from standardized, factory-made architecture.

The history of pre-fab is the story of experiments to leverage factory production to create architecture more cheaply. Pre-fab can be categorized into three main categories: shelter, structure, and architecture. Shelter describes pre-fab's long-held association with the utilitarian single family house. Structure refers to 19th century iron innovation that pioneered modern construction methods. In the 20th century, many modernist architects became intrigued by the success of mass production in other fields, notably the automobile, and sought to translate this movement into architecture.

To architects, pre-fab has never been fully capitalized to bring architecture to the masses. Actually, pre-fab's legacy in the built environment is extremely widespread.


MUÑOZ
DUCHAMP


# PRE-FAB'S PARADOX

"By making the parts in a factory and assembling them 'dry,' we reduce the cost of building by between twenty and thirty per cent, and even by much more than that if mass production methods are employed...Indeed there is no reason why we shouldn't build with the rapidity of a Henry Ford."[1]

-Le Corbusier, 1953

Since the dawn of mass production, many architects have wondered how to leverage its advantages in architecture. One such architect was Jean Prouvé. In 1949, Prouvé designed a house prototype for French colonial officers in the Congo. La Maison Tropicale was carefully designed to suit the climate using standardized parts that could be easily packed, shipped, and erected. He hoped the concept would demonstrate a cheap but quality house that could be mass produced for export.[2]

Only three Maisons Tropicales were ever produced.[3] They languished in the African jungle until 2001, when a Prouvé enthusiast undertook a rescue mission to recover the houses and restore them. The houses, designed to be cheap, toured exhibitions internationally as singular works of architecture. The ingenuity of the design aimed at mass production instead became bespoke.

In 2007, one Maison Tropicale for $4.97 million.

*Fig. 1: La Maison Tropicale restored and on display at the Tate Modern*

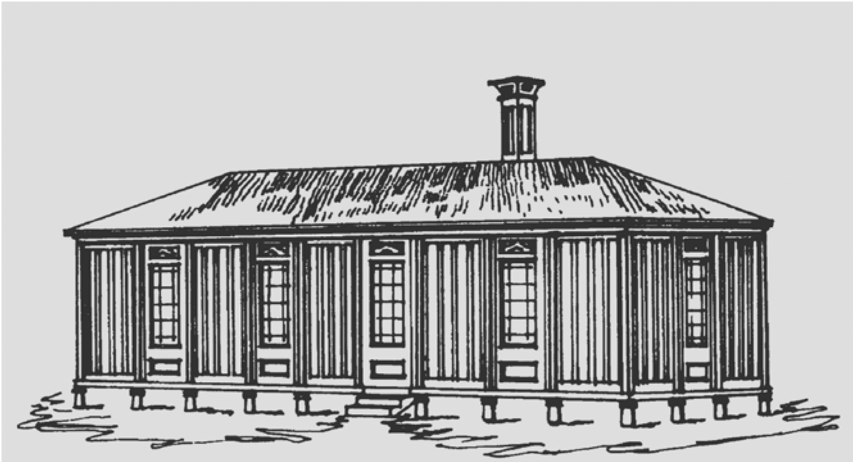


*Fig. 2: Manning Portable Colonial Cottage*

# PRE-FAB AS SHELTER

Pre-fab traces its beginnings to times of movement and crisis, when the need of shelter far outweighed the desire for architectural design or quality of construction. Pre-fab's primary advantages – portability, ease of construction, and cheapness – only comprise "highest, best use" in unique circumstances. Pioneers separated from the industry, temporary workers or soldiers on assignment, and cities rebuilding from disaster have all used manufactured buildings to meet their basic needs quickly and affordably. While the types of pre-fabricated houses have changed with time, pre-fab itself remains most closely associated with the utilitarian single family home.

**The Manning Portable Colonial Cottage**
The first factory-made single family house to gain any significant traction was John Manning's Colonial Cottage for Australian colonists in the 1830s and 40's. Upon landing in Britain's new and remote colony, emigrants found a scarcity of building resources and labor.[4] Manning, a London builder, responded with a simple design whose parts could be shipped overseas and easily erected by colonists in Australia. Here, Pre-fabrication makes perfect sense – colonists needed shelter from the Australian climate, but there were neither time nor resources to build houses. Manning, and followers like Peter Thompson, sensibly met this demand with a standardized home that could be shipped.[5]

The colonial cottage companies were short-lived, largely due to a drop-off in emigration from Great Britain around 1844.[6] The Manning and Thompson cottages proved to be only a temporary solution to unique circumstances, a pattern that becomes familiar over pre-fab's history. The colonial cottage

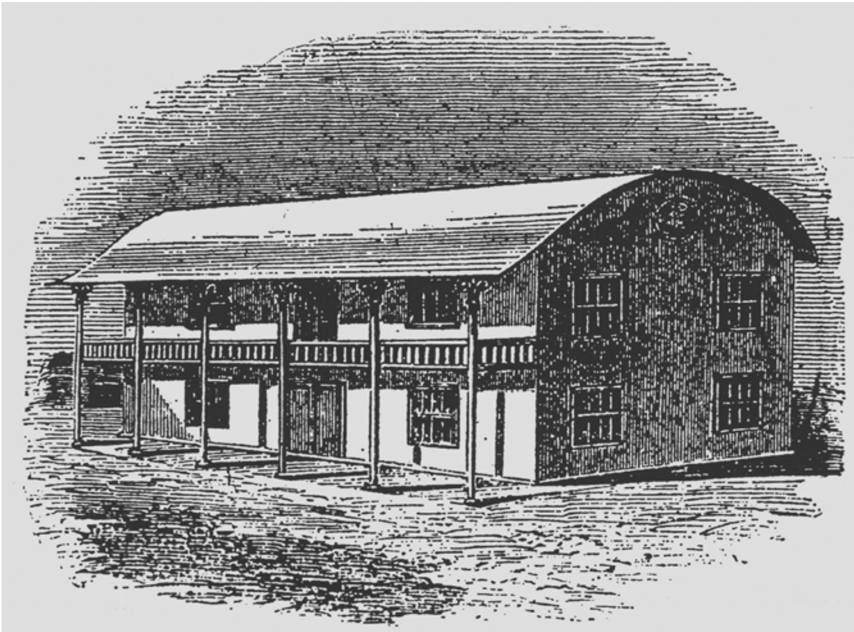


*Fig 3: Corrugated Iron House for San Francisco by John Walker, 1849*

was ill-suited to the extreme Australian heat, for instance, and the colonists could soon afford to invest time and labor into designing a more comfortable, permanent architecture.

**Experiments with Iron**

The mass production of iron radically influenced engineering capabilities given its tensile strength, but some British ironmongers also identified the potential for iron as a roofing and wall material. Britain's unsurpassed capacity for iron production along with its comparatively small lumber supply made it the primary country to experiment with iron pre-fab structures. While iron houses, schools and churches were built, the most enduring legacy of iron pre-fab is the shed.

Iron had proven a superior material for bridges and ships in the early 19th century, and since it is not malleable, iron building components are necessarily pre-fabricated at the mill. London ironmonger Richard Walker recognized the potential of fluted, or corrugated, iron to become a durable building material in 1829.[7] Shortly thereafter in 1837, another firm patented the galvanization process that protected iron from corrosion.[8] Walker and others identified the potential of this stronger material to be shipped around the empire like Manning's cottages.

In 1849, the California Gold Rush brought speculators from around the world to the unsettled West. Large quantities of iron pre-fab structures were shipped to shelter the 49ers.[9] Several English

*Fig. 4: The Nissen Hut was easily transportable and could be assembled in 4 hours.*

engineers ran successful iron pre-fab businesses, shipping out not only homes but shops, churches and other typologies required by colonists.

Despite its success as a mass-produced, portable building material, corrugated iron was eventually relegated to the realm of the temporary or utilitarian structures we associate today with corrugated sheet metal. In fact, it may have been a victim of its own success. Corrugated iron went from being a wunder-material to the material of cheap sheds. The decline of corrugated iron in the 1880s and 90's had nothing to do with a lack of supply or demand for pre-fab structures. The mass production of corrugated iron curtailed the sophistication of the design of earlier iron pre-fabs,[10] which is always a danger of mass production.

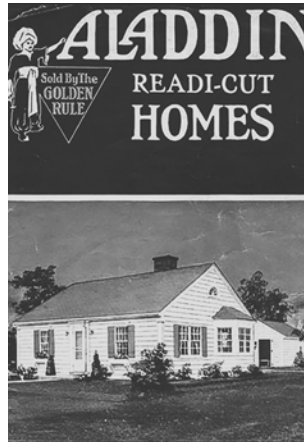
**Kit Houses**

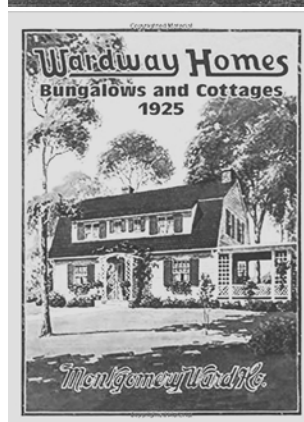
Of all the attempts to give architecture and housing to the masses, Sears may have been the closest to realizing the pre-fab dream. Kit houses made up a sizable industry in the early decades of the 20th century. Customers could browse different plans, sizes and styles in a catalog and order their preferred home to be shipped to them. Any inexperienced owner could put the house together him or herself in under 90 days.[11]

Sears was not the first to offer mail order homes, but the ruthless and clever Richard Sears soon came to dominate the industry. Between 1908 and 1940, Sears would ship out an estimated 75,000 homes.[12] This success led others to believe in the mail-order house, and inspired others to build their own kit house enterprise.

Kit houses offered consumers real choice, but they also leveraged mass production and standardization too. These homes were not solely cheap, easy-to-build shelters like the colonial cottages. Cheaper, simpler homes were available for lower income customers, but top-range homes were spacious and dignified. The array of styles and sizes meant that mass produced housing did not mean monotonous neighborhoods. They boasted brand new luxuries like electricity and central heating. Kit houses were not merely shelter, but architecture for the masses.

Production of the Ford Model T also began in 1908 and revolutionized the country and the world. A formerly inaccessible commodity was brought within reach of the middle class, and Sears appeared to have recreated that success for housing. Yet unlike Ford and other automobile manufacturers, Sears' Modern Homes did not last. The reasons for the kit house industry's decline are open to debate, but the Great Depression hit the new housing market hard. In Sears' case, the company had given mortgages more freely than the competition, which initially contributed to Sears' success in the industry.[13] But when customers could not make their payments in the 30's, Sears had to foreclose on their own customers. Sears repossessed tens of thousands





*Figs 5-7: The Kit House industry was not limited to Sears' catalog homes.*


*Fig. 8: Sears Roebuck Catalog Home 1908-40*


*Fig. 9: Ford Model T 1908-27*

of homes that it did not want in an historically bad market.

Others would pick up where the kit houses left off in terms of the cheap, manufactured home after the Depression. Sears and others proved that houses could be made cheaper and erected more easily from factory production.

**Tract Houses**

In the 1940s, the Long Island real estate developer Levitt & Sons purchased a 7 square mile tract near Hempstead. Like most, returning Seabee William Levitt knew there would be soaring demand for affordable housing for the returning GIs, and Levitt had a plan to capitalize on it. He also had experience with Pre-fabrication techniques from his war experience.[14] The company would bring the assembly line to Long Island to lower production costs and house the postwar population, all while making a handsome profit.

Levitt's idea was to build essentially identical houses to leverage the power of the assembly line. Each contracting job was standardized, so specialized labor efficiently moved from house to house completing their respective jobs. At the height of production, workers were finishing some 20 houses per day.[15] Since these houses were built on site using precut parts, they were not "pre-fab" in the traditional sense. Whereas pre-fab brings house construction into the factory, Levitt brought the factory to the site.[16] Assembly line construction reduced time on site, which is pre-fab's main advantage.


*Figs. 10-11: Levittown put the American Dream within reach by bringing the assembly line to the site.*

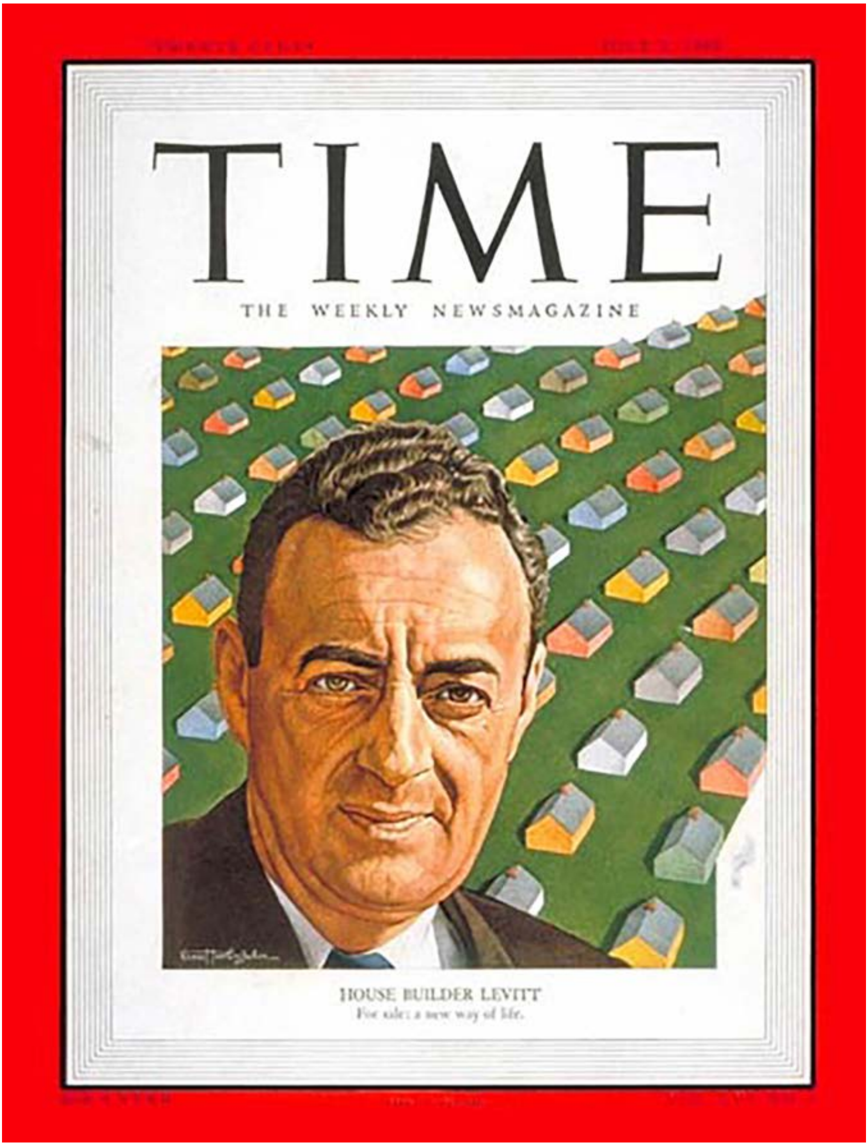



*Fig. 12: William Levitt's influence on American housing was great enough to make him a famous man.*

*Figs. 13-16: Clockwise from top left: Levittown NY, Park Forest IL, Houston TX, Highlands Ranch CO. The tract house truly became the new generic for the U.S.*

The ruthlessly efficient process was a resounding financial success, ever the barometer for pre-fab's survival in America, and also gave thousands affordable, convenient housing. Workers could take the train to work in Manhattan, and families had a safe neighborhood in which to raise their kids. With every neighborhood resident owning the same house, there was an egalitarian social component to Levittown.

In relation to pre-fab's history, Levittown's legacy is mixed. Levitt provided mass housing at a low price, and gave thousands their slice of the American Dream. Those who were able to purchase their own home in such a development that they could not have otherwise are no doubt grateful to Levitt's ingenuity. The single family typology was also subsidized through the G.I. Bill, which encouraged home buying over renting.[17] In the U.S., tract houses and suburban developments proliferated for decades following Levittown's success, truly becoming the "New Generic." Yet, taken to its logical extreme, mass production results in the monotony of the most efficient product repeated endlessly. Levittown is anti-architecture, drumming out creativity in favor of profitability.

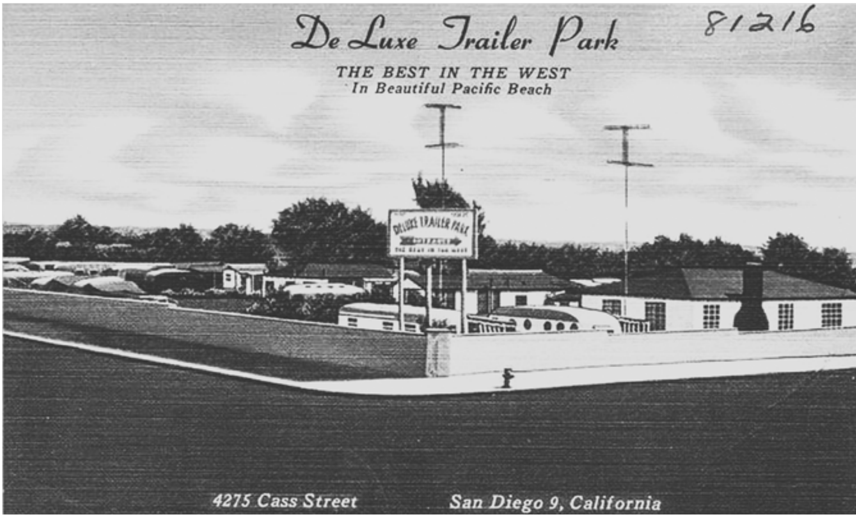
**Mobile Homes**

Mobile homes trace their roots back to a leisure toy from the dawn of the automobile age: the trailer. Car owners could hitch their trailer to their car and explore the country with comfortable sleeping accommodation traveling with them. Soon, the Depression turned trailers into full-time shelter for a migrant class looking for work who set up impromptu communities - the so-called trailer park.[18]

During World War II, the U.S. government bought trailers as a sensible way to house the wartime workforce. The trailers were thought to be a temporary solution, and that people would move back into conventional houses when the nation stabilized. Trailers were, in fact, even more affordable than tract houses, so there was a market for them among the lower class.

Mobile homes, as they became known, are a unique type of housing. Technically classified as transportation rather than housing, mobile home parks cropped up on land that was not zoned residential. Often, this land was in commercial or industrial zones, far removed from the rest of the residential housing stock. City governments also wanted to shield mobile homes from view as much as they could, given the stigma they had acquired as slums.

*Fig. 17: Trailers became permanent housing for some.*





*Figs. 18-19: Mobile Homes are simply driven from the factory and dropped on site.*

Despite their name, mobile homes were seldom moved after their initial journey from the factory. They became communities unto themselves. Yet one legacy from the first improvised trailer parks was that mobile home owners do not own the land they occupied. While this may make living in a mobile home less of a cost burden, residents are vulnerable to a land sale when their homes are not, in fact, able to move off the site.[19]

Mobile homes require almost no time on site and represent a large sector of the U.S.'s affordable housing stock. Many people who would be priced out of traditional housing can afford to have a mobile home to call their own. But while mobile homes are pre-fab, are they architecture? Like Levitt's tract houses, mobile homes represent the extreme of cost-cutting and amount to little more than a soulless box. The U.S. government presumed that they would only be temporary, there has always been a market for the cheapest house factories can produce, no matter how deficient.

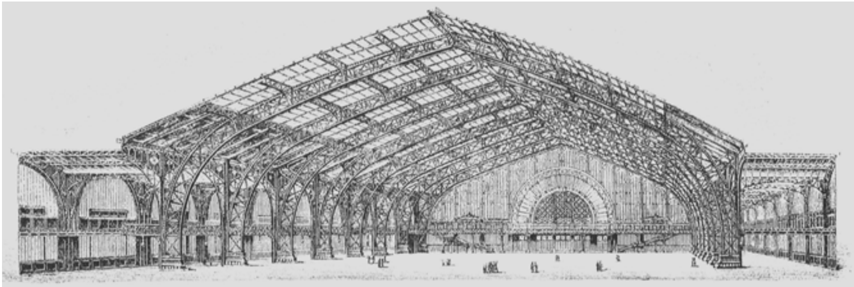


*Fig. 20: Galerie des Machines, 1889*

# PRE-FAB AS STRUCTURE

The Industrial Revolution led to the mass manufacture of iron, which in turn spurred major advances in engineering. It was an architect, John Farnolls Pritchard, who initially suggested that cast iron could be deployed as a bridge structure in the 1770s.[20] Continuing experiments throughout the 19th century confirmed iron's structural capabilities, ultimately leading to the framed construction of tall buildings so familiar today.

Train stations, shopping malls and skyscrapers designed with iron or steel frames do not strike us as pre-fabricated buildings today. This raises an enduring problem for pre-fab: how is it defined? Innovations with iron in the 19th century took Pre-fabrication and changed it into mass production.

Iron frameworks introduced a standardized, factory-made kit of parts that reduced time on site and could even be disassembled and moved. So successful was this construction system that it has ceased to be "pre-fab" and become orthodox. The next chapter will more deeply examine how pre-fab is defined today. Over history, the concept has been disputed and ever-evolving. The advances made in building technology in the 1800s show that pre-fab has, in fact, radically shaped the construction industry more than we realize.

**Crystal Palace**

By 1851, engineers and architects had been working with cast iron for decades. The Crystal Palace was not the first building to use an iron framework - bridges and greenhouses had done that - but it was nonetheless a significant turning point in engineering and architectural history. Instead, the Crystal Palace was revolutionary in how it showed the world the tremendous potentials of iron and glass construction.

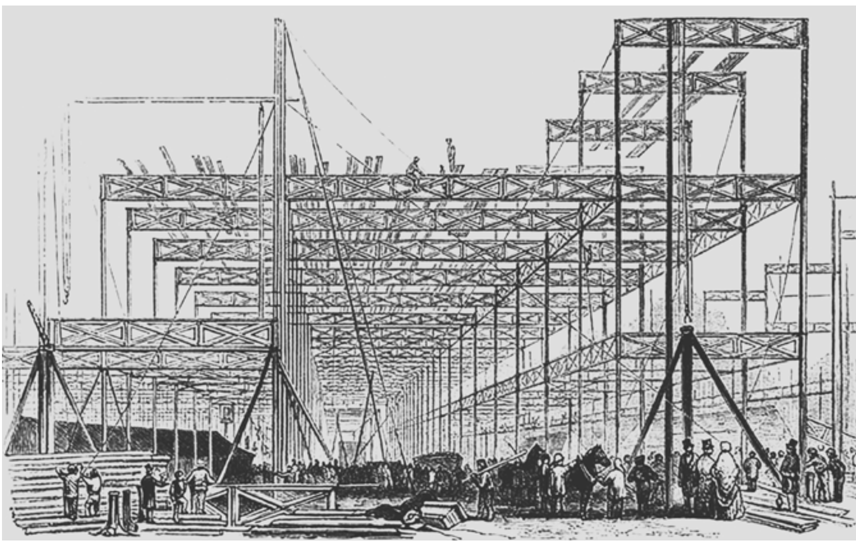
Commissioned for "The Great Exhibition of the Works of Industry of All Nations" (considered the first World's Fair), architect Joseph Paxton wanted to create an awe-inspiring display of Britain's industrial might as an exhibition in itself. To contemporary eyes, the Crystal Palace does not seem the least bit "pre-fab," but in fact factory production was a major emphasis for

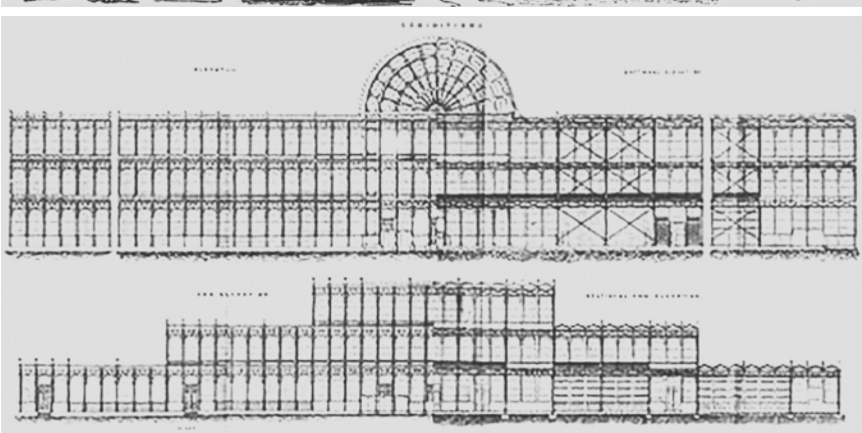
Paxton:

"all the roofing and upright sashes would be made by machinery, and fitted together and glazed with great rapidity, most of them being finished previous to being brought to the place, so that little else would be required on the spot than to fit the finished materials together."[21]

-Joseph Paxton, 1850

Paxton's competition entry won largely because it was faster and markedly cheaper to build than other entries. In under one year, Paxton and engineering firm Fox & Henderson were able to design, manufacture parts and erect the monumental Crystal Palace. Further padding its pre-fab credentials, the entire building was disassembled, moved,





*Figs. 21-22: Paxton and his engineer, Fox & Henderson, used modular construction to complete the Crystal Palace in about 5 months.*

and reconstructed at another site in 1854.

**Eiffel and the French**

Although the British, with their superior iron manufacturing capacity, pioneered the pre-fabricated iron structure, the French were not far behind. While France had a handful of iron buildings before 1851, the Crystal Palace sensation kicked iron frame architecture into high gear. It wasn't only Gustave Eiffel - France boasted numerous talented and bold designers who created soaring spaces and unprecedented spans. Although Eiffel's namesake tower is the most visible legacy of French Second Empire iron architecture, there are train stations, libraries, and, famously, arcades that display the French fascination with iron.

Like Paxton in the 1851 "Works of Industry" exhibition, the French hosted their own World's Fair in 1889 seeking to show off their own industrial capabilities. During the interim between these two exhibitions, iron had already become a mainstay of Parisian structural engineering.[22] Masonry pillars and timber joists were mostly replaced by the iron framework by the 1860s. In little over a decade, Paxton's pre-fab experiment had proven so successful that the iron framework ceased to be a novel approach. Pre-fabrication of iron and glass was no longer "pre-fab."

*Fig. 23: Henri Labrouste, Bibliotheque Saint-Genevieve, Paris. Designed 1838, finished 1850.*

*Fig. 24: "Lunch Atop a Skyscraper," by Charles C. Ebbets, 1932*

**American Skyscrapers**

Pre-fab's value proposition in America has always been and will always be the deciding factor in its survival. In the U.S., architects and engineers realized the potential of iron frameworks to build high and "make the land pay." As a result, skyscraper building proliferated rapidly in the U.S. until the 1930s.

For one-off displays of engineering accomplishment like the Crystal Palace and the Eiffel Tower, the designers placed an order with iron foundries and glassmakers for each specific component required. These structures were pre-fabricated, but not mass-produced. In the U.S., construction happened at such a rate and volume that standardized, mass-produced components were called for.

The once-mighty Bethlehem Steel Corporation began its life as Bethlehem Iron Company in 1860, switching to steel in 1899. Bethlehem Steel was the first to produce I-beams for U.S. skyscrapers, and could presumably manufacture them to standardized dimensions without having an order.[23] By the early 20th century, the Pre-fabrication of metal structure had met mass production.

Skyscraper construction represents the moment when 19th century Pre-fabrication techniques became mass-produced. With standardized parts, manufactured not for a specific design but to be used in buildings not yet designed, came a turning point for Pre-fabrication.

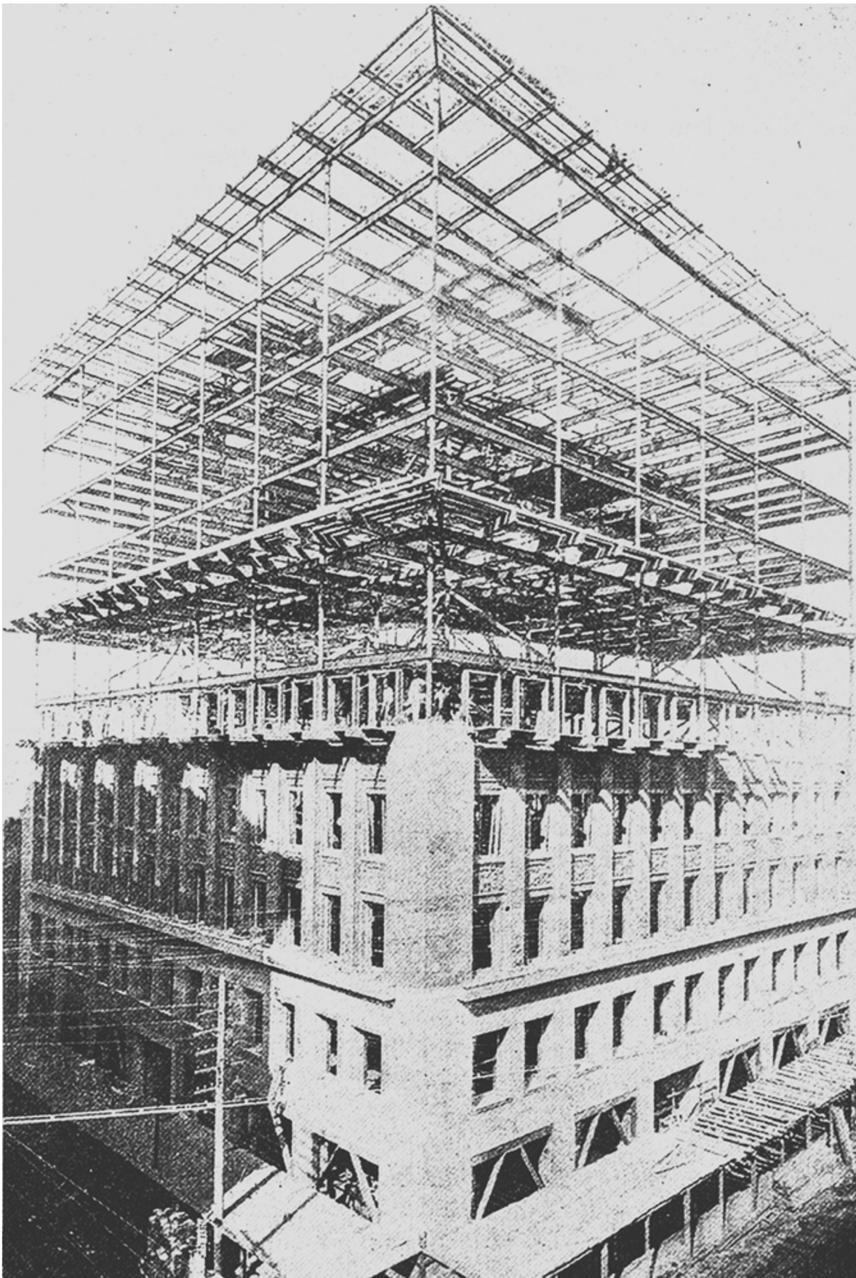


Fig. 25: Wainwright Building under construction, 1891

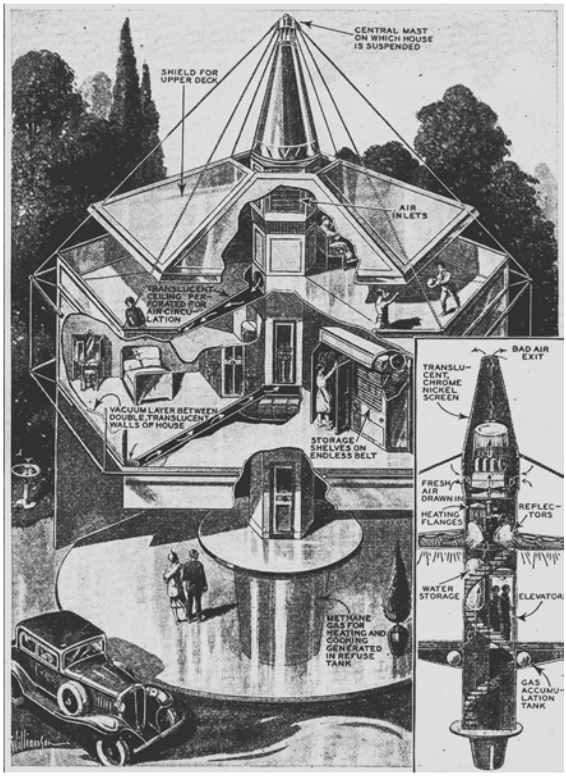



*Fig. 26: Diagram of Buckminster Fuller's Dymaxion House*

# PRE-FAB AS ARCHITECTURE(?)

Modernist architects had a particular fascination with the potential of mass-produced, pre-fabricated housing. In his groundbreaking 1924 Modernist treatise Vers Une Architecture, Le Corbusier advocates for a whole-hearted embrace of factory-made houses on a grand scale, coining the famous house as "a machine for living." This dream has endured to the present day, with little to show for architects' continuous attempts at designing architecture's own Model T.

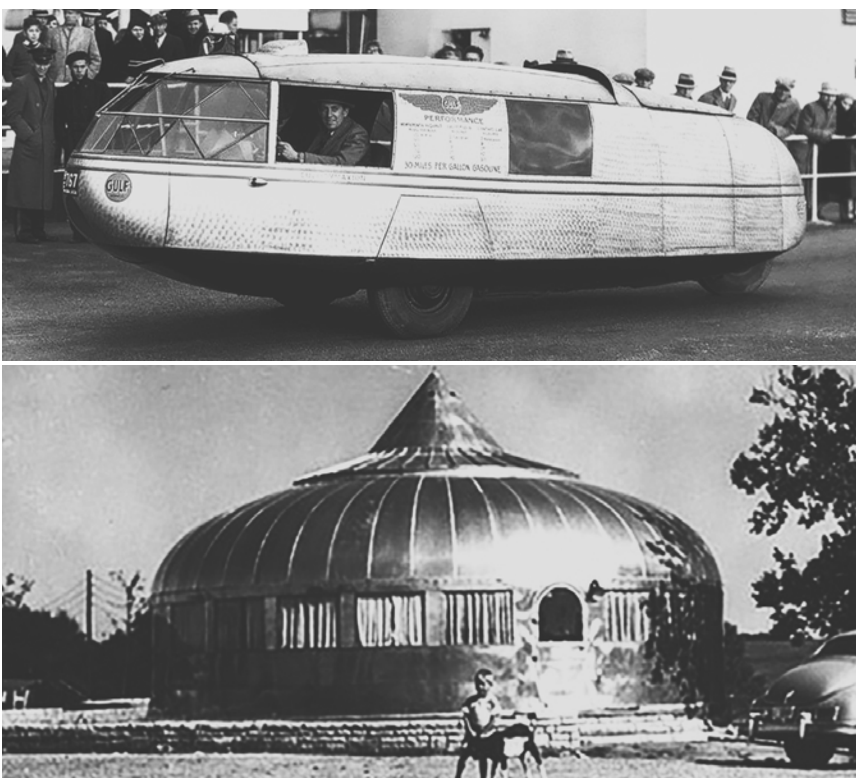
Several architects had thought deeply about a new relationship between architecture and industry that would embrace the factory. Inspired by great technological advances in other industries such as the automobile and aircraft, factory-produced architecture seemed the inevitable next stage of progress.

As we know, pre-fab historically flourishes under certain conditions.

After World War II, architects in Europe and the U.S. recognized the opportunity to realize Le Corbusier's dream of mass-produced housing for millions of returning G.I.s. They were right - the postwar period saw a vast output of new, mass-produced homes, but none designed by architecture's leading lights. Forward-thinking, carefully considered prototypes lost out to William Levitt's rudimentary but cheap houses. So why has no architect's proposal for a mass-produced building ever been mass-produced?

**Buckminster Fuller's Dymaxion House**

Fuller was a radical thinker who believed architecture and industry could solve the world's problems just as Le Corbusier did. Inspired by "Mass Production Houses," Fuller set to work on his own mass-producible house in 1927. The 4D House, later renamed the Dymaxion, was a futuristic hexagonal unit fixed to central mast. Fuller went to great lengths to engineer flexibility, mobility, ease of assembly and more into his design.[24] Not content to leave the Dymaxion simply as concept, Fuller relentlessly advertised and toured the




*Figs. 27-28: Fuller's Dymaxion Car was no Model T, so it's unsurprising that the Dymaxion House remains an eccentric curiosity rather than mass-produced house.*

country promoting the house in lectures.

By 1944, conditions seemed to be perfect for Fuller to realize his long-held dream of mass-producing the house. Finally, the manufacturing industry had taken an interest in pre-fabricated housing to meet the coming demand from returning soldiers. Fuller had spent the past ten years refining the Dymaxion and theorizing on the house in modern society.

Buckminster Fuller convinced Beechcraft, maker of small aircraft that had boosted production for the war, to turn him loose in their factory to design a new Dymaxion prototype that they could mass-produce to the tune of 60,000 units per year.[25] The final Wichita Dymaxion prototype was built and marketed, but never mass-produced. The house checked many boxes - cheap, factory-made, efficient, fitted with ingenious features like moving shelves - but the public didn't bite.

Ironically, Americans gladly bought another mass-produced house - that of the Levittown tract house. Yet Fuller had devoted almost twenty exhausting years to designing the perfect mass-produced house. It is safe to say that Fuller had considered housing and mass-production to an unprecedented degree, and yet William Levitt's get-rich-quick scheme of the assembly line house is what truly started a new housing model. Fuller was convinced that housing simply had not caught up to modern society, but he was mistaken. Housing's intransigence instead came from thousands of years'

*Fig. 29: Fuller tirelesslessly promoted his Dymaxion through magazine profiles like this one.*

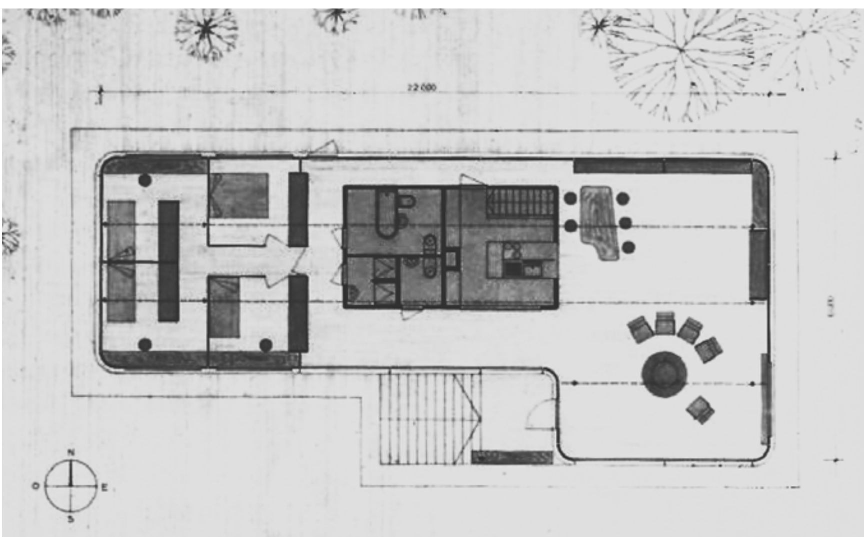
*Figs. 30-32: Clockwise from top: Metropole Aluminum House (1949), Les Jours Meilleurs House (1956), Ferembal Demountable House (1948).*

experience with human comfort.

**Jean Prouvé**

Jean Prouvé was a metal artisan from France who was also a self-taught architect and engineer. Through his original practice, Jean Prouvé brought practical tactics into his architectural designs along with keeping them aesthetically pleasing. Prouvé specified his work through standardization and mass production. With standardization and mass production, soon followed Pre-fabrication.

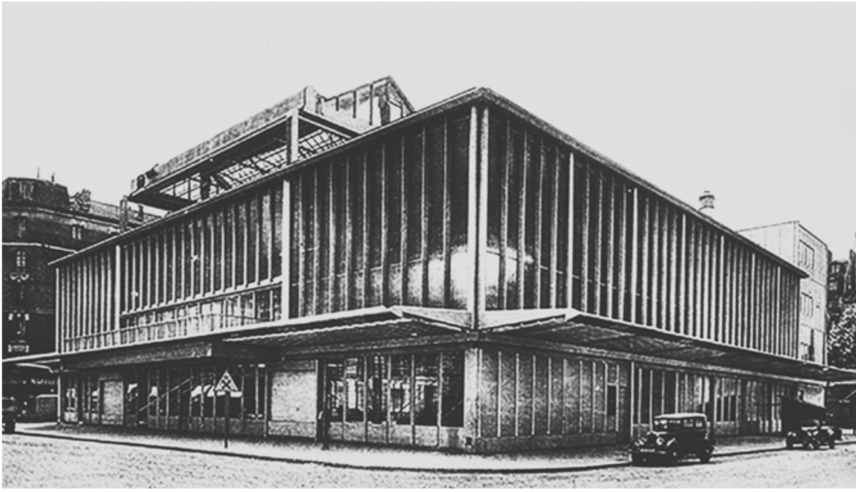
During World War II, Prouvé was tasked with designing and constructing pre-fabricated housing units due to the shortage of housing in France. The French Minister asked Prouvé and his team to construct around eight hundred of these living units, otherwise known as "demountable houses". Although asked for eight hundred, only about four hundred of the units were physically erected. Even so, Prouvé's artisan work with the demountable homes was a groundbreaking example for

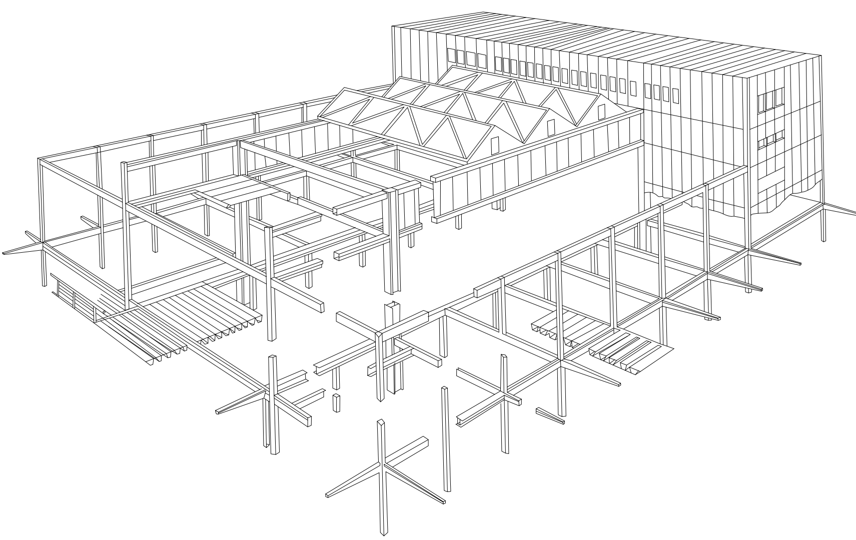


*Figs. 33-34: Gauthier House, 1962. As in other projects, Prouvé separated the load-bearing core from the outer facade system.*

mass production, Pre-fabrication, and architectural values all combined into a single form.

Along with these developments, French developers started to work with double-sided, wooden panels through the technique of pre-fabricated on the Ferembal Demountable House and began to use those techniques for interchangeable facade faces. The concept of double-sided, wooden panel led to the idea of interior partition walls later on. Jean Prouvé was the first in





*Figs. 35-36: Jean Prouve, Maison de Peuple, 1939. The frame structure allowed flexibility of space and program.*

France to express that Pre-fabrication was advancing in a way that looked toward a dense future and need for multi-purpose spaces. With these aspects driving the project, France designers and fabricators, alongside Prouvé, were tasked with pushing Pre-fabrication practices into the future through materials, ideas, and aesthetically pleasing and functioning designs.

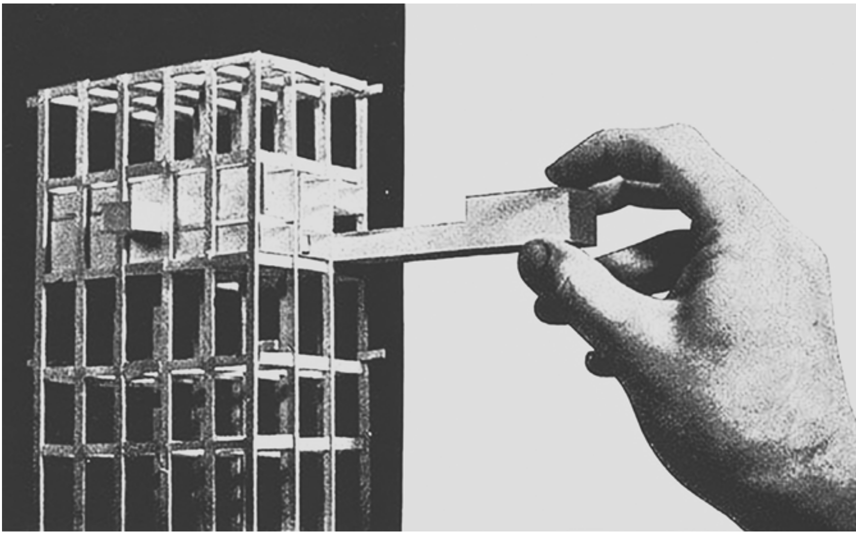


*Fig. 37: Le Corbusier's diagrammatic model of the structural frame supporting pre-fabricated units.*

**Is Pre-fab Scalable?**

Since most pre-fab architecture focuses on housing and so much housing construction is urban, several architects and developers have tried to bring pre-fab to the urban scale. Three projects stand out as built architectural propositions that use pre-fab in a high-density project: Le Corbusier's Unité d'Habitation in Marseille (1952), Moshe Safdie's Habitat 67 in Montreal (1967), and Kisho Kurokawa's Nakagin Capsule Tower in Tokyo (1970). Like Fuller and Prouvé's ideas, none of these projects was widely repeated despite each striving to provide a new model of multi-unit construction.

**Unité d'Habitation**

Le Corbusier was an ardent believer in the power of mass-production for good, and he thought France faced an urgent housing crisis after the war. Further, he saw sprawl as inefficient, so Le Corbusier resolved to build vertically.[26] In fact, Le Corbusier had many ideas about how he would improve lives with his designs for buildings and towns, and Pre-fabrication was how he would realize his vision:

"By making the parts in a factory and assembling them 'dry,' we reduce the cost of building by between twenty and thirty percent...It is worth pausing to consider what such an innovation would mean both to construction and to the economy of the nation. From now on everything down to the least object that goes to create a home can have a name and a specification. Think of the rapidity that would ensue from that alone."[27]

-Le Corbusier, 1953

Le Corbusier had taken great care to design a comfortable and efficient apartment unit to be mass-produced. The interlocking "bottle and wine-bin" maisonette units could be stacked easily for construction. He believed this would be architecture's Model T: "it is essential that this new technique, the first real advance in the history of housing, should spread all over the country, replacing artisan-built houses."[28]

Unité was repeated four more times in western Europe. The building is a modernist icon, leaving two controversial legacies: the public housing tower by the park and the Brutalist style. Like Le Corbusier's radical idea for La Ville Radieuse, of which Unité was part, the public was unreceptive to this novel concept of mass housing.

**Habitat 67**

Like the Eiffel Tower and the Crystal Palace, Habitat 67 was built as an avant-garde proposal for the World's Fair but

*Fig. 38: Unite d'Habitation's greatest influence was not on pre-fabricated housing but on the Brutalist style and concrete design.*


*Fig. 39: Precast concrete units being craned into place at Habitat 67*

became permanent and became a city landmark. It was also a breakthrough in Pre-fabrication. Moshe Safdie's design ostensibly took a major step toward showing the world the feasibility of dense pre-fab housing.

Safdie launched his architecture career on the back of Habitat's international acclaim, but he never repeated the Pre-fabrication system he pioneered: "It turns out that transporting many heavy boxes is not feasible for high-rise buildings-not then, and not today."[29] As an exposition, Habitat 67 was removed from the market forces that ultimately determine if pre-fab is scalable or not.

**Nagakin Capsule Tower**

The Japanese Metabolist School experimented with the building as organism - that it they could grow, shrink, and reconfigure as needed. Kisho Kurokawa's Capsule Tower features 2.5m by 4m concrete cubes that can "plug in" to the larger system. Capsules could theoretically be joined to make larger spaces. Flexibility was at the heart of Kurokawa's concept.[30]

The capsules were meant to be mass-produced, but not one has ever been added to the original construction. In fact, the Capsule Tower itself is on the brink of demolition despite its architectural significance. Its useful life appears to be over due to maintenance issues, but it has survived solely on the strength of its architectural significance. Like others before it, the radical design meant for mass-produced genericism has become a singular work of architecture.

**Conclusion**

If History teaches us one commonality among pre-fab successes, it is to *know*

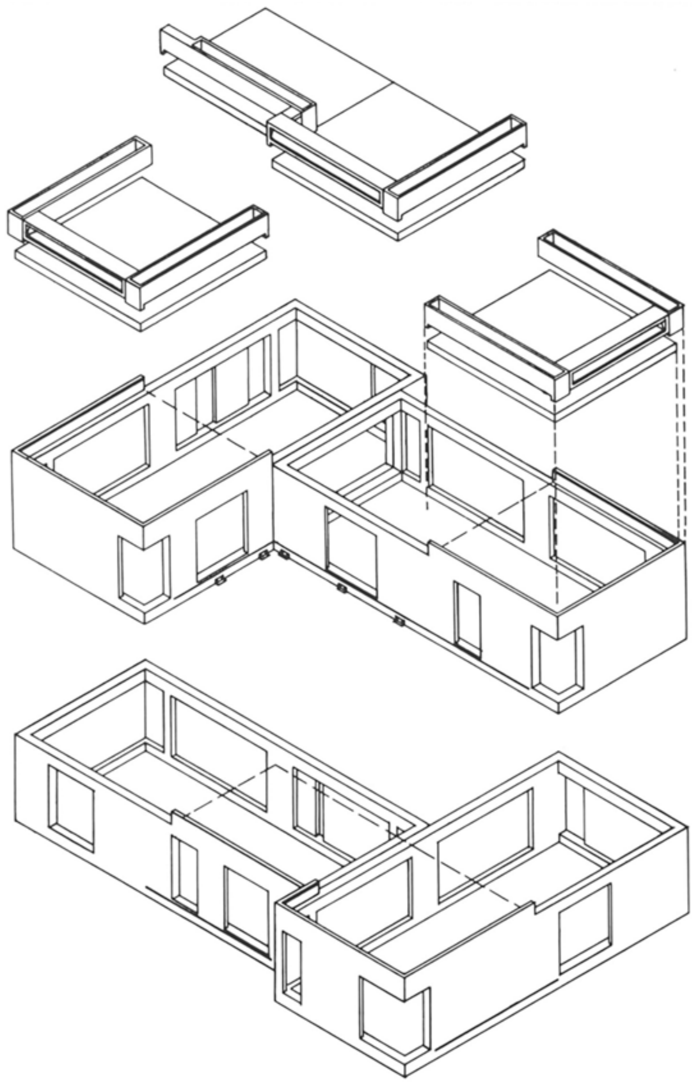
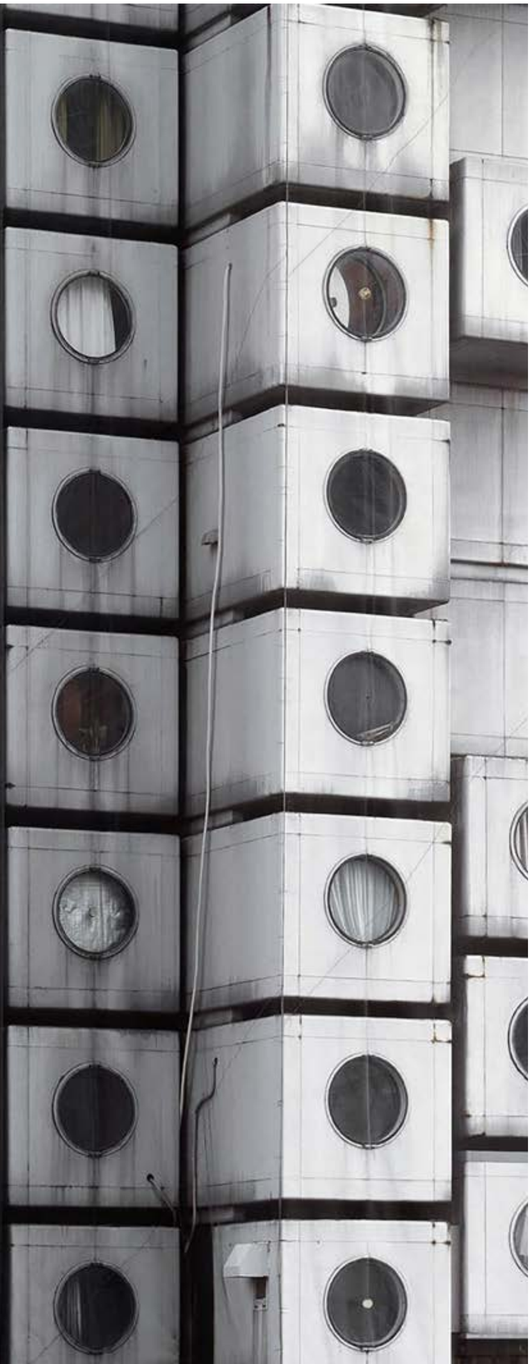


*Fig. 40: Assembly detail for Habitat 67*

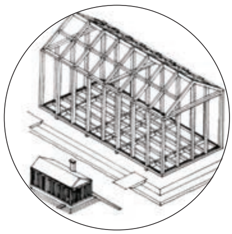


*your market*. Aesthetics, ingenuity and even cost are obsolete when one's knowledge of the market is inferior to competitors'. Efficient, sustainable and cheap though the Dymaxion House was, it is obvious to see why Americans vastly preferred William Levitt's traditional-looking cheap homes. In fact, none of the architects' pre-fab designs achieved mass production and leveraged economies of scale like Levitt, so their economic viability was never proven. History shows that, despite its reputation, pre-fab can be successful and can even become generic. When pre-fab fails, it tends to be from a flawed understanding of market tastes. This is as opposed to market demand, which for affordable housing is fairly easily measured.

Did Le Corbusier, Safdie or Kurokawa care at all about market demand, or were their apartments intended as radical experiments meant to provoke discourse? The Dymaxion House, Unité d'Habitation and the Capsule Tower combined Pre-fabrication with an accompanying polemic of what housing should be, rather than solely leveraging factory production to make housing cheaper. John Manning, Sears and William Levitt did not attach such a moral prerogative to their houses. If pre-fab is to reach the economies of scale required to make it competitive, market tastes cannot be defied or ignored.

*Fig. 41: The Nagakin Capsule Tower has fallen into disrepair, relying on philanthropic preservation efforts to stave off demolition.*

# THE HISTORY OF ARCHITECTURE &



Manning Portable
Colonial Cottage
1833

The Manning Colonial Cottage, which was developed in London, England, was the first documented example of prefabrication

Crystal Palace
1851

The Crystal Palace in London, England was prefabricated from wrought-iron and based on a four-foot modular system

Post Industrial Revolution

## ANTEBELLUM ERA (1825-1861)

The architecture during Antebellum developed different methods and techniques that could be used within all architectural typologies. Within the US, construction along with material advances occured at a rapid pace. Easy and cheap structures were being erected through the use of Balloon Frames. Both Greek and Gothic Revivals were taking place during this era within architecture.

## THE CIVIL WAR (1861-1865)

Antebellum architecture arose during the Civil War Era. These designs can be characterized as "Georgian", "Neo-classical", and late "Greek Revival" styles that are better known as plantation homes and what would have been considered during this time period, mansions. Initally built for soliders to live within but were later converted into homes, schools, and other public sectors.

Cement is introduced into prefab for foundation elements; the cement was generally brought to the site via slabs

# THE INTEGRATION OF PRE-FABRICATION

Home Insurance
Building
1885

The Home Insurance Building in Chicago,IL was the first skyscraper developed through prefabrication

After the Civil War, the Victorian Style emerged within architecture. This was to follow the lead of Britian and what they were producing during this period. The US also created the "Stick Style". This was a method of construction that used wooden rod trusswork.

## RECONSTRUCTION (1865-1877)

## THE GILDED AGE (1870-1900)

Technology was advancing during the Guilded Age in history. Architecture began to adopt this technology and made further advances. One of which was the elevator. Moving people and goods higher became much easier and buildings began to be built much taller. Conservative building techniques began to vanish and the emergence of skyscrapers became much more common within urban fabrics.

Steel took the place within construction over the cast iron that had been used in architecture since the late 18th century

# THE HISTORY OF ARCHITECTURE &

Eiffel Tower
1887

The Eiffel Tower in Paris, France was an example of prefabrication developed off site and transported in segments too be erected

The Progressive Era was a time of which social activism and political reform were at hand in the US. The architecture during this time played a role in anti-trust laws, prohibition, and suffrage. The Progressive Era began to look deeper than structural components and how architecture can begin to affect/make more efficient the cleanliness, hygiene, and space. within buildings for the public.

## THE PROGRESSIVE ERA (1890-1920)

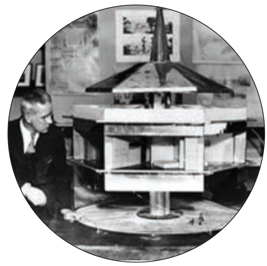
## THE GILDED AGE (1870-1900)

Technology was advancing during the Guilded Age in history. Architecture began to adopt this technology and made further advances. One of which, was the elevator. Moving people and goods higher became much easier and buildings began to be built much taller. Conservative building techniques began to vanish and the emergence of skyscrapers became much more common within urban fabrics.

# THE INTEGRATION OF PRE-FABRICATION

Le Corb
Maison Citrohan 1925

Maison Citrohan in Paris, France was intended to be an example of modern, commercial scaled prefabrication in Europe during this time.



Fuller
Dymaxion House
1933

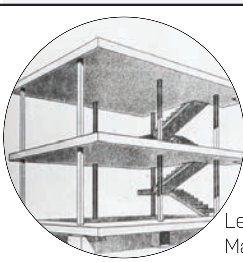
The Dymaxion House was developed by Buckminister Fuller in order to provide sustainable, autonomous living quaters for the future

A period of reckless spending fueled skyscraper construction that make the steel framework ubiquitous in the U.S. Kit houses prospered in this bustling economy, whose speculation ultimately led to the Great Depression.

## THE ROARING 20'S (1920-1929)

## THE GREAT DEPRESSION (1929-1939)

Construction was all but halted due to the Great Depression. Not many structures were being built because there were not many jobs that were paying for the labor and developement of new buildings.



Le Corb
Mass Production
1923

Le Corbusier intially wanted to push architecture forward into the future with his mass produced, three component, prefabricated concept

Abundance of time and massly produces nails made the concept of mass production within the US betweent the 1920's and the 1930's.

# THE HISTORY OF ARCHITECTURE &

Aladdin Homes
1906-1981

Aladdin Homes were prefabricated pieced catelog homes in the US that could be "designed" by home owners before being erected

Levittown
Tract Homes
1945

Levittown was an assembly line concept that was considered to be the "ideal" place to live in the mid 1940's

Construction was all but halted due to the Great Depression. Not many structures were being built because there were not many jobs that were paying for the labor and development of new buildings.

## THE GREAT DEPRESSION (1929-1939)

## WORLD WAR II (19

Structures composed during the World War I
standard plans with intentions of being cons
inexpensively. Most of these designs were s
frame buildings. These structures had easy
which were also aids by the addition of exte

Jean Prouve
1939-1970

Jean Prouve's Military Shelter design, to Tropical House, all the way to his final concept of the Train Station all incorroporated prefab

Abundance of time and massly produces nails made the concept of mass production within the US betweent the 1920's and the 1930's.

# THE INTEGRATION OF PRE-FABRICATION

Habitat 67
1967

Habitat 67 consists of prefabricated modular units to reduce housing costs

Capsule
Tower
1970

Capsule Tower in Ginza, Tokyo is a tower made of individual, prefabricated units

The Post War Era brought the notion of "needs over wants" within just about everything, including architecture. So with this concept in charge, much of the design during this era lacks in originality but makes a strong argument in just how sturdy it is constructed.

**POSTWAR ERA (1945-1970)**

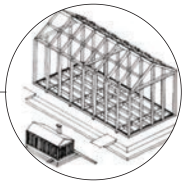
**I (1939-1945)**

War II Era were developed on
constructed extremely fast and
ere simple rectangular wood-
easy access points on both ends
exterior stairs.

Mobile Home
1950

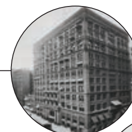
Mobile Homes were the first exploration of modular prefabrication development

# THE HISTORY OF ARCHITECTURE &



Manning Portable
Colonial Cottage
1833

Crystal Palace
1851



Home Insurance Building
1885

Eiffel Tower
1887

Jacksonian Era (1825-1849)
Civil War Era (1849-1865)
Reconstruction Era (1865-1877)
The Gilded Age (1870-1900)
The Progressive Era (1890-1920)
The

1830

Post Industrial Revolution

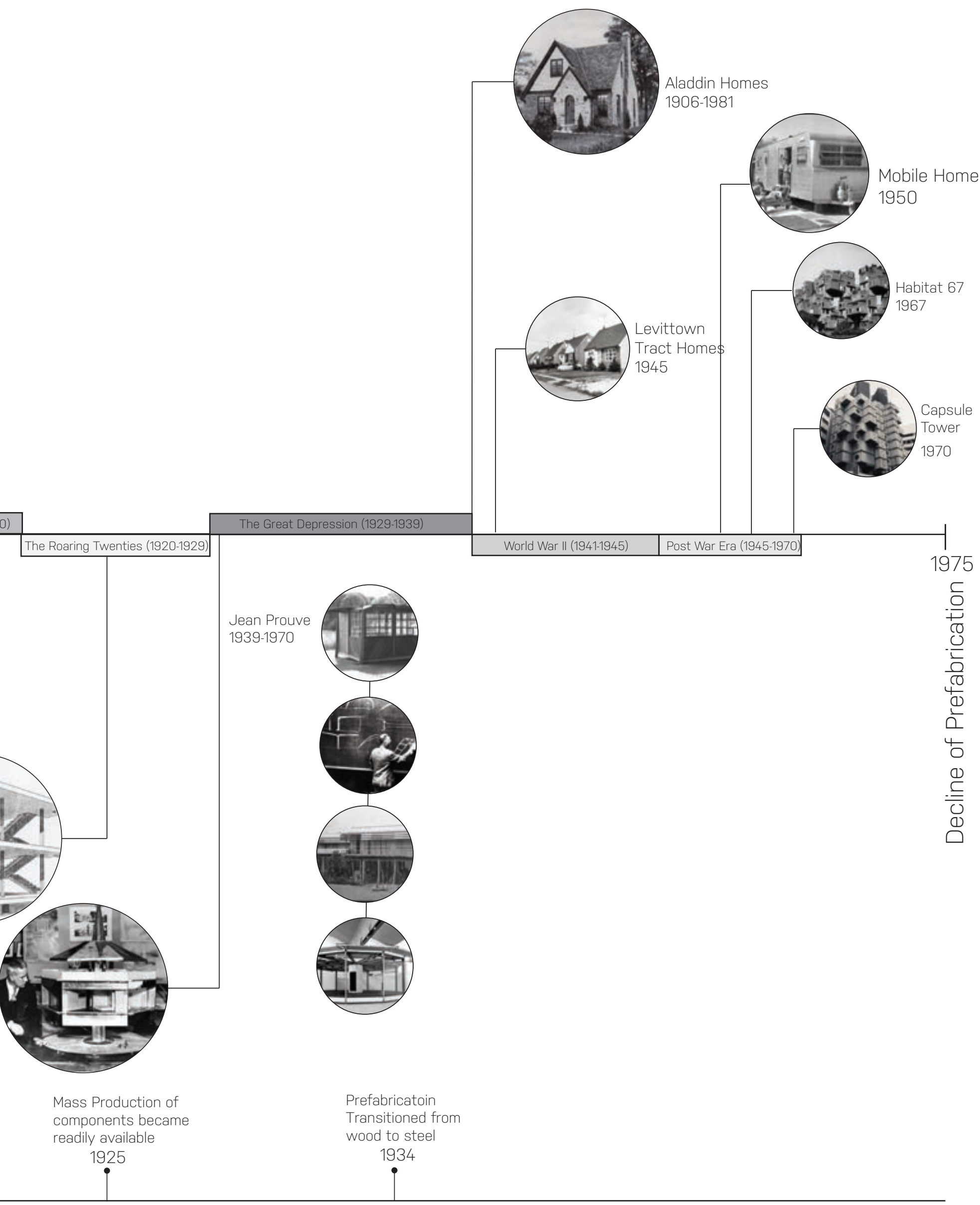
Le Corb
Mass Production
1923

Fuller
Dymaxion House
1933

Cement Enters
Prefabrication
1848

Wrought Iron added to
construction practices
within prefab
1851

# THE INTEGRATION OF PRE-FABRICATION



# 02

# Current State of Pre-fabrication

*Nick Hennessey*
*Jeffrey Richmond*

**ABSTRACT**

The development of pre-fabrication over the course of history has ultimately led to a diverse yet slowly changing array of techniques and methodologies. The current state of architectural pre-fabrication will be presented in comparison to two countries: United States and France. These two seemingly different countries share a common knowledge of pre-fabrication practices, yet their applications of such knowledge differ in their physical manifestations. Pre-fabrication in the United States has boomed in suburban areas compared to an urban context. Pre-fabrication in France does not have as large of a presence in the suburban context, as mass production has not gained as much traction in the country. The comparison will stem from discussions of context, accessibility, modular vs pre-fabrication, proprietary vs open-source and specific case studies. These case studies along with the analysis of hybrid structures will serve as an attempt to establish a dialogue that will explicitly give insight into the current state of architectural pre-fabrication in the United States and France.

*Fig. 1: Blu Homes Breezehouse.*

# OVERVIEW

Architectural pre-fabrication has made significant strides within the past couple of decades as the advancements in the manufacturing and construction industries have grown. Through advancements in computing, additive and subtractive manufacturing, and parametric modeling, pre-fabrication as a method of designing and construction has flourished. However, pre-fabrication has not reached its full potential within the built environment. This chapter component of New Generics will focus specifically on the current state of architectural pre-fabrication in the United States and France.

**United States**

A country known for its industrialization and the assembly line, efficiency by time, money, and materials has always been a priority. The architectural discipline has experienced many eras of pre-fabrication throughout its history and today there are a few trends that are most prevalent in the United States. The most common and potentially most unnoticed instance of architectural pre-fabrication in the United States are manufacture homes or mobile homes. According to the U.S. Department of Housing and Urban Development (HUD) and the U.S. Census Bureau, there are approximately 10.5 million manufactured or mobile homes, which makes up for approximately 8% of the total homes across all 50 states. Much of the success from these homes have come from their affordability and quality control. Since 1959, the United States Census Bureau and the U.S. Department of Housing and Urban Development have conducted the Manufactured Housing Survey (MHS). The MHS produces monthly regional estimates of the average sales price for new manufactured homes and more detailed annual estimates including selected characteristics of new manufactured homes. Furthermore, the MHS produces monthly estimates of homes shipped by status. The coverage of manufactured homes included in the survey includes


*Fig. 2: US Census Bureau, MHS.*

all new manufactured homes that have received a Federal Inspection.

**Manufactured Homes by the Numbers**

The data from the MHS shows the current shipments of new manufactured home per state in figure 1 (above). In 2017, there were a total of 92,902 shipments which was an increase of approximately 1,100 homes from the previous year. Since 1994, the amount of manufactured homes shipped has decreased nearly 80% from its peak in 1998 373,143 to 2018 with 74,354 homes shipped. The state of Texas is the largest consumer of manufactured homes in the United States while Hawaii remains the smallest. Comparatively, the state of Texas has the second largest state by population (28,304,596) and Hawaii is 40th (1,426,393). Furthermore, the ratio of manufactured homes shipped to state population is the greatest among the state of Alabama and the lowest in the state of Hawaii. On the other end, companies like Blu Homes create luxury pre-fabricated homes that are nearly half as expensive than comparable luxury homes. Yet, the luxury pre-fab home market remains a niche market for individuals whom are typically conscious

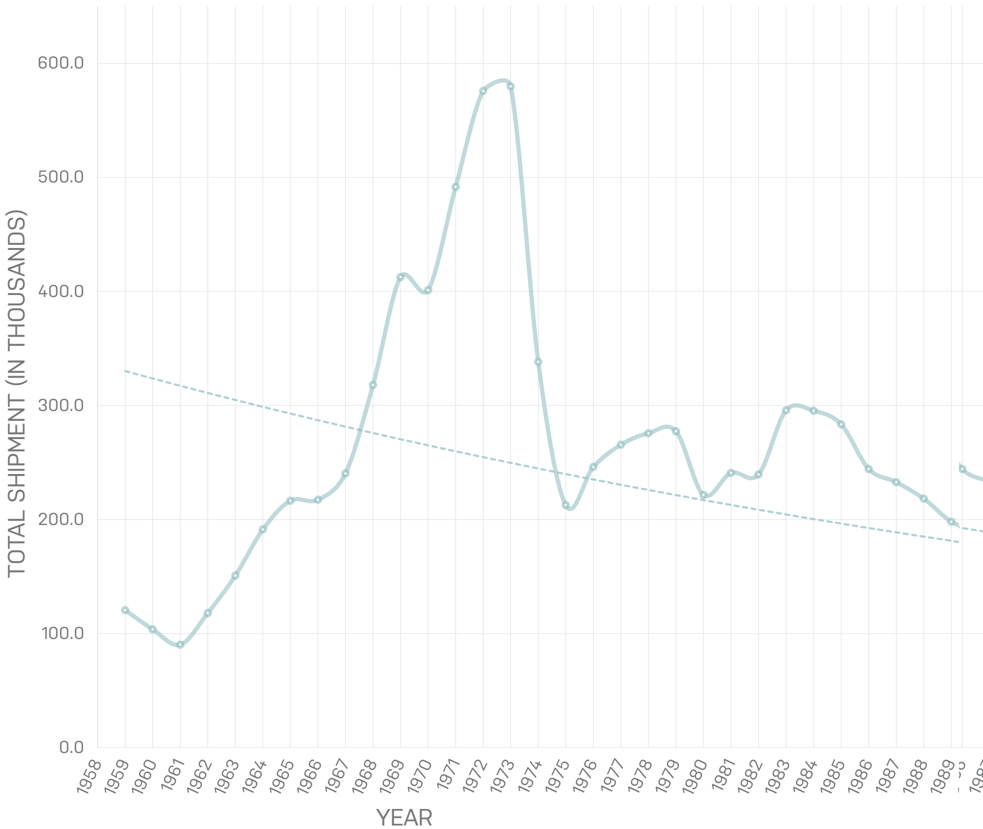
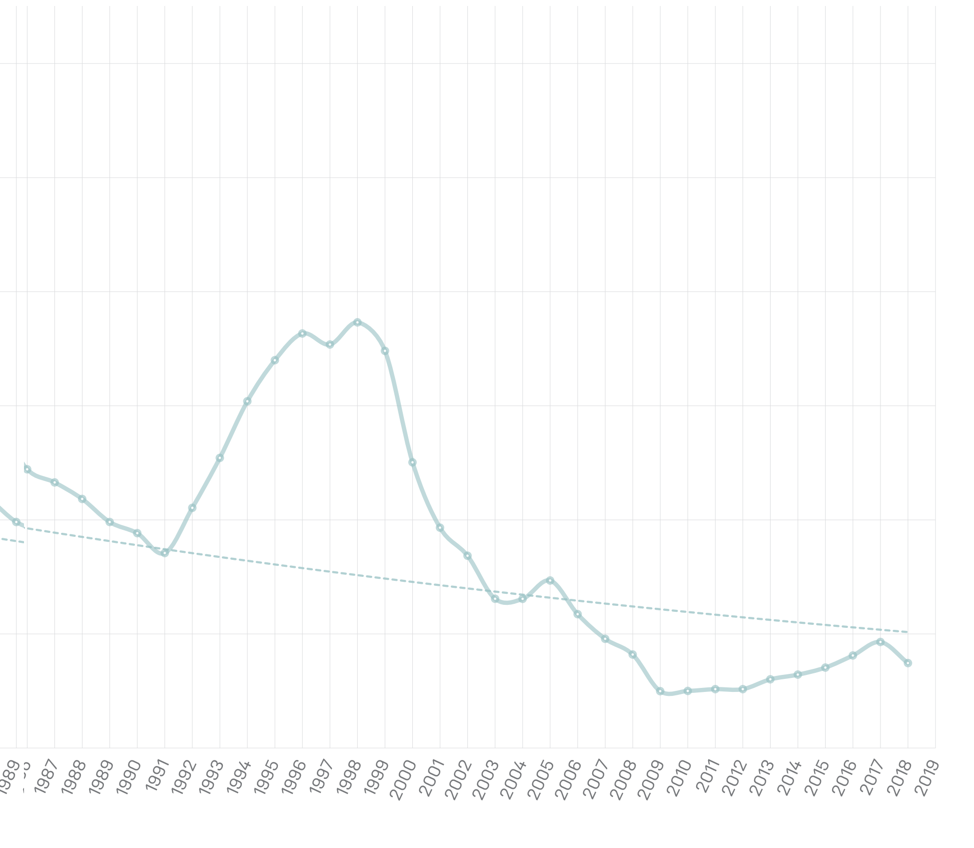



*Fig. 3: Annual Manufactured Home Shipments in the United States (1959-2018), MHS.*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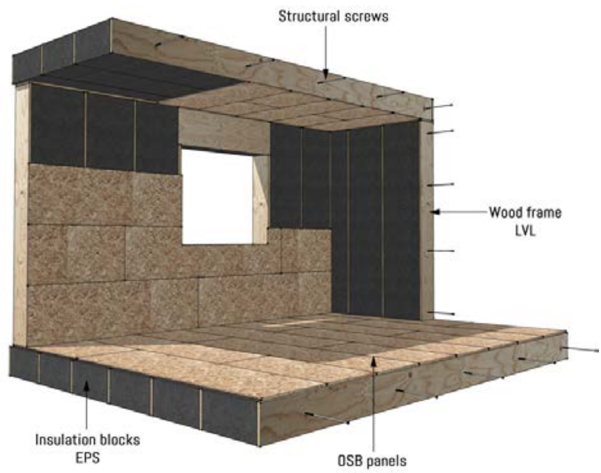



*Fig. 4: PopUp House assembly.*

of the design discipline and may consider themselves hobbyists or admirers. In fact, the market is so small that a company like Blu Homes only builds and designs homes in the state of California. One could infer that due to the small market space for luxury pre-fab homes in the United States that a company like Blu Homes is unable to achieve a profitable economy of scale so they must remain small in order to turn a reliable profit and reduce extraneous costs.

**France**

A country rich in its history and architecture, France has been graced with designers like Jean Prouve, Le Corbusier and many more influential architects and designers. As stated in the previous chapter, many architects have attempted to utilize the logic of pre-fabrication as a method of design. However, many, if not all attempts, have led to a single relic of the potential glories of pre-fabricated architecture. Jean Prouve's brilliant pre-fab La Maison Tropicale was made a total of three times, but it has traveled across the globe on display as an icon of pre-fabricated architecture. Compared to the United States, where the majority pre-fabricated architecture is marketed to low income families, it seems that the French market for pre-fabricated architecture has become a fad of a time that never came to fruition.

**PopUp House**

PopUp House is a research and design office that specializes on pre-fabricated, well insulated, high performance homes and offices. The concept of the PopUp House was conceived in 2012 and a patent for the modular insulated frame technology was issued in 2013. Since then they have built over 360+ homes and offices in France and 19 across neighboring European countries. According to their office, "demand for PopUp Houses is the highest in PACA, Auvergne-Rhône-Alpes and Languedoc-Roussillon Midi-

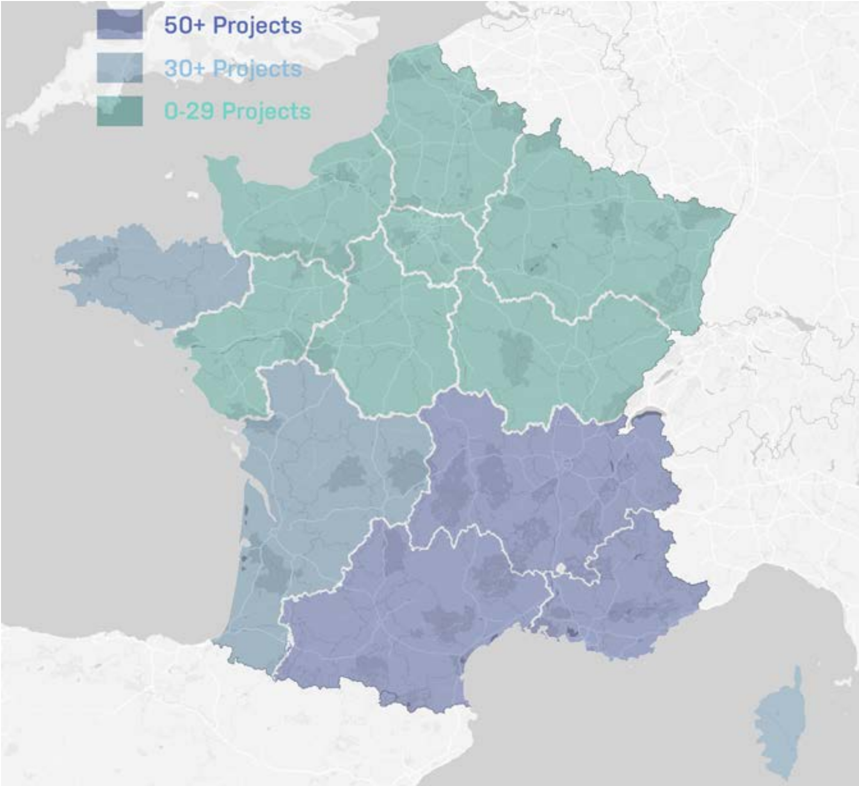



*Fig. 5: PopUp House project distribution after its first 5 years.*

Pyrénées with more than 50 project in each region." Each of the 360+ projects utilize their patented technology which is assembled simply by laying the insulated blocks down with wood frames in between each block. The insulated blocks and wood frames are then fastened with structural screws. The technology is simple and has begun to receive more traction compared to previous attempts through history. Although, the motives of PopUp house are different then those of Clayton Homes and other manufactured home producers in the United States, in terms of scale, PopUp house serves as a comparable example to that of Blu Homes.

**Conclusion**

Compared to the United States, France tends to utilizes pre-fab as another design tool for achieving a set of design goals. Meanwhile, pre-fab within the United States is predominantly used to capitalize on the benefits from the economies of scale from mass production. Regardless of motives, both countries seek to explore the potentials of pre-fab architecture.

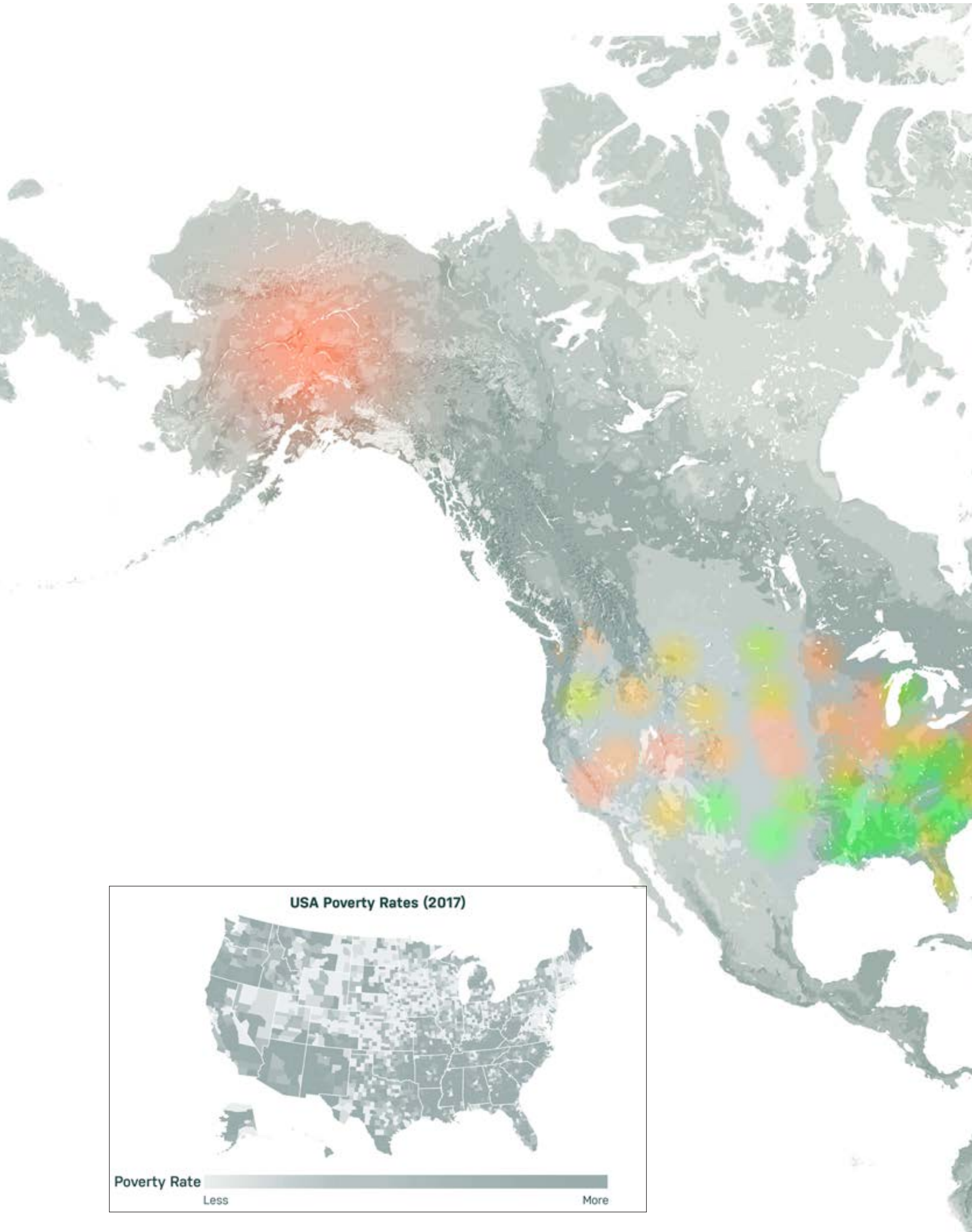
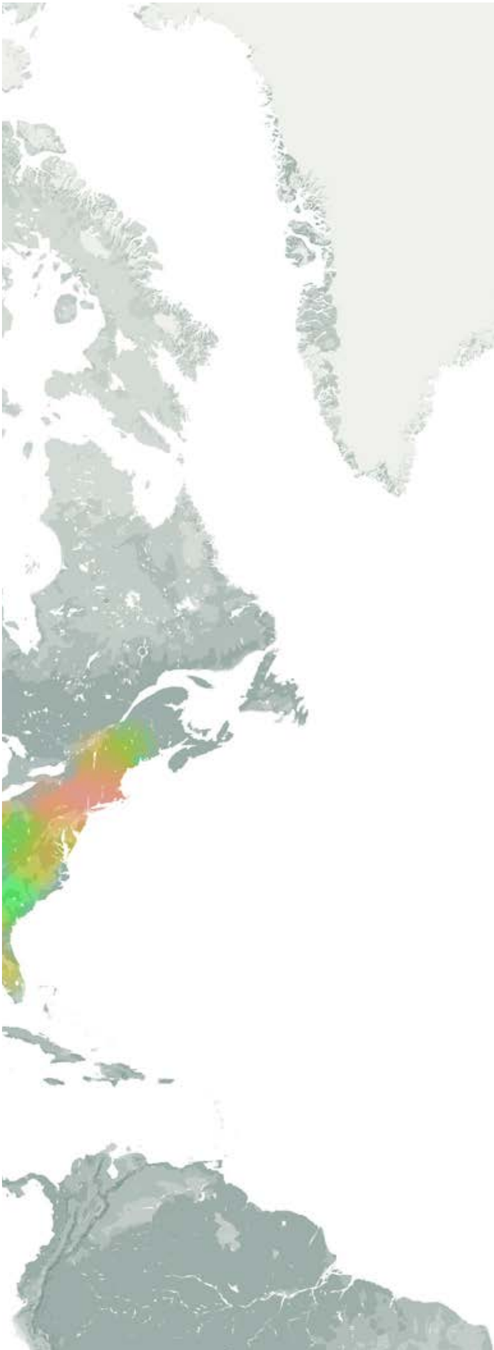
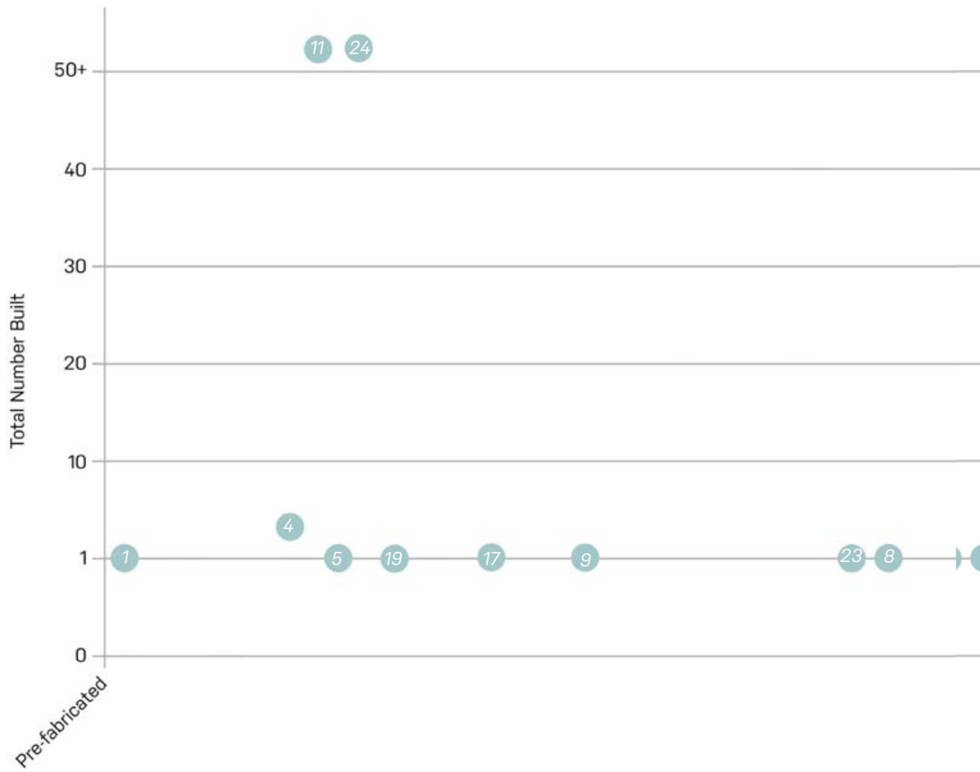



*Fig. 6: MHS/US Census 2017.*



**State of Manufactured Homes in the USA**
The following data was collected from various surveys conducted by the United States Census in 2017. Comparing state populations to manufactured home shipments (MHS) generates regional comparisons as well as an insight into the current proportions of manufactured home purchases. Generally speaking, the southern United States has a greater proportion of residents purchasing manufactured homes, while the Northeast has the lowest.

| State | Population | MHS | Ratio MHS/Pop | GDP |
|---|---|---|---|---|
| Alabama | 4,875,120 | 6046 | 0.00124017460 | **210.95** |
| Alaska | 739,786 | 59 | 0.00007975279 | **52.79** |
| Arizona | 7,048,876 | 1721 | 0.00024415240 | **319.85** |
| Arkansas | 3,002,997 | 1766 | 0.00058807918 | **124.92** |
| California | 39,399,349 | 3681 | 0.00009342794 | **2746.9** |
| Colorado | 5,615,902 | 934 | 0.00016631344 | **342.75** |
| Connecticut | 3,573,880 | 113 | 0.00003161830 | **260.83** |
| Delaware | 957,078 | 387 | 0.00040435576 | **73.54** |
| Florida | 20,976,812 | 5855 | 0.00027911772 | **967.34** |
| Georgia | 10,413,055 | 2852 | 0.00027388696 | **554.3** |
| Hawaii | 1,424,203 | 8 | 0.00000561718 | **88.14** |
| Idaho | 1,718,904 | 341 | 0.00019838222 | **71.89** |
| Illinois | 12,786,196 | 1344 | 0.00010511336 | **820.36** |
| Indiana | 6,660,082 | 1694 | 0.00025435122 | **359.12** |
| Iowa | 3,143,637 | 470 | 0.00014950836 | **190.2** |
| Kansas | 2,910,689 | 342 | 0.00011749795 | **157.8** |
| Kentucky | 4,453,874 | 2807 | 0.00063023786 | **202.51** |
| Louisiana | 4,670,818 | 5776 | 0.00123661423 | **246.26** |
| Maine | 1,335,063 | 525 | 0.00039323987 | **61.4** |
| Maryland | 6,024,891 | 851 | 0.00014124737 | **393.63** |
| Massachusetts | 6,863,246 | 213 | 0.00003103488 | **527.45** |
| Michigan | 9,976,447 | 4791 | 0.00048023109 | **505** |
| Minnesota | 5,568,155 | 713 | 0.00012804960 | **351.11** |
| Mississippi | 2,989,663 | 3665 | 0.00122589068 | **111.71** |
| Missouri | 6,108,612 | 1301 | 0.00021297801 | **304.9** |
| Montana | 1,053,090 | 273 | 0.00025923710 | **48.1** |
| Nebraska | 1,917,575 | 186 | 0.00009699751 | **121.77** |
| Nevada | 2,972,405 | 425 | 0.00014298186 | **156.31** |
| New Hampshire | 1,349,767 | 392 | 0.00029042049 | **80.52** |
| New Jersey | 8,888,543 | 471 | 0.00005298956 | **591.7** |
| New Mexico | 2,093,395 | 1253 | 0.00059854925 | **97.1** |
| New York | 19,590,719 | 1429 | 0.00007294270 | **1547.1** |
| North Carolina | 10,270,800 | 3835 | 0.00037338864 | **538.3** |
| North Dakota | 755,176 | 302 | 0.00039990678 | **55.49** |
| Ohio | 11,664,129 | 1912 | 0.00016392137 | **649.13** |
| Oklahoma | 3,932,640 | 1791 | 0.00045541926 | **189.16** |
| Oregon | 4,146,592 | 1408 | 0.00033955595 | **236.22** |
| Pennsylvania | 12,790,447 | 1545 | 0.00012079328 | **752.1** |
| Rhode Island | 1,056,486 | 38 | 0.00003596829 | **59.46** |
| South Carolina | 5,021,219 | 3797 | 0.00075619088 | **219.1** |
| South Dakota | 873,286 | 259 | 0.00029658096 | **49.93** |
| Tennessee | 6,708,794 | 2664 | 0.00039709074 | **345.22** |
| Texas | 28,322,717 | 17676 | 0.00062409267 | **1696.2** |
| Utah | 3,103,118 | 275 | 0.00008862054 | **165.53** |
| Vermont | 624,525 | 127 | 0.00020335455 | **32.2** |
| Virginia | 8,465,207 | 1266 | 0.00014955334 | **508.66** |
| Washington | 7,425,432 | 1207 | 0.00016254947 | **506.35** |
| West Virginia | 1,817,048 | 1119 | 0.00061583403 | **76.8** |
| Wisconsin | 5,792,051 | 612 | 0.00010566205 | **324.06** |
| Wyoming | 578,934 | 136 | 0.00023491452 | **40.29** |

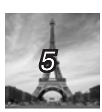



**Dymaxion House**
R. Buckminster Fuller

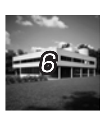
**Falling Water**
Frank Lloyd Wright

**The Pierre**
Olson Kundig

**La Maison Trop-icale**
Jean Prouve

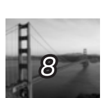


**Eiffel Tower**
Gustave Eiffel



**Villa Savoye**
Le Corbusier

**Centre Pompidou**
Renzo Piano



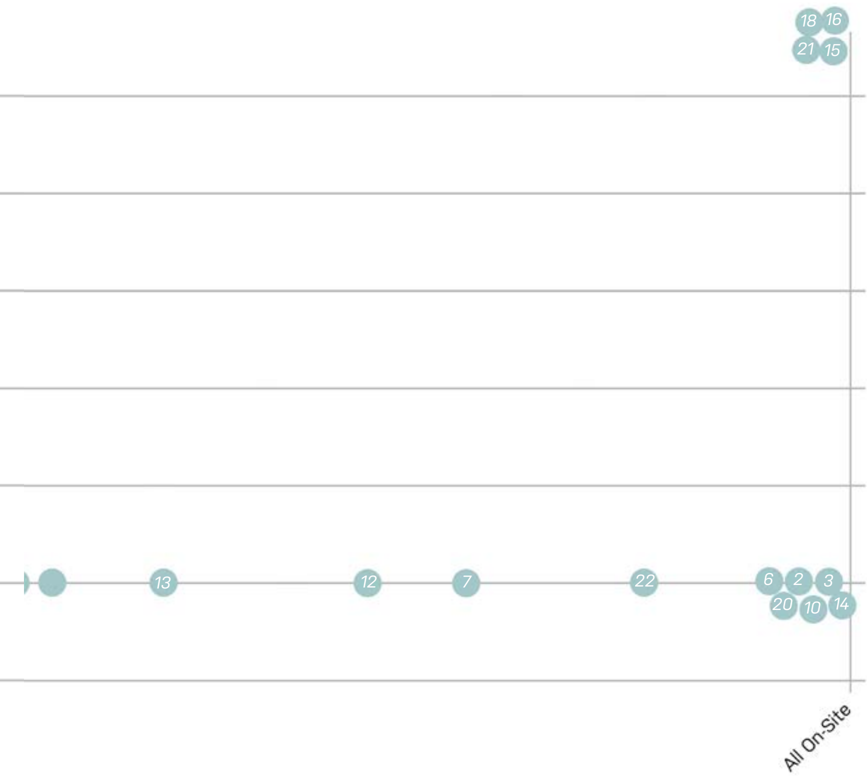
**Golden Gate Bridge**
Strauss

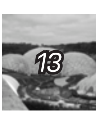
**3 Box**
Stephan Malka

**Unite d' Habita-tion**
Le Corbusier

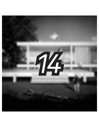
**Sears Catalog Homes**

**WTC Transporta-tion Hub**
Calatrava




**Eden Project**
Nicholas Grimshaw

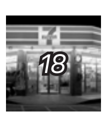



**Farnsworth House**
Mies


**Roman Aqueducts**

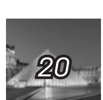

**Walmart**


**Maison Marly**
Karawitz

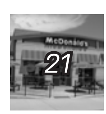



**Convenience Store**

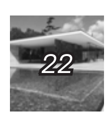

**Aux Quatre Arrondissements**
Post-Office Archi



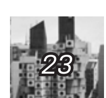

**Palais du Louvre**
I.M. Pei



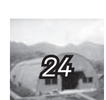

**McDonalds**




**Barcelona Pavilion**
Mies



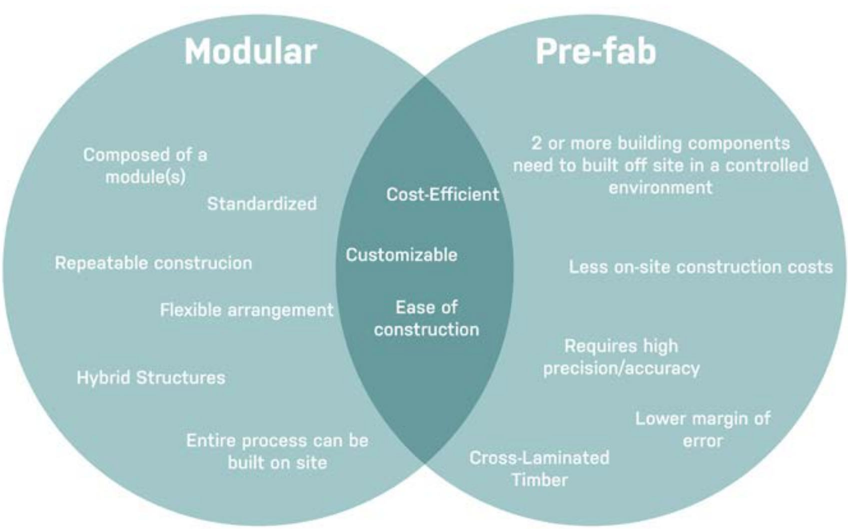

**Nakagin Capsule Tower**
Kisho Kurokawa




**Quonset Huts**

# PRE-FABRICATION AND MODULAR ARCHITECTURE

A common misconception of pre-fabricated architecture is that it is "modular." In some cases, modular architecture can in fact be pre-fabricated, however the two terms are not interchangeable. In order to be considered modular architecture, it must be composed of a module or a standardized unit/sections for easy construction or flexible arrangement. The proposal (right) by Penda for a modular tower utilizes a module that is repeated throughout every level of the building. Although there is a module, the proposal is not constructed pre-fabricated parts, but instead a standardized unit that is built on-site. On the other hand, for architecture to be considered pre-fabricated it must consist of at least 2 elements that are fabricated beforehand, off-site and in a controlled environment. With the advancements in current technologies, there has been an increase in the amount of customization when it comes to pre-fabricated assemblies. The wall (left) is constructed of cross-laminated timber and can be CNC routed to form high precision details and assemblages. There is no longer the presumption that pre-fabricated architecture is bland and incapable of being site specific.



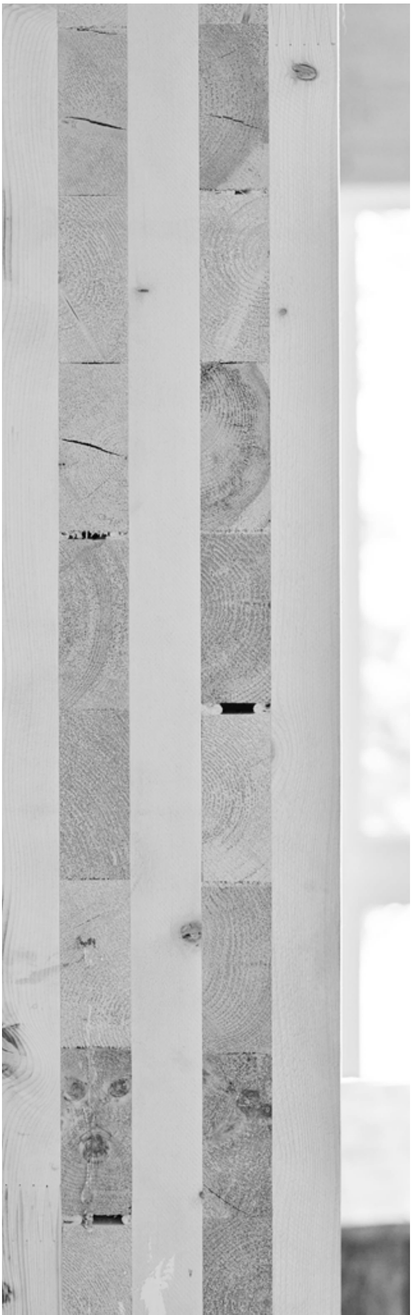


*Fig. 7: Cross-Laminated Timber.*

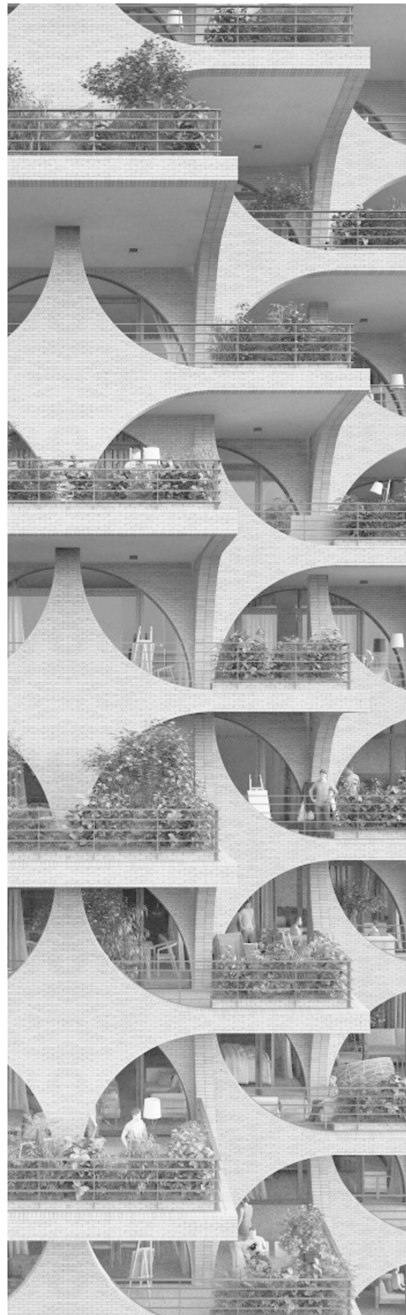


*Fig. 8: Tel Aviv - Studio Precht.*

*Fig. 9: Tower within a Tower.*

# MODULAR ARCHITECTURE

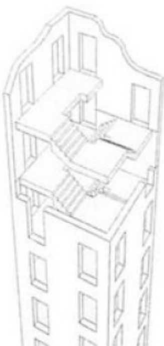
**Modular building** is a construction technique whereby building modules are prefabricated off-site. It is a type of off-site fabrication referring specifically to volumetric units which may be a structural element of a building. Modular building refers to the application of a variety of structural systems and building material, rather than a single type of structure. Pre-fabrication by off-site manufacture leads to a reduced overall construction schedule, improved quality, and reduced resource waste. The **disadvantages** to this type of construction include the lack of design guidance and relatively small structural spans due to the module transport limits. The **advantages** of modular building outweigh the disadvantages particularly for hotel and residential development applications. Modular building is there for increasingly popular and promoted. With the recent promotion several relevant studies have been conducted. The **workforce** is trained for specific tasks required by factory production, similarly to the workforce employed in the auto industry made famous by Henry Ford's innovate use of the assembly line. The **equipment** within a factory are designed to be larger, more powerful, and more sophisticated than on-site construction, ensuring precision control and achieving the specifications necessary for the design standards. The **framing materials** used in the factory must be of high quality to ensure they function within the equipment in the factory. This means that better materials, applied with tighter specifications, go into modular homes. The **factory** also provides an advantage in climate-controlled environment. When materials are delivered, they are stored under cover, protected from the elements, and assembled indoors, ensuring a dry, temperature controlled, and weather proof material. This also serves as an advantage in the construction process due to minimal delays due to weather

*Fig. 10: BIG, 79 & Park, Stockholm.*

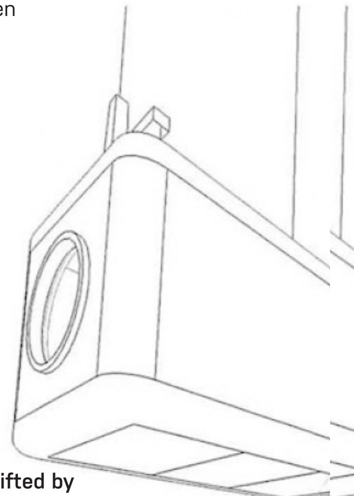
conflicts. The factories also exceed most building code and standard specifications. One reason for this is they must deal with transportation challenges and must be strong enough to move. Due to the lack of assigned site, the modules also must meet multiple state building codes and standards, often meaning the modules are built to the most demanding code, even if the code in the area the module is being delivered to requires one lesser. Finally, manufacturers have a buying power for goods, purchasing materials in high volumes, thus leveraging economies of scale to decrease costs. **Modules** are also inherently portable, allowing a range of locations for the module to be sited. For example, modular homes are often used by manufacturers at home shows due to the easy transport from show to show. Another advantage for building modular is its energy efficiency. Due to the inherent design, modular manufacturers can be more successful at sealing a structure because they have the luxury of building from the inside out, versus the on-site construction techniques are compelled to build from the outside in.

**Conclusion**

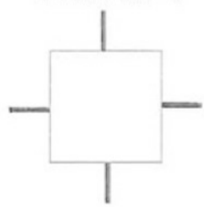
Building modules within a factory setting allows for quality control to be inspected along the process due to regulations. They are subject to far more inspections, having each state of the construction process armed with extensive checklists of performance standards, monitors of work for code compliance and craftsmanship. With these regulations set upon the manufacturers themselves, a warranty is often issued with the modules, allowing for an extended period for customer satisfaction of the products. Modular construction can be considered pre-fab wall assemblies, where wall panels are stacked in the order in which the building is being erected and transported to site.



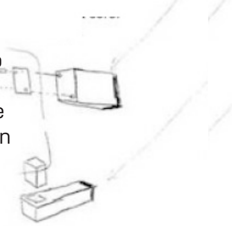
**Service Risers** are exterior fins on the lift shafts that are concealed when capsules are attached.

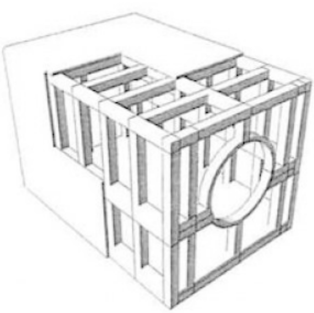


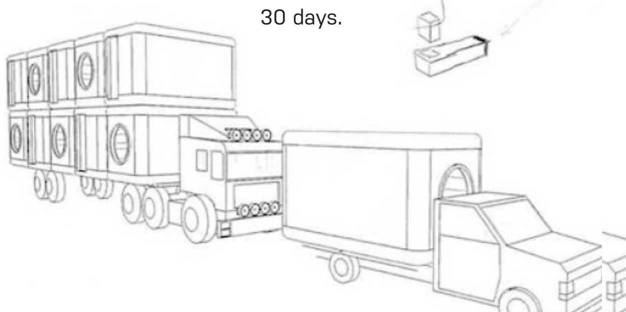
**The Lift Shafts** are circled by staircases that link the staggered levels. The stairs are constructed of reinforced precast concrete and include components for running the lifts, reducing the build time.



**Lifted by Crane** and attached with four high-tension bolts into the core. All capsules were installed within 30 days.







**The Capsules** were pre-fabricated out of light-weight steel truss boxes. Clad with galvanised ribbed steel panels, rust prevention paint and kenitex (impervious weatherproof plastic with an estimated 20 year life span)

**Large Trucks** brought capsules from the assembly plant 450km away in Shinagawa. The capsules were reloaded onto smaller trucks before weaving their way into downtown Tokyo.

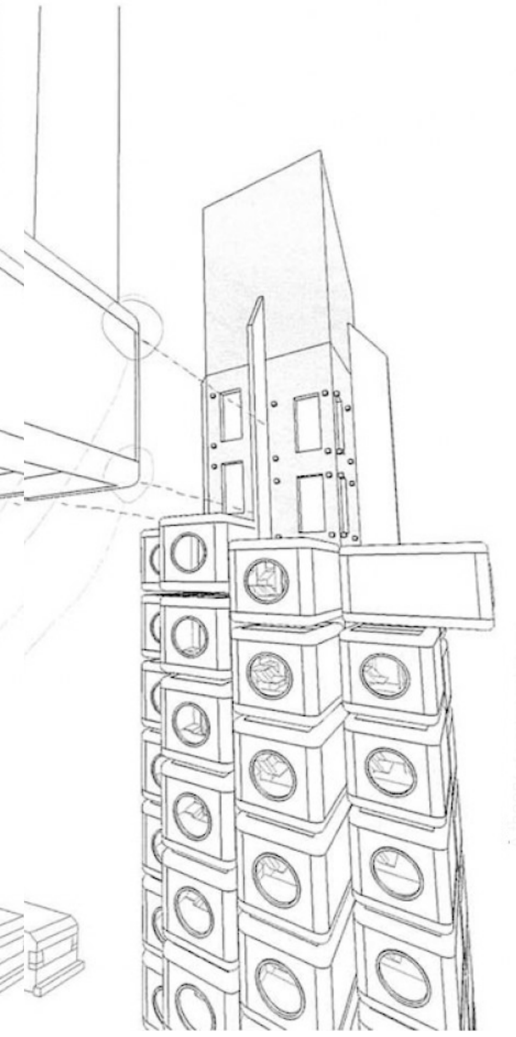


*Fig. 11: Nakagin Capsule Tower by Kisho Kurokawa, Tokyo, Japan.*

# MODULAR STEEL BUILDING

Modular Steel Building modules are a type of steel module classification due to the structural needs of the design. Many of these modules consist of, but are not limited to, applications such as hotels and residential apartments. Most constructions using this type are hybrid systems, utilizing a core system of vertical circulation coupled with the models. While these modules are suited for high rise construction and are high in design and structural strength, they have the tendency to corrode overtime and often have lack of design guidance during the construction process.

**Applications:** Hotel, Residential Apartments
**Advantages:** Suited to high rise buildings, high strength
**Disadvantages:** Corrosion, Lack of design guidance

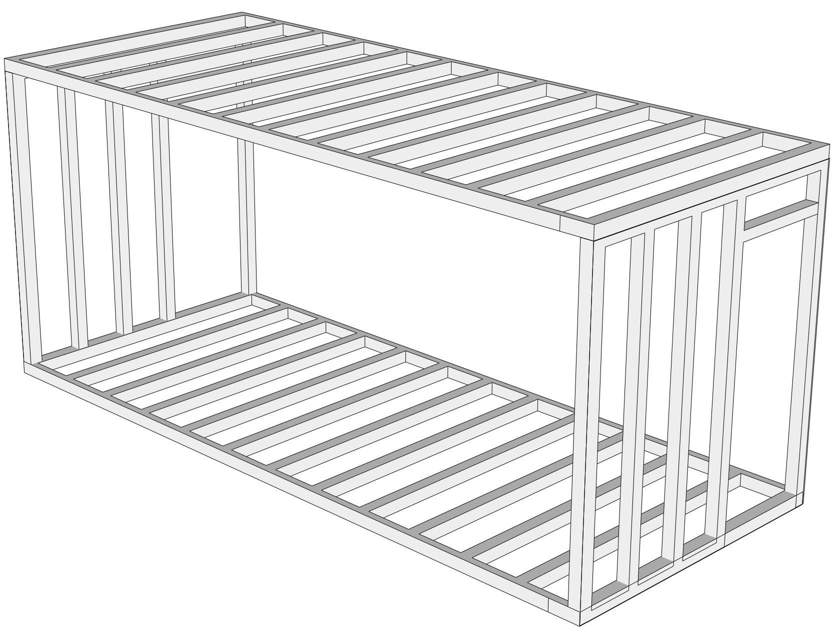


*Fig. 12: MSB Module.*

*Fig. 13: 461 Dean Street under construction, SHoP.*

*Fig. 14: 461 Dean Street, SHoP.*

# LIGHT STEEL FRAME

Light Steel Framed modules are another type of steel module classification based on the materiality used in construction. Many of these modules consist of, but are not limited to, applications such as 10-story buildings ranging from office buildings to dormitories, as well as constructions of up to 25-storys with an additional core for reinforcement. While these modules are a great use due to their lightweight construction, they are only suited to low rise buildings due to the need for additional reinforcement and limitations in strength.

**Applications:** Maximum 10-storey, 25-storey with additional core
**Advantages:** Lightweight
**Disadvantages:** Suited to low rise buildings

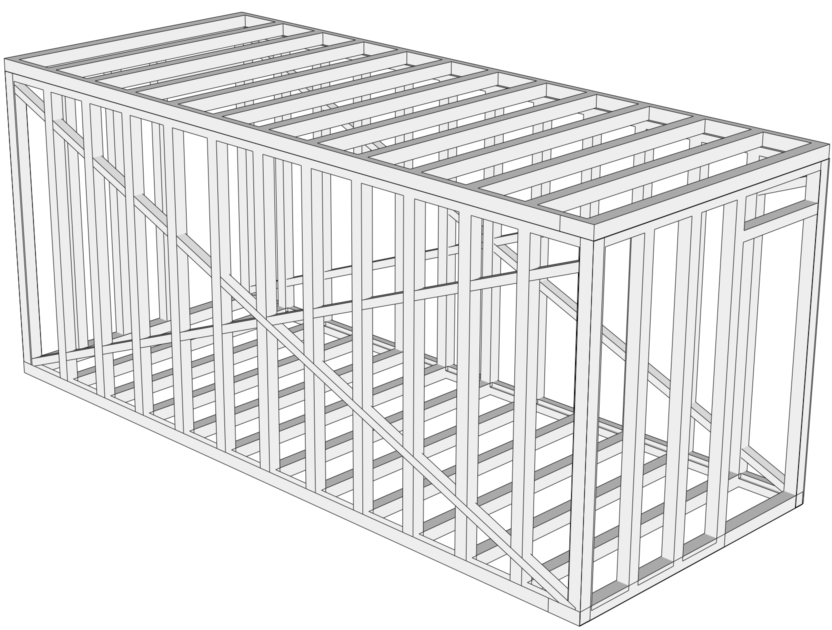


*Fig. 15: LSF Module.*

*Fig. 16: LSF Module - Under construction.*

*Fig. 17: LFS Module - Built.*

# CONTAINER MODULE

Container modules based on existing shipping container dimensions. Many of these modules consist of, but are not limited to, Post-Disaster housing, military operations, and residential developments. Due to existing industry standards of transporting shipping containers these modules are easy to transport as well as recyclable, however once thresholds are cut through the container walls additional reinforcing is required to strengthen the container as well as height limitations and spanning widths.

**Applications:** Post-Disaster housing, military operations, and residential developments
**Advantages:** Recycle shipping containers, easy transport
**Disadvantages:** Additional reinforcing required to strengthen container when openings are cut into the wall

*Fig. 18: Container Module.*

*Fig. 19: Container-Skyscraper Mumbai, India.*

*Fig. 20: Aether's San Francisco.*

# PRECAST CONCRETE MODULE

Precast Concrete Modules are a type of modular construction consisting of reinforced concrete forms which are transported then placed in situ. Many of these modules consist of, but are not limited to, applications such as hotels, prisons, and secure accommodations. Precast Concrete Modules offer many advantages when placed on site such as fire resistance, acoustic insulation, thermal performance, high mass which helps meet vibration criteria, and high load capacity. While these are all positive solutions of the module, the transportation of these modules can be difficult due to the weight and potential cracking at the corners.

**Applications:** Hotel, Prison, Secure accommodation
**Advantages:** Fire resistance, acoustic insulation, thermal perfor mance, high mass helps meet vibration criteria, high capacity
**Disadvantages:** Heavy, potential cracking at the corners

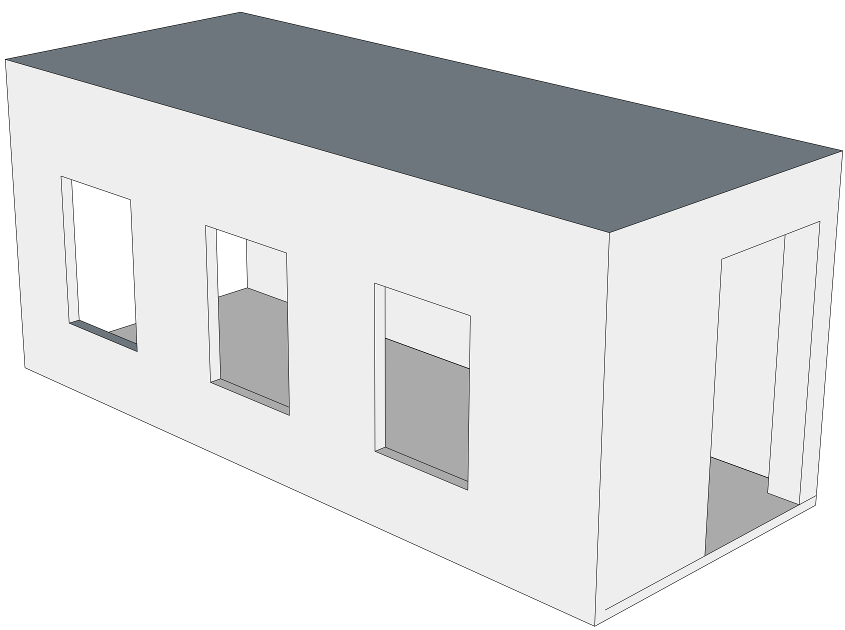


*Fig. 21: Precast Concrete Module.*

*Fig. 22: Construction of Crowne Plaza Changi Airport Hotel.*

*Fig. 23: Crowne Plaza Changi Airport Hotel.*

# TIMBER FRAME MODULE

Timber Frame Modules are a makeup of dimensioned lumber formed as typical stud walls. Many of the modules consist of, but are not limited to, applications such as 1 to 2-storey buildings, educational facilities, and housing. Timber Frame Modules are easy to fabricate due to the sustainable material of lumber, however, are poor in fire resistance and durability.

**Applications:** 1 to 2-storey, educational buildings, housing
**Advantages:** Sustainable material, easy to fabricate
**Disadvantages:** Poor fire resistance, durability

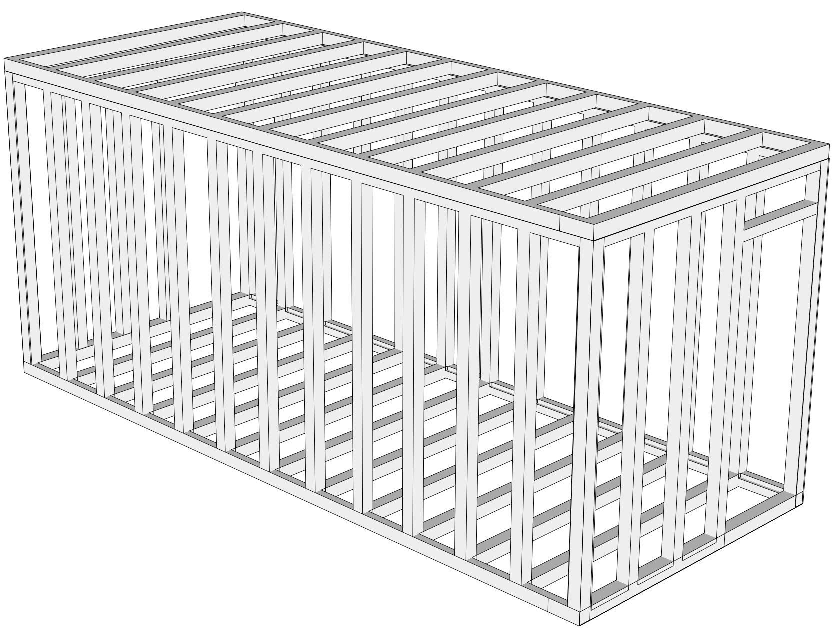


*Fig. 24: Timber Frame Module.*

Fig. 25: Timber Frame Module.

Fig. 26: Modular Timber Tower Toronto.


*Fig. 27: The Belle, Clayton Homes.*

## PROPRIETARY & OPEN SOURCE HOMES

"Open Source Architecture (OSArc) is an emerging paradigm describing new procedures for the design, construction and operation of buildings, infrastructure and spaces. Drawing from references as diverse as open-source culture, avant-garde architectural theory, science fiction, language theory, and others, it describes an inclusive approach to spatial design, a collaborative use of design software and the transparent operation throughout the course of a building and city's life cycle."

-Carlo Ratti

Over the recent years, there has been a movement within many disciplines to democratize accessibility to otherwise difficult to reach or expensive knowledge and tools. In the realm of computers and coding there is GitHub, purchased by Microsoft, but remains accessible for free to everyone to review code, manage projects and build software. The term open source is typically associated with computers and software; however, it can apply to disciplines such as architecture. Carlo Ratti, Director of the MIT Senseable City Lab and founding partner of CRA, and about fifteen other contributors were asked to write an op-ed for Domus in 2011 in an open-source format. On the other end of the spectrum, companies and manufacturers collaborate internally and design homes that are economical and can be efficiently built to turn a profit. The following will attempt to draw a distinction between two methodologies of creating an architecture.

**Proprietary Designs**

In today's capitalist driven society, companies and individuals seek to earn the largest profit margins for proprietary designs, knowledge, manufacturing processes, etc. The boom of industrialization and technology has led many to find success in

*Fig. 28: Users can come up with their own version of the Hermit House with the Hermit House 3D design app.*

implementing mass production and leveraging their economies of scale. Companies like Clayton Homes, Champion Homes, and Cavco Industries have managed to leverage the manufactured homes markets for over 50 years. These companies are three of the largest manufacturers and sellers of manufactured homes in the United States and have achieved this through mass production through mass customization. In short, these three key players within the market produce and own their own architectural plans and designs in which they build thousands of homes a year to prospective homeowners. All their proprietary designs are built within their own climate-controlled factories that have welders, plumbers, carpenters, roofers, etc., all under the same roof. The efficiencies within the manufacturing process are like that of Henry Ford's assembly line. Each home built has similar structural logic, but the finishes and aesthetics have been customized to the specifications of the client. The customizations range from flooring, paint, energy efficient appliances, counter tops, etc. The efficiencies within the structural logic and manufacturing process allows for a system of integrating mass customization for each home built. Although, the materials used on each home are similar in terms of material makeup, the customization aesthetics brings forth a sense of ownership and participation within the house building process for the clients which is crucial to the success making the house a "home".

**Open Source**

The architecture profession has stereotypically been a service for the wealthy and inaccessible to the masses. With the incorporation of technology and the internet, the accessibility of the architecture discipline has begun to expand. Websites and social media such as Pinterest, Instagram, Facebook, Houzz, and more have begun a movement of creating an access to knowledge including that of architecture and DIY construction. For architecture, access to online resources has created a diverse community for small projects such as building an outdoor shed or renovating a space within the home. However, there is still little access and knowledge available to larger scale projects like designing and building one's own home.

Within the past few years there have a been several members of the architecture community that have spoken out to create an accessible and open source network for anyone to design and build their own home or space. These open source communities within architecture have not grabbed as much traction as other disciplines that have welcomed open source networks. However, some of the major contributors to the movement have created platforms that are available to everyone around the world at no cost. Some of the most prevalent platforms are WikiHouse, Paperhouses, Bricks, Elemental, Opendesk, and AKER. Each of these platforms address a variety of accessibility issues within the realm of design. Wikihouse, Paperhouses, Elemental and Bricks all address issues at the building scale and housing. Opendesk is "a global platform for local making. We host digital furniture designs that can be made anywhere in the world through a global network of local makers." AKER "exists to help people in urban areas grow food and create habitats for wildlife, even in small spaces like balconies, rooftops, backyards, and counter tops." All these platforms have begun to address issues of access to knowledge and design though their own specific means.

Some of the most promising and surprising instances of open source stems from the nature of "open source" as a concept. For example, in a small rural town in the Chinese province of Hebei lies Er-tai Elementary School. The elementary school wanted to construct a library addition that was not only economical but had structural integrity. The architecture firm Dot Architects utilized the WikiHouse platform to build the Huaxia Star Library (Fig. 29). The library was constructed in just one week by untrained builders.

**Conclusion**

Whether architecture is built through proprietary or open source architecture, the outcome should create a space that is respectful of its context, materiality, and the people whom inhabit it.

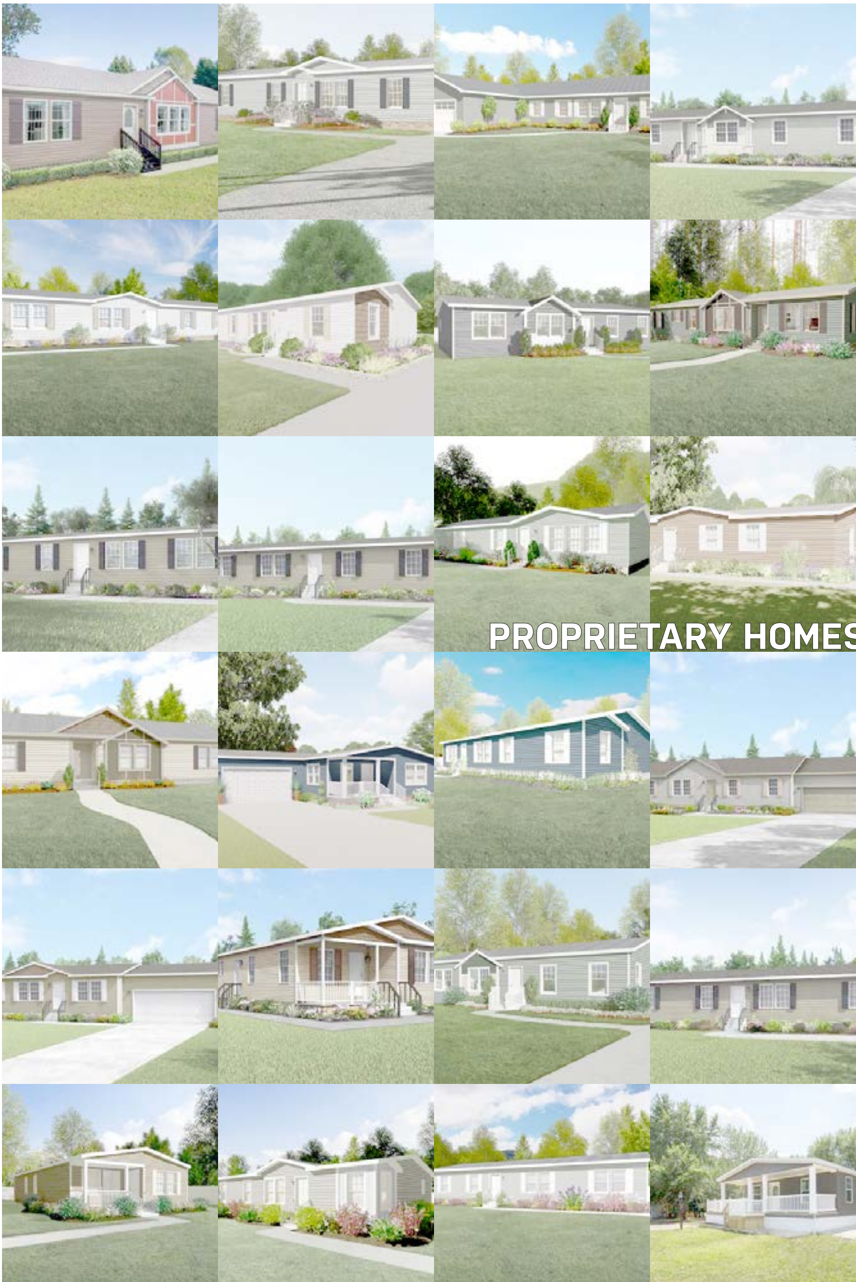



Fig. 29: Clayton Homes.

**Clayton Homes**
Clayton Homes is recognized as an innovator within the manufactured home industry since 1956. In 2015, 34,000 homes were built across America and delivered to homeowners, fulfilling their pursuit of affordable homeownership. Clayton strives to produce affordable, sustainable and long-lasting homes.

**Champion Homes**
Champion Homes provides factory-built solutions for single-family, multi-family, commercial and even government buildings. Founded in 1953, Champion has 28 facilities located throughout North America and has produced more than 1,700,000 factory-built manufactured homes, modular homes and mobile homes.

**Cavco Industries**
Cavco is a leader in manufactured homes, modular homes, commercial buildings, RV's and vacation cabins. Founded in 1965, Cavco has 19 manufacturing facilities in the United States alone. Cavco is focused on building energy efficient homes for the modern homebuyer that use alternative energy sources such as solar and wind.

**Skyline Homes**
Skyline was founded in 1951 and produced some of the first "house trailers" or "mobile homes". These units evolved into what is now known as a manufactured home or modular homes that are built today. There are 8 manufacturing facilities in the United States that have produced hundreds of thousands of homes.

**Giles Industries (Clayton Homes)**
Founded in 1959, Giles Industries was purchased in 2006 by Southern Energy Homes and then later that year they were purchased by Clayton Homes. They have built over 86,000 homes that are pre-built in climate-controlled facilities. Their focus remains on creating affordable, high quality manufactured homes.

**Highland Manufacturing (Champion)**
For more than 20 years, Highland Manufacturing has earned a reputation of building high quality manufactured homes. Located in Worthington, Minnesota, Highland builds all their homes and works with a larger network of independent retailers and builders throughout 10+ states.

**Destiny Industries**
Founded in 1978, Destiny Industries contributes to the southern part of the United States. Located in Moultrie, GA the company was recognized as a 2018 Energy Star Certified Homes Market Leader after it contributed 51 energy star certified homes in 2017. Altogether, they offer 74 floor plans to choose from.

**Franklin Homes**
Founded in 1969 in Russellville, Alabama, Franklin Homes was purchased by a subsidiary of C3 Design, Inc. Each home produced by Franklin are backed with a 10-year structural warranty, ensuring the structural integrity of the home. All homes are built in Russellville, AL, yet there is a network of Franklin Retailers in 13 states.

*Fig. 30: Example of a manufactured homes build facility.*


Fig. 31: Open Source Projects.

**Affordable Housing - Space 10 (IKEA)**
This micro-house designed and built by IKEA utilizes one material and one machine to make the entire structure. There is an accompanying website that documents the process and invites architects and designers to give feedback and aide in creating a low-cost, sustainable house available to anyone.

**Growroom - Space 10 (IKEA)**
IKEA's DIY "Growroom" is intended to provide a garden structure for people and communities to "grow their own food much more locally in a beautiful and sustainable way." The structure requires 17 sheets of plywood that are CNC milled and easily assembled with a rubber hammer and metal screws.

**LEKA Open Source Restaurant - IAAC FAB LAB Barcelona**
A restaurant where the entirety of the furnishings, ceiling fixtures, and more are available to download on the restaurant's website. The fabricated ceiling is designed to mitigate sound waves and echo, while the furniture and other pieces are designed to be withstand continuous use.

**Open Source House - Studiolada Architects**
Located in Baccarat, France the architect and client created a "reasoned and universally accessible house." All plans, sections, details, cost estimates, etc. are available online as open source to encourage a "collaborative society" and inspire projects and ideas.

**Hermit Houses**
These small houses are affordable, customizable and serve as a new "e-building vernacular" that the internet can facilitate with open-source software where mass customization brings it to reality. The software allows for adjusting to local constraints and the specific needs of clients without a lot of added costs.

**Huaxia Star Library - WikiHouse**
Inspired to construct a library for the Er-tai Elementary School that was economical, but sturdy; easy to build, but did not require expensive labor, Dot Architects utilized the WikiHouse blueprint to create an entirely different building. The addition to the school was constructed within a single week with untrained labor.

**The Folk House - Paperhouses**
Similar to a traditional Hungarian farmhouse, the Folk House is meant for a typical suburban land form. At the core of the design are issues revolving around sustainability the use of local and responsible materials like ones used in the folk architecture of the past. The house is 3 bed/2 bath and totals 1,420 sqft.

**Wikihouse 4.0 - WikiHouse**
The first two-story design that can be assembled in days without any prior construction skills. The total cost of the building comes in at less than 66,000 USD with up-to-code electrical and ventilation systems. The timber structure is CNC-manufactured and wrapped in Tyvek waterproofing and clad in fiber cement.

Fig. 32: Huaxia Star Library, Dot Architects via Dezeen.

# CASE STUDY | PARIS, FRANCE

"A vault completes, on the axis, the existing pediment of the building on the Boulevard de La Villete giving it a new statute. The typology is simple and economical. It is a barrel vault with wooden structure, open at one end onto the boulevard and at the other end onto the roofs of Paris. The elevation has an intrados and an extrados. The intrados is made of clear wood giving the interior space a warm atmosphere. The extrados is a sheet of metal capturing the colors of the Parisian Sky."

-Post-Office Architectes

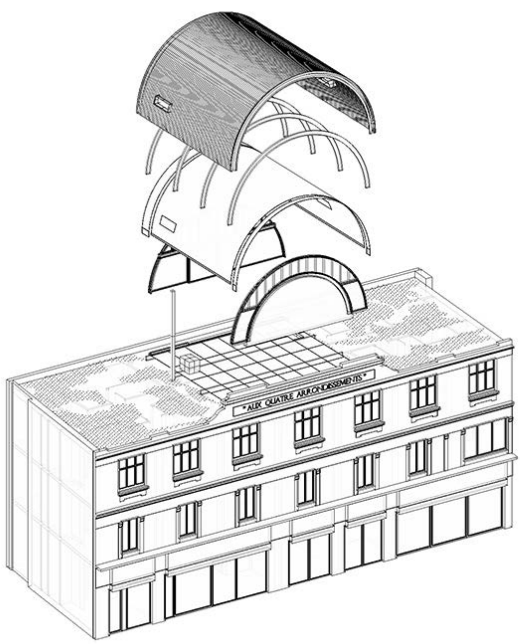



*Fig. 33: Aux Quatre Arrondissements rooftop studio addition. Post-Office Architectes.*

*Fig. 34: Interior Studio.*

Located nested within the urban fabric of Paris, at the intersection of four districts, lies a small rooftop intervention constructed as a single barrel-vaulted volume. Conceived by Post-Office Architectes, it sits atop an existing apartment building that served as a two-story department store in the 19th century. An additional floor was added in the early 20th century as well as a pediment with the name "Aux Quatre Arrondissements." The 900 SF addition sits atop the roof and serves French photographer, Matthieu Deluc, as an extension to his 3rd floor apartment. The design was conceived in 2012 and built in 2016 on a tight budget of 220,000 USD. The 900 SF single barrel-vaulted volume was laid out along the building's axis. The space is supported by four pre-assembled wooden arcs that allow for large open ends with views to the Boulevard de La Villete and the other across the city with the Eiffel Tower in sight. On the side of the Boulevard de La Villete, there are a set of doors that open out onto a terrace constructed with timber decking that wraps around the intervention. On the interior, the barrel-vaulted ceiling is clad in insulated wooden panels while the exterior is clad with corrugated metal that blend in with the Parisian sky. With the structure being reduced to four pre-fabricated wooden arcs, the total onsite assembly only took a mere 15 days. All parts of the building were pre-fabricated and assembled in a factory, including the interior wood and exterior metal cladding, the insulated wooden panels, as well as the timber terrace floor. Additionally, the design includes a series of operable glass sections that allow for natural ventilation as well as solar panels installed on the roof.

*Fig. 35: Interior View Aux Quatre Arrondissements.*

# CASE STUDY | DETROIT, MICHIGAN

"Open to the neighborhood and without fencing, the community is accessible from the street via three pathways. The strategic placement of the huts is driven by a need for openness and security, views and privacy, socializing and solitude. Within the community, pathways connect visitors to the eight huts, the communal pavilion, gardens and eight parking spots (alongside the back alley). Each pre-fabricated steel Quonset Hut is assembled on top of a four-inch radiant heat, which is also the finished floor. The end walls feature custom steel framing around polycarbonate panels that provide a higher level of security, natural light and high thermal volume."

-EC3

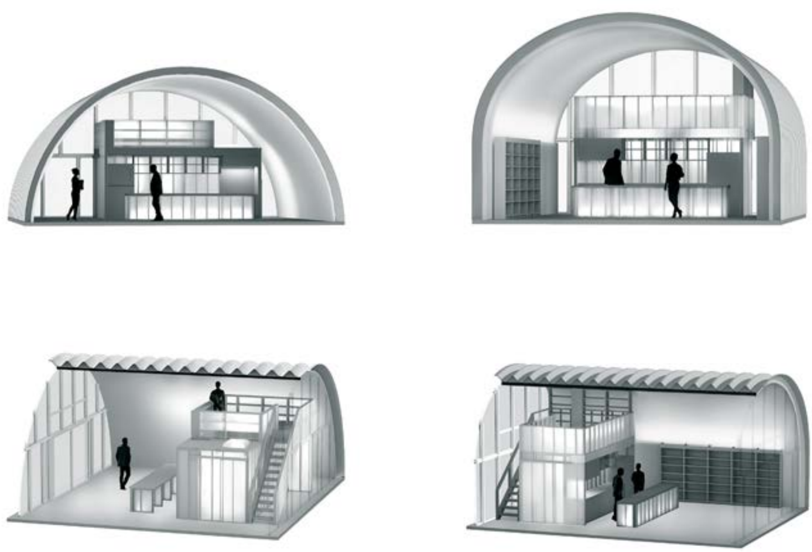


*Fig. 36: True North Development utilized Quonset Huts for its economic and aesthetic qualities.*


*Fig. 37: Quonset Huts Entrance.*

True North is located in Core City, a quiet neighborhood a few miles from downtown Detroit and has become a catalyst for the redevelopment of a long-neglected area. It is the neighborhood's first new construction project in over 60 years. The affordability of the design and creative use of pre-fabricated materials is finely attuned to the context and community of Detroit. Edwin Chan, founder of EC3 commented on the design saying, "We tried to capture the beauty of Detroit's toughness with the raw aesthetic in its design, while creating an inviting place for the neighborhood." However, it was the client that challenged EC3 to utilize Quonset Huts, which are a pre-fabricated lightweight structure that consists of corrugated galvanized steel that forms a semicircular barrel-vaulted volume. Quonsets huts became popular during the second world war due to their lightweight and pre-fabricated nature. For the interiors of the volume, a variety of layouts and configurations were developed ranging from 475 SF to 1,600 SF allowing for a greater diversity of lifestyles to exist within the community. Furthermore, many of the units house a polycarbonate "island" that contains a kitchen, a bathroom, and a mechanical/storage closet. Atop the "island" is a mezzanine space that can function as an elevated bedroom, office or extra storage. The development was built in less than a year. The complex has been described as not only a place for living, but one work creative inspiration and working. Six of the huts house a single rental unit, one contains two units and serves as a flexible event space on the ground level and a rental unit above.

*Fig. 38: Quonset Huts make up the True North Development near Detroit, MI.*

# 03

# Transportation + Logistics

*Maksim Drapey*
*Austin Wiskur*

**ABSTRACT**

This research introduces an operational hedging and regression vision for logistic operations in Pre-fabrication construction, aiming to improve the efficiency and effectiveness of decisions throughout the logistic and supply chain process. This research yields the question, "What hedging and regression strategies exist that present potential improvement in quality and efficiency of operational executions?". To answer this question, three components are investigated; (i) Operational Hedging for Pre-fabrication Construction; addressing the uncertainty within the three phases of a Pre-fabrication project (ii) Life Cycle Assessment / Cradle to Cradle; an evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (iii) Regression Model Proposal for Pre-fab. Buildings (LCA). These three components will be used to shed light on the major logistic methodologies and solution systems that can enable new approaches for government authorities, pre-fabricated manufacturers, and contractors to reap the green benefits of the pre-fabricated building initiative in France and the US.

**Components:**

1. Operational Hedging for Pre-fabrication Construction
   a. Pre-fab. Factories
   b. Pre-fab. Logistics
   c. On-Site Assembly
2. Life Cycle Assessment / Cradle to Gate
   a. Inputs
   b. Process
   c. Outputs
3. Regression Model Proposal for Pre-fab. Building (LCA)
   a. Challenges
   b. Fundamentals
   c. Potential Solutions

**Highlights:**

**1.** Propose a vision of operational hedging to address the uncertainties within the three key phases of a Pre-fabrication project.

**2.** Examine the energy-saving potential of pre-fabricated construction using the input-output (I-O) method of analysis.

**3.** The proposed regression model offers potential solutions that are important and timely to help effectively reduce buildings' life cycle carbon for achieving long-term sustainability.

# OPERATIONAL HEDGING FOR PRE-FABRICATION CONSTRUCTION

**Uncertainties from "Pre-fab Factory":**

The innovative contracting method The innovative contracting method known as Construction Manager at Risk (CMAR) is a delivery method that provides a number of time and cost savings advantages. With the CMAR process and position, the CMGC (construction manager and general contractor) is selected early in the design phase. Work is done closely with the architect to examine alternate materials, systems, and equipment for cost, quality, and availability. The CMAR performs constructibility reviews and offers valuable engineering suggestions [1]. This component encompasses the roles of four integral groups; the consultant, local authority, main contractor, and subcontractor. This early coordination fosters collaboration and focuses the team on finding the best solutions for the construction project. Additionally, there is an effort to coordinate all subcontractor bids and determine a guaranteed max. price for construction [2].

The CMAR process customizes a solution that includes responsibilities generally associated with risk:

(i) Establishment of parameters for quality, cost, and time
(ii) Provision of constructibility reviews and cost analysis
(iii) Preparation of bid packages
(iv) Development of phasing and sequencing plan
(v) Ensuring constructibility of the design while minimizing cost and schedule
(vi) Preparation of the overall project schedule and provisions of periodic detailed updates
(vii) Establishment and maintenance of all quality control standards
(viii) Guaranteeing the construction cost
(ix) Identify alternative contracting practices that have the potential to reduce lifecycle costs while maintaining product quality
(x) Offer valuable engineering guidance [3]

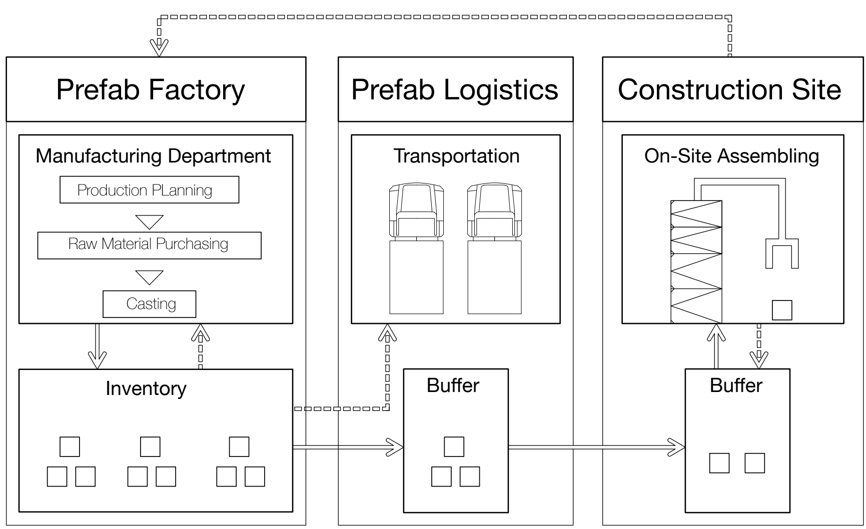



*Fig. 1: The Pre-fab Supply Chain*

*In this figure, the three departments are introduced as 'the pre-fab factories', 'pre-fab logistics', and the 'on-site assembly'. The pre-fab factory carries the responsibility to produce pre-fab. constructions according to the on-site schedule and delivers the finished pre-fab to the construction site. In practice, in order to focus on its core responsibilities, the pre-fab factory always outsources its logistics function to a third-party logistics team (3PL). A 3PL company provides shipping, warehousing services, and the final construction site assembles pre-fabs by crane tower. The dashed line in figure 1 shows material flow, while the dotted line represents the information flow.*

**Uncertainties from "Pre-fab Logistics":**

Logistic uncertainties often derive from shortage of materials, equipment delays, subcontractor labor delays, and transportation delays. These are some of the major causes of logistic set backs; leading to cost and time overrun [4]. The transportation and delivery of pre-fabricated materials is far from satisfactory. Taking Saint-Gobain for example, The pre-fabs are transported from Courbevoie region to Paris construction site and cost for cross-border logistics can account for 15-25% of the total Pre-fabrication production cost [5].

Saint-Gobain is a French multinational corporation that produces innovative Materials and conducts research into various areas of material fabrication, energy, and environment. The penalty for the late delivery pre-fab components is assembly shutdown. Additional costs for rescheduling will occur [6]. A demonstrative case from Paris France is presented to question how these strategies are used for different decision makers to cooperate so as to improve the quality and efficiency of operational executions.

_ Uncertainties within the logistic process include;

(i) Lack of materials
(ii) Traffic restrictions
(iii) Low efficiency of custom clearance in shipping process
(iv) Pre-fab damage in transportation and assembly process.
(v) Construction waste can be largely reduced by up to 70 percent.
(vi) Transportation facility uncertainty; lack of specially trailers, trailer breakdown
(vii) Transportation process; traffic jam, bad weather condition, low efficiency of custom clearance, accident, re-routing, disruption
(viii) Crew uncertainty; lack of driver, unskillful driver

_ Approaches to mitigate supply chain uncertainties;

(i) Improvement of supply chain visibility
(ii) Dual sourcing
(iii) Transshipping
(iv) Holding safety stock

**Uncertainties from "On-Site Assembly":**

_ Uncertainties from "On-Site Assembly":

(i) Material uncertainty; Tardiness delivery of pre-fabs, lack of other building material

(ii) Assembly process uncertainty; damage, accident, wrong operation, crane tower breakdown

(iii) Crew uncertainty; Lack of worker, unskilful worker. [7]

Two Major concepts exist that mitigate uncertainties. First is financial hedging which requires purchasing insurance in advance to avoid price fluctuation. This method of hedging is used on a global market to anticipate foreign exchange risk. Secondly, operational hedging utilizes strategic approaches to mitigate uncertainties by avoiding the following five factors:

(i) Avoidance
(ii) Control
(iii) Cooperation
(iv) Imitation
(v) Flexibility
(vi) Insurance [8]

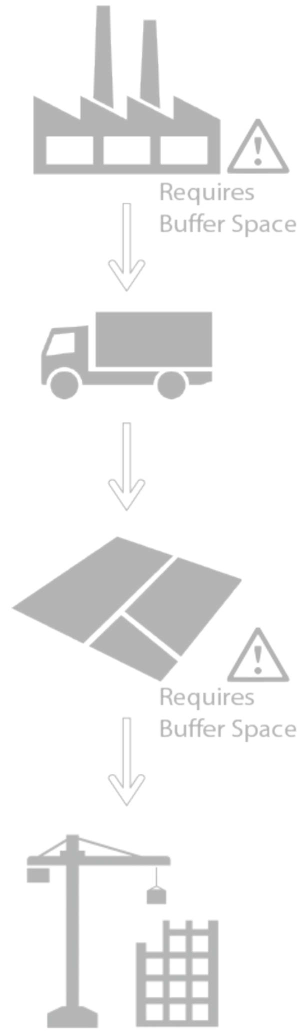



*Fig. 2: Phases of Pre-fab That Require Buffer Space*

*illustrates what phases within the Pre-fabrication construction process require buffer space.*

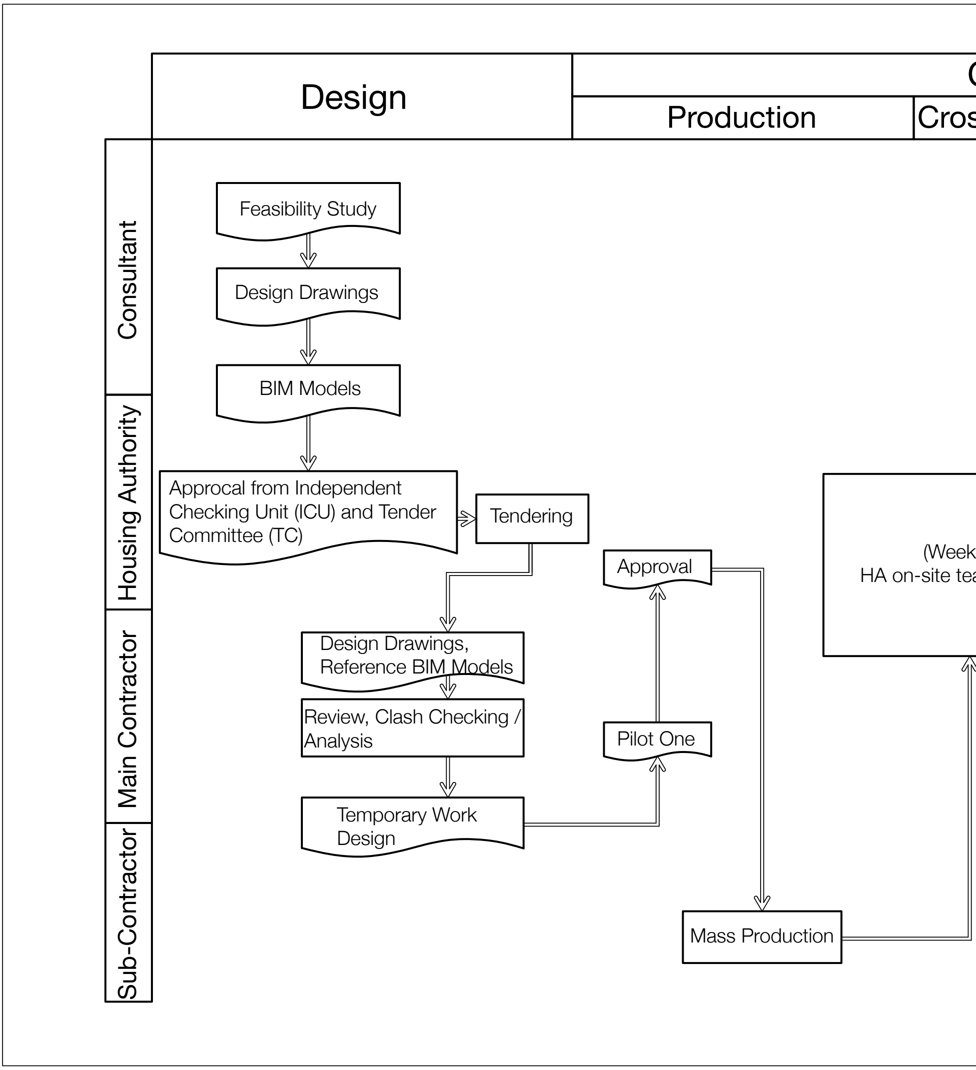
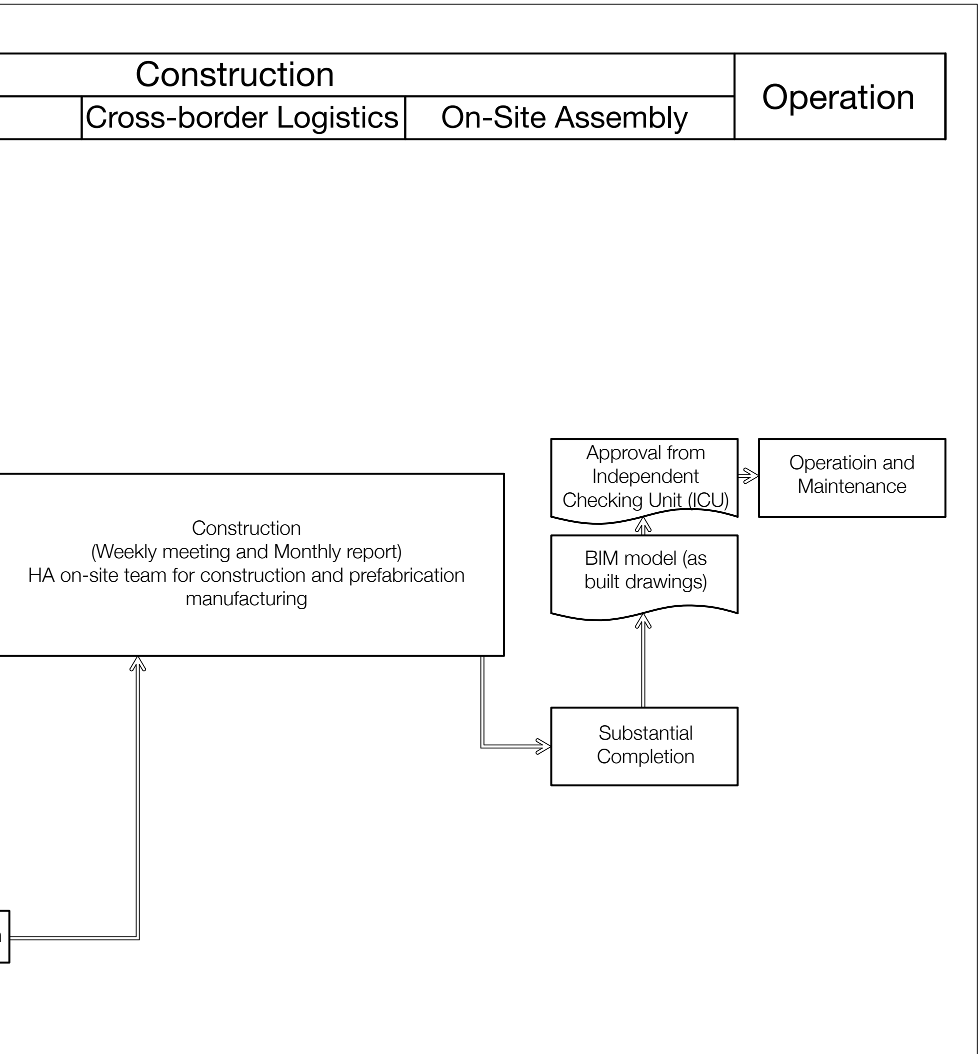



*Fig. 3: Typical Operation in Pre-fabrication Construction*

*gives a brief description of typical operations in Pre-fabrication construction in the above three phases.*


Construction
Cross-border Logistics
On-Site Assembly
Operation
Approval from Independent Checking Unit (ICU)
Operatioin and Maintenance
Construction (Weekly meeting and Monthly report) HA on-site team for construction and prefabrication manufacturing
BIM model (as built drawings)
Substantial Completion

Saint-Gobains International reputation as one of the world's leading construction supply manufacturer positions itself as the highest standard of production. In using Saint-Gobain as a precedent, we aim to illustrate appropriate hedging techniques through Saint-Gobains third party logistics team (3PL).

Building site supplies and supply chain integration has been a major issue for several years [9]. Backed by its national network, Raab Karcher and Saint-Gobain have come together to create LeanWorks, a comprehensive third party logistics team. This solution offers to take complete control of customers' logistics for a building or renovation project and find the methods for max efficiency.

The teams are able to be more efficient as a result of the energy developed around materials supply. The goods are delivered to the building site in the morning, prior to the workers' arrival, which means they can begin work without waiting or delay. A national logistics manager distributes the various jobs to the project managers, or "logistics managers", who shoulder the responsibility of tracking each building site [10].

MATERIALS STORED IN
**BUFFER SPACE / LOGISTIC HUB**

**All the materials needed for the building site are delivered to one the six logistic hubs.** The temperature-controlled warehouses are protected against dust and freezing. Non-brand-speciifiic materials, such as floor equipment and coverings, are also stored at this same site.

SAFE DELIVERY
**AT HEIGHTS**

**Saint-Gobain works with a nationwide crane leasing company and therefore can deliver materials at heights for its customers,** which reduces the level of inconvenience generated by transportation and logistics.

TARGETED
**DELIVERY**

**Saint-Gobain also offers to move materials from the point of u**
materials on the building site from the unloading point of the t
equipment: forklifts, stackers, electric tractors, etc. As part of
the organizations specializing in integration into the workplace
smooth operation and who liaises with the project managers t

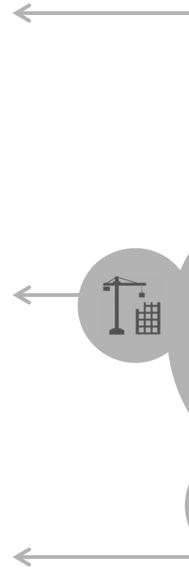


*Fig. 4: Five Phases to Optimize costs and Save Time*

*This diagram illustrates the five phases proposed to a customer according to Saint-Gobains and LeanWorks process of logistics.*


SHARED
**TRANSPORTATION**

**All materials are placed in consignment so they can transported together.** The supplier can therefore combine its goods into a single load and make only one trip to the building site. This solution cuts freight movements by approximately 75%, which has a positive effect for local residents in terms of noise reduction and traffic safety around the building site.

WASTE
**REUSE**

**The customer can arrange for the collection of demolition and packaging waste generated at the building site at the same time as materials are delivered.** Waste is removed by the Saint-Gobain logistics teams and requires no additional transportation

**from the point of unloading to their point of use at the building site.** They are moved by a team of runners who shift the ading point of the truck to the place where the materials will be used. These teams are provided with all the necessary ors, etc. As part of its Social responsibility approach, Saint-Gobain recruits unemployed as runners, working closely with into the workplace. They are supervised by a logistics coordinator on the building site who is responsible for the project's project managers to organize the flow of materials.

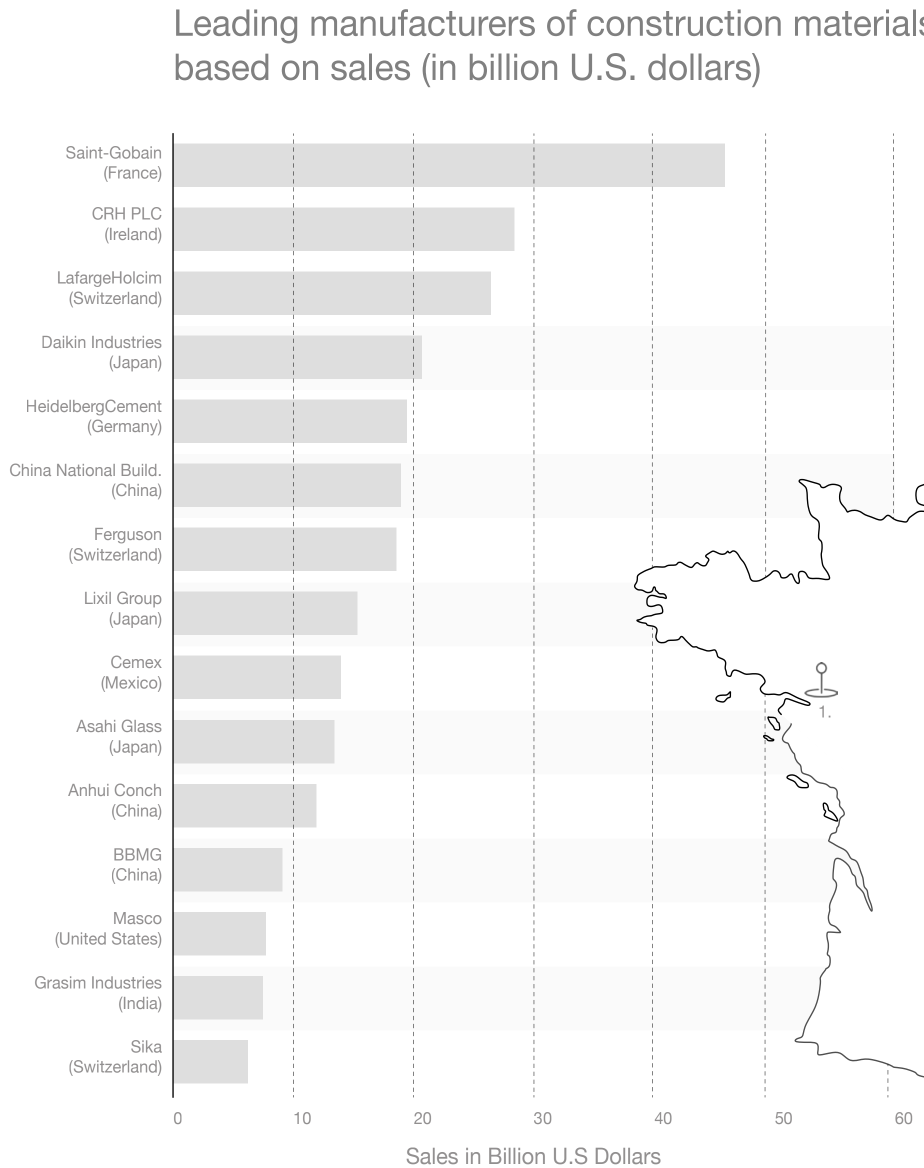
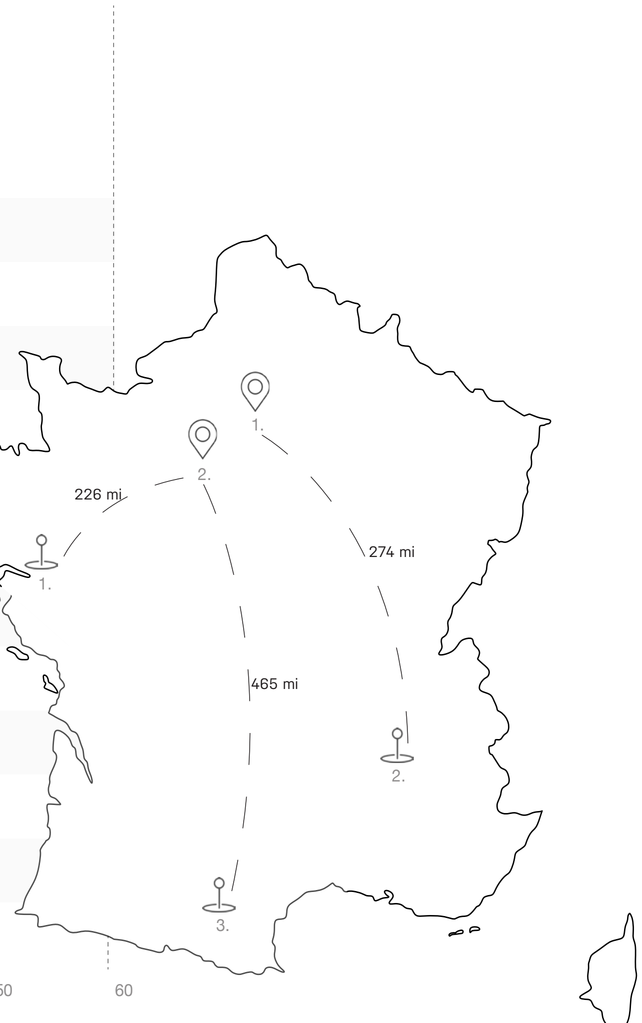



*Fig. 5: Leading Manufacturers of Construction Materials Worldwide*

*This chart illustrates the leading manufacturers of construction materials worldwide as of May 11, 2018. The map of France includes the locations of two major manufacturing facilities operated by Saint-Gobain, and the regions of interest, via INSEE for expected increase in population.*

materials worldwide as of May 11, 2018,




Saint-Gobain Manu. Plants:

1. Courbevoie
2. La Défense

largest Rise in Population by Region:

1. Pays de la Loire
2.Avergne-Rhône -Alpes
3. Occitanie

# LIFE CYCLE ASSESSMENT / CRADLE TO CRADLE

Life cycle assessment (LCA) is defined as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product's boundaries throughout its life cycle. The Paris Agreement calls for global action to eliminate (GHG) green house gasses as soon as possible, and to reach carbon neutrality by 2050 [11]. Therefore, reducing carbon emissions from buildings has become a key strategy for addressing climate change and achieving sustainability. The cradle-to-cradle GHG (Green House Gasses) mitigation proposes research focused on building construction and operational phases to calculate total energy use. The research presented in this chapter has made use of the important elements of Life Cycle Assessment method in which the aim is to develop a systematic and comprehensive framework for conducting environmental life cycle evaluation for French and US pre-fab construction. After the identification of the system and its boundaries, the stock analysis is formulated in order to collect information on the quantities of energy and materials used and environmental releases, such as air emissions and carbon foot prints, through out the life cycle of the system. As a result, the Life Cycle Assessment (LCA) can be carried out with a great deal on attention oriented towards the potential human and ecological effects of the elements identified in the stock analysis [12]. Important life cycle stages are built in to this framework; namely the pre-fab-building stage, operation including major maintenance activities, and finally, the stage of pre-fab dismantling /recycling.

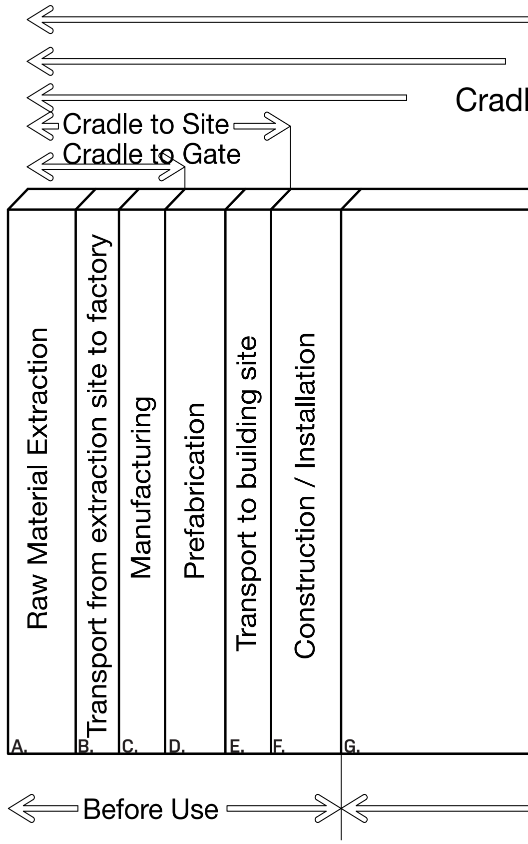
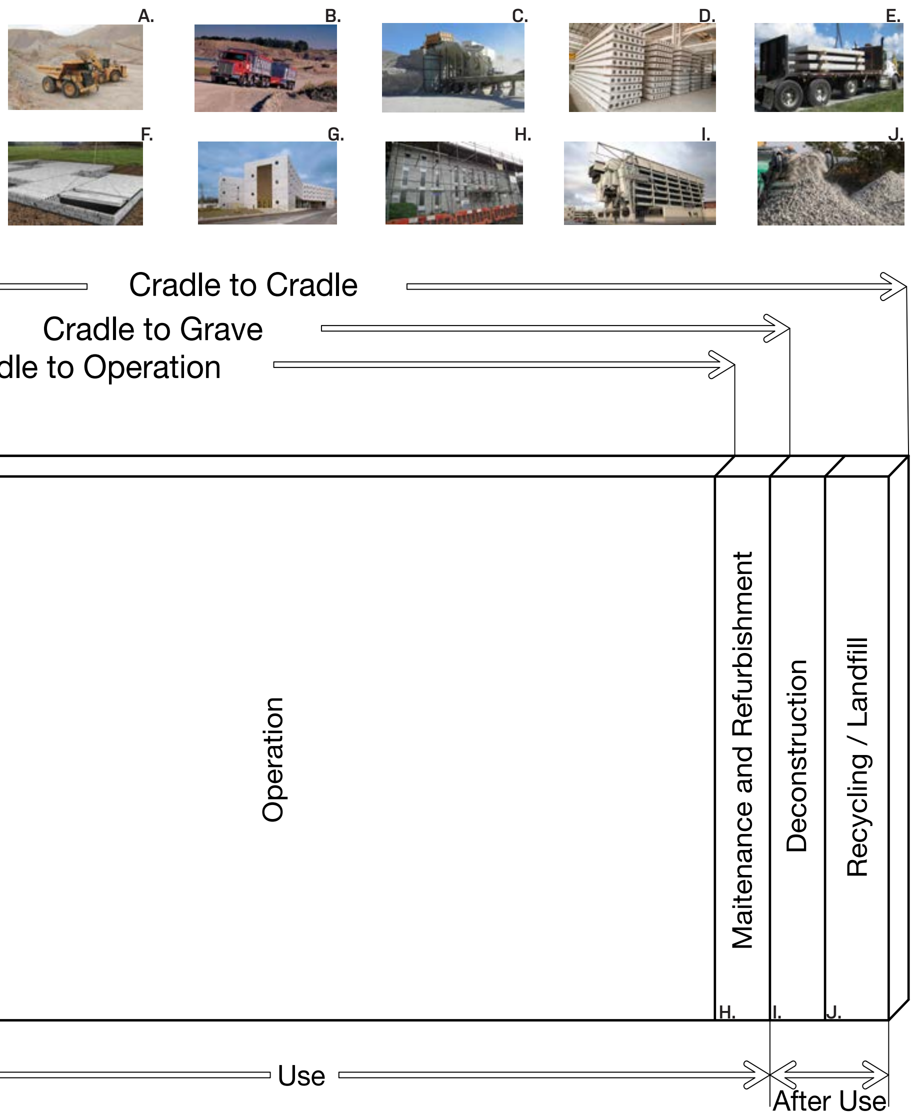



*Fig. 6: Cradle to Cradle (LCA)*

*Visualizes the life cycle expectancies of pre-fab material, and the framework for carbon emission.*


A.
B.
C.
D.
E.
F.
G.
H.
I.
J.
Cradle to Cradle
Cradle to Grave
radle to Operation
Operation
Maitenance and Refurbishment
Deconstruction
Recycling / Landfill
H.
I.
J.
Use
After Use

**Inputs / Energy + Raw Material:**

Pre-fabricated construction not only reduces waste, noise, dust, operation cost, labor demand, and resource depletion, but additionally enhances the quality control process, as well as ensures the health and safety of workers [13]. In general, previous LCA studies in the Pre-fabrication industry have focused on concerns in two directions: building materials and components (BMCs) and whole buildings (WBs). BMC related studies have primarily highlighted the life-cycle analysis of energy consumption and environmental emissions for certain building products. While studies relevant to whole buildings (WBs) have focused on holistically understanding the relative environmental load of each life-cycle boundary during the life span of buildings holistically [14].

In this chapter we will use I-O (Input-Output) analysis as the preferred standard for life cycle assessment. The I-P-O method is a hybrid analysis method that uses a top-down system aiming to modify and disaggregate the direct supply chain of the Pre-fabrication construction being investigated. The I-P-O based model uses the system boundaries (cradle to cradle) for the energy quantification that covers the whole life cycle of the pre-fabricated components, including Pre-fabrication manufacturing, transportation, on-site assembling, and recycling in the demolition phase.

The I-P-O analysis basic procedures include:

(i) Calculation of the initial total environmental burden of the product being studied by using I-P-O analysis

(ii) Disaggregation of the complex upstream process based on I-P-O analysis and determination of the key paths with significant environmental impact

(iii) Modification of key paths with both delivered quantity and energy intensity data derived from process-based inventory

(iv) Subtraction of the corresponding I-P-O value of the key paths represented in the process inventory from the initial total environmental impact calculated by I-P-O model

(v) Integration of modified energy paths derived from the process-based analysis into remaining unmodified I-P-O framework. [15]

Transportation from an off-site factory to the construction site is an important process in pre-fab construction. Unlike that in conventional building material transportation, Pre-fabrication logistic requires a careful load–unload control process, as well as additional protection to avoid possible damage during transportation. [16]

**Process / Maintenance:**

Additional construction techniques and equipment have been used to orchestrate on-site assembly works for pre-fabricated components. This process includes relevant construction-machine use, horizontal and vertical transportation, and lifting works associated with the precast construction process. However, separating energy consumption related to pre-fab construction from the total energy used in a construction site is difficult for researchers and analysts. Therefore, pure input–process-output analysis is performed to estimate direct energy use from on-site assembly works for pre-fabricated components.

**Outputs / Emissions:**

In our research, a limited number of studies have focused on energy use during the demolition process. Relevant studies are restricted not only by the variations in customer requirements, contractor preferences, and market regulations , but also by the limitations in the availability of public documents and building demolition data. Energy consumption associated with building deconstruction is relatively small compared with the life-cycle energy use of a building. However, the energy-saving potential of recycling and or reusing is considerable and cannot be ignored during the entire life cycle of a building [17]. In our research, a limited number of studies have focused on energy use during the demolition phase. Relevant studies are restricted not only by the different requests in customer requirements, contractor preferences, and market regulations , but also by the limitations in the availability of public documents and building demolition data. Material-recycling processes can be categorized into two categories, namely, reusing and recycling materials. Given the features of certain materials and the attributes of the pre-fabricated components most commonly used, steel was recycled using mixed recycling methods, whereas concrete and aluminum were recycled as raw materials with suitable processing. [18]

| **Recycling Method:** | |
|---|---|
| **Reuse:** | Reuses materials without further processing |
| **Recycle:** | Recycle materials as raw materials with suitable processing |

# REGRESSION MODEL PROPOSAL FOR PRE-FABRICATED BUILDINGS (LCA)

Buildings contribute to remarkable carbon emissions over their life cycle and worldwide account for over one-third of carbon emissions [19]. Reducing the carbon emissions of buildings over their life cycle is therefore a matter of urgency and importance for addressing climate change. In working through component Life Cycle Assessment / Cradle to Gate, It became apparent that LCA often varies, using inconsistent methods, models, and units of analysis in order to estimate buildings' life-cycle carbon emissions.
Additionally, Pre-fabrication is not a commonly recognized life-cycle stage in (LCA). It is traditionally considered to be part of the manufacturing and / or construction stages. The implication of Pre-fabrication in building carbon emissions are therefore only implicitly accounted for or embedded elsewhere in the building's life cycle. The challenge is that pre-fabricated buildings' LCA is currently a labor-intensive process with limited accountability. While there has been limited exploration for concrete solutions, a significant amount of data is needed for calculating buildings' LCC which includes but is not limited to the production process and material consumption of pre-fabricated components, production efficiency of production equipment, transportation method, and travel distance for key construction materials and waste of materials during the production of specific precast building components. The life-cycle stages include 'cradle to gate', 'cradle to site', cradle to end of construction', 'cradle to operation', and 'cradle to cradle'.

**Challenges:**

The first limitation to Pre-fabrication construction is the challenge of working against socio-technical systems. Simply put, socio-technical systems emphasize the combination of social and technical aspects through active engagement of stakeholders; this is critical to defining and address the complex issue of energy and carbon emissions [20]. Even within the most articulate and developed studies of pre-fab LCA, the definitions and extent of the adopted life cycle vary from one another. For example, the 'building life cycle' may be adopted in studies as raw material extraction to final disposal, or the closed loop life cycle from manufacturer to site.
Secondly, it is important to address the methods, models, and units of analysis

used for estimating pre-fab buildings' LCA. The use of various methods and models yields discrepancies in reported results and leads to a fragmented understanding of pre-fabricated buildings' LCA. For example, researchers revealed that building a house in the UK by using an off-site panelized timber frame system resulted in a 34% reduction in embodied carbon dioxide compared to traditional masonry construction. However, their result was based on the cradle-to-site pre-fab system boundary. A case study in Australia assessed the environmental performance of pre-fabricated steel construction in Australia and argued that, provided that the materials are reused at the end of the 50-year building lifecycle, pre-fabricated steel buildings can result in up to 81% savings in embodied energy and 51% savings in materials relative to conventional concrete construction [21]. The use of implied or inconsistent units of analysis hampers effective comparison among design alternatives. Furthermore, there is a significant need for additional data when calculating buildings' LCC, which includes but is not limited to the challenges of the production process.

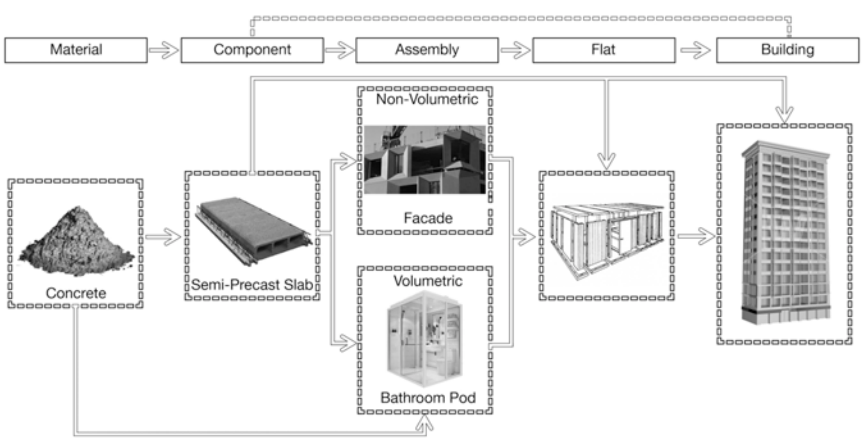



*Fig. 7: Cradle to Cradle (LCA)*

*Visualizes the life cycle expectencies of pre-fab material, and the framework for carbon emission.*

**Fundamentals:**
After noting the challenges associated with pre-fabricated building LCA, it can be helpful to rethink the fundamentals of the sociotechnical system that is currently in place. The validity and reliability of the LCA of buildings is questionable and thus requires an improved system that identifies temporal, spatial, functional, and methodological dimensions. This requires the boundaries of the LCA to redefine the scope of buildings; and discuss how research should be conducted with concern for the service and value of carbon emission analysis today. [The following is an excerpt from "The Green to Gold Business Playbook: How to Implement Sustainability Practices for Bottom-Line Results in Every Business Function," by Daniel C. Esty and P.J. Simmons]
The following example illustrates how LCA analysts findings can be incomplete, uncertain, and controversial:
"Company A spends tens of thousands of dollars to generate its own primary data, while Company B uses publicly available data based on sector averages. Company A inadvertently omits a few seemingly insignificant manufacturing-related inputs from the study, but Company B meticulously includes every single one. Company A assumes that consumers will use the product about 8 hours a week for 32 weeks, while Company B assumes 7 hours a day for 40 weeks.

Company A weights impacts on local watersheds 33 percent more than Company B. Now imagine the difficulty in deciding whose final numbers are "better" when they end up being different; yet this type of scenario happens all the time in real life." [22]

**Potential Solutions:**
The current LCA methods and standards set in place by the International Organization for Standardization (ISO) impose subjective difficulties for drawing system boundaries; 'boundaries' pertaining to the life cycle edges (e.g., cradle-gate, cradle-cradle). The decision to include or exclude certain processes in the LCA process are typically not made on scientific basis, but rather a value system. In particular, the requirement of deciding which processes could be excluded from the LCA can be rather difficult to meet because many excluded processes have often never been assessed by the manufacturer or project manager, and therefore their authenticity cannot be guaranteed. LCA studies utilizing the Input Output method (I-O) have shown that, in practice, exclude processes that can contribute as much to the products carbon emission study as included processes; thus the subjective determination of the LCA boundary may lead to inaccurate results. The International Organization for Standardization (ISO) published the 14040 series of Environmental Management Systems (EMS) standards, that in short presents a basic framework to objectively evaluate the environmental aspects of a product. This process take into account the whole life-cycle and provides the rationale for environmental labels, metrics, and declarations. It should be noted that 4 countries/economies participate in this LCA framework.

The 'boundaries' referred to in this chapter refer to the system limitations addressed in "Life Cycle Assessment". The boundary selection problem has been a critical obstacle for comparative assessment to be disclosed to the public since the equivalence of the system boundaries of two product systems is difficult to prove. The choice of system boundary has a direct influence on rankings in comparative studies, which leads to wrong conclusions and decisions about which product to promote. The subjectivity of system boundary selection allowed by the International Organization of Standards is one of the key aspects of a lack of confidence in LCAs, especially in comparative studies. Thus we propose further research surrounding methods to improve boundary selection practices using hybrid, economic input-output analysis.

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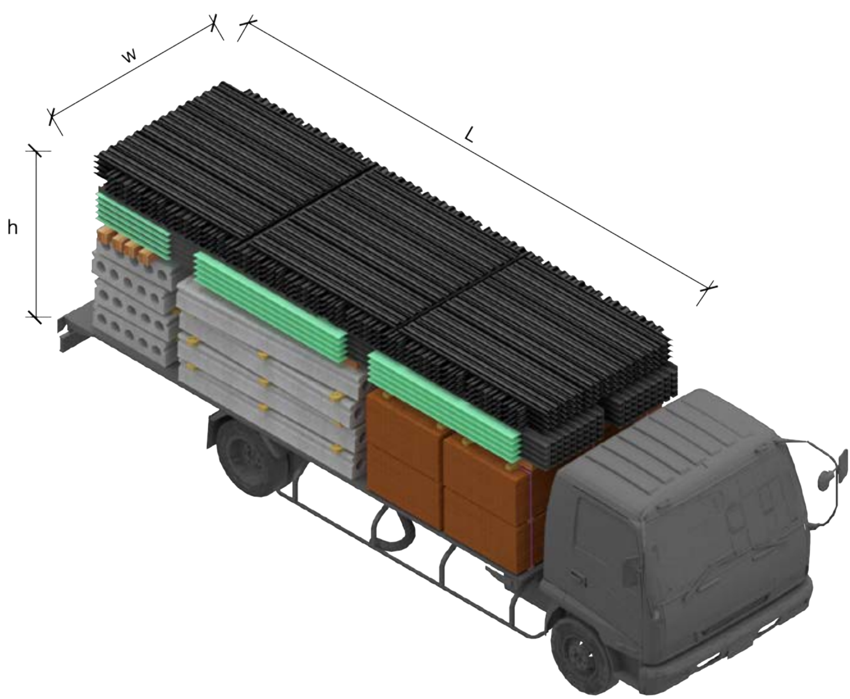
# FREIGHT TRUCKS

Freight trucks are cargo vehicles commonly used in the transportation of pre-fabricated parts from off-site locations to the construction site for installation. Understanding size and weight regulations is critical for the design and planning of pre-fabricated components. Although it is preferable to stay within the guidelines of regulation standards it is also possible to obtain permission for the transportation of oversized loads through the use of special permits. Trucks may come in a variety of standard sizes but are also often customized for transportation of specialty items. Trucks are adjustable, having the ability to haul a variety of box containers, platform beds, and custom flat beds. [23]

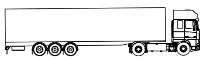


## Regulation Standards FR [24]

| | |
|---|---|
| **Length (L)** | 16 m |
| **Height (h)** | 4 m |
| **Width (w)** | 2.5 m |
| **Max Load** | 40 t |

## Regulation Standards USA, MI [25]

| | |
|---|---|
| **Length (L)** | 53 ft |
| **Height (h)** | 13 ft 6 in |
| **Width (w)** | 8 ft 6 in |
| **Max Load** | 80,000 lb |



## Oversize Standards FR [24]

| | |
|---|---|
| **Length (L)** | 23 m |
| **Height (h)** | 4.3 m |
| **Width (w)** | >2.5 m |

* Escort Vehicles and Permits Required

## Oversize Standards USA, MI [25]

| | |
|---|---|
| **Length (L)** | 150 ft |
| **Height (h)** | 15 ft |
| **Width (w)** | 16 ft |

* Escort Vehicles and Permits Required

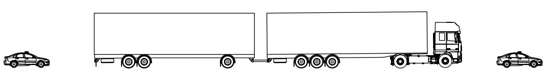
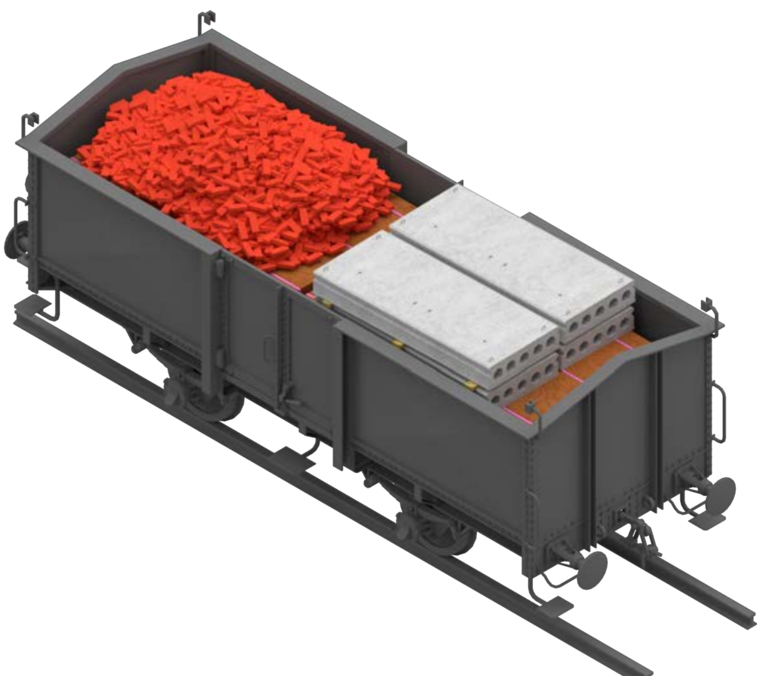


**Fig 8:** *Freight trucks can often be modified with custom parts and armatures in order to transport custom cargo. For the purposes of transporting pre-fabricated parts, it is beneficial to imagine a truck as a moving flat bed that can be modified to carry anything as long as it fits within the scope of size and weight regulations.*

# CARGO TRAINS

Cargo trains are a less common mode of transportation for pre-fabricated parts as compared to freight trucks. Most of the time parts transported by train will have to go through some form of processing and additional transportation (usually by road) to get the parts to their final destination. Thus the cargo will likely be subject to standards and regulations pertaining to road vehicles as well as rail. Transportation by train can be advantageous in terms of schedule and cost when shipping across long distances. In addition shipping by train produces less carbon emissions than truck shipping. Trains are also able to haul larger loads than trucks such as heavy construction equipment. Like trucks, cargo train containers come in a variety of options including box cars, open top, and flat cars. [23]

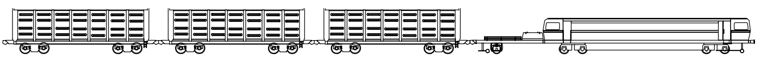


**Covered 11-7038** EU [26]

| | |
|---|---|
| **Length (L)** | 17.46 m |
| **Height (h)** | 3.1 m |
| **Width (w)** | 2.79 m |
| **Max Load** | 68 t |

**50' Standard Boxcar** USA [27]

| | |
|---|---|
| **Length (L)** | 50 ft 7 in |
| **Height (h)** | 10 ft 11 in |
| **Width (w)** | 9 ft 6 in |
| **Max Load** | 200,000 lb |

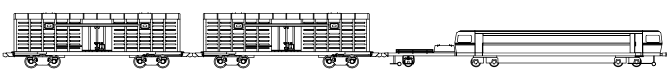


**Covered CMGV 11-9733** EU [26]

| | |
|---|---|
| **Length (L)** | 23.34 m |
| **Height (h)** | 3.67 m |
| **Width (w)** | 3.1 m |
| **Max Load** | 50 t |

**60' Hi-roof Boxcar** USA [27]

| | |
|---|---|
| **Length (L)** | 60 ft 9 in |
| **Height (h)** | 13 ft |
| **Width (w)** | 9 ft 6 in |
| **Max Load** | 200,000 lb |



**Platform 23-469-07** EU [26]

| | |
|---|---|
| **Length (L)** | 24 m |
| **Height (h)** | --- |
| **Width (w)** | 2.7 m |
| **Max Load** | 69 t |

**86' Auto Boxcar** USA [27]

| | |
|---|---|
| **Length (L)** | 86 ft 6 in |
| **Height (h)** | 13 ft |
| **Width (w)** | 9 ft 6 in |
| **Max Load** | 140,000 lb |

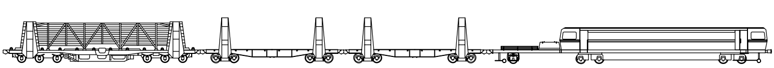



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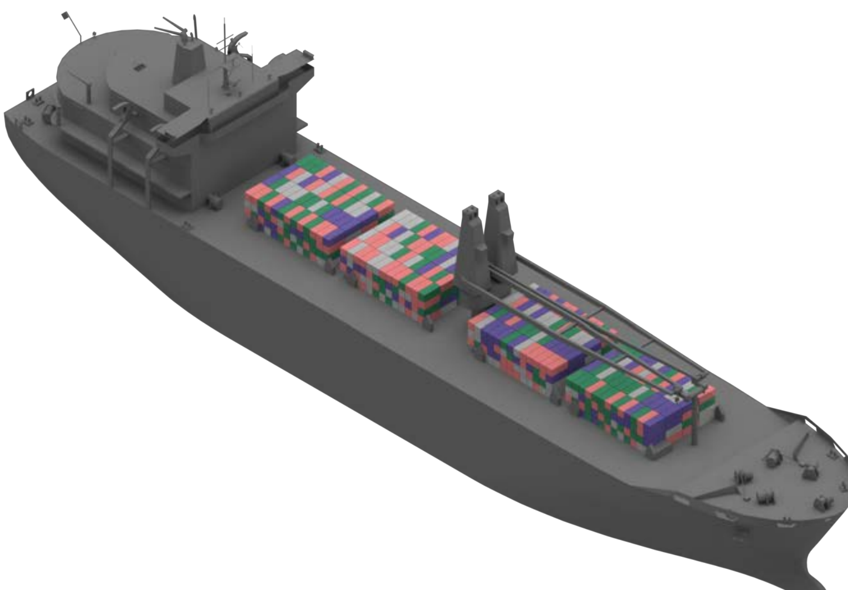
**Fig 9:** *For the transportation of a large number of pre-fab components across long distances train shipping can significantly reduce shipping time and cost.*

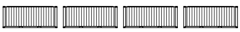
# INTERNATIONAL SHIPPING

International shipping is usually delegated to either shipping by sea or by air. Air transport is the fastest mode of international shipping, however it is also the most expensive mode of transportation and least efficient in terms of carbon emissions. In addition, weight limitations are much more stringent compared to other modes of international shipping, making it an unlikely choice for the transportation of pre-fabricated components. Shipping by ocean freight may be the most dependable and affordable option for international transportation. However shipping times for ocean freight are considerably longer than other modes of transportation (23-43 days). [23]



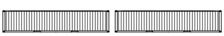
## 20' Dry Freight Containers [28]

| | | | |
|---|---|---|---|
| **Length (L)** | 5.9 m | **Length (L)** | 19 ft 5in |
| **Height (h)** | 2.38 m | **Height (h)** | 7 ft 9 in |
| **Width (w)** | 2.34 m | **Width (w)** | 7 ft 8 in |
| **Max Load** | 22.1 t | **Max Load** | 48,721 lb |



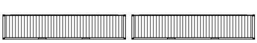
## 40' Dry Freight Containers [28]

| | | | |
|---|---|---|---|
| **Length (L)** | 12 m | **Length (L)** | 39 ft 6in |
| **Height (h)** | 2.38 m | **Height (h)** | 7 ft 9 in |
| **Width (w)** | 2.3 m | **Width (w)** | 7 ft 7 in |
| **Max Load** | 27.4 t | **Max Load** | 60,397 lb |



## 45' High Cube Dry Containers [28]

| | | | |
|---|---|---|---|
| **Length (L)** | 13.58 m | **Length (L)** | 44 ft 6in |
| **Height (h)** | 2.69 m | **Height (h)** | 8 ft 10 in |
| **Width (w)** | 2.34 m | **Width (w)** | 7 ft 8 in |
| **Max Load** | 28.6 t | **Max Load** | 63,052 lb |

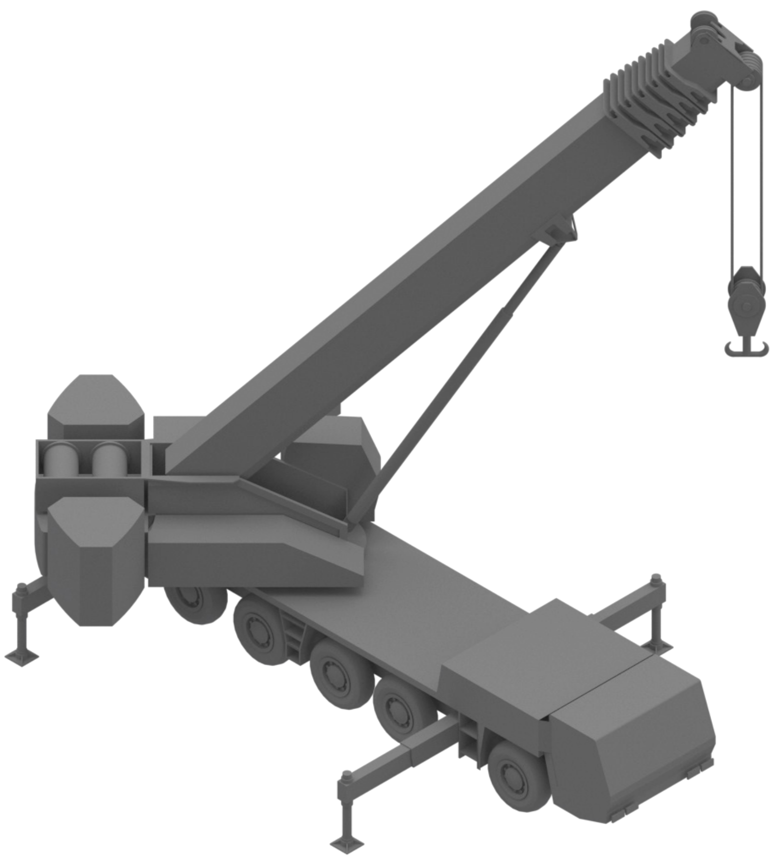



CMA CGM
MAERSK
SEALAND
HANJIN
HAMBURG SÜD
CHINA SHIPPING
CMA CGM LA TR


**Fig 10:** *Ocean transport is the most dependable form of international transportation, especially when it comes to heavier components. Shipping times tend to be much greater than other forms of transportation. It is important to plan far in advance when choosing this mode of transportation.*

# MOBILE CRANES

Mobile cranes are designed move and travel around a job site with relative ease. These cranes do not require permanent foundations, however they are also limited in carrying capacity for this reason. Outriggers and counter weights can be used for structural support when accommodating for heavier loads. Typically mounted on wheels or crawlers, mobile cranes have the ability to transport themselves to the job site without much additional setup or processing. The size of mobile cranes can vary greatly. Size generally tends to impact mobility and maneuverability of the crane. [29]



## Terex (RT345-1XL) [30]

| | | | |
|---|---|---|---|
| **Max Length (L)** | 46 m | **Max Length (L)** | 154 ft |
| **Max Load** | 40.8 t | **Max Load** | 45 t (US) |

## Liebherr (LTM 1750-9.1) [30]

| | | | |
|---|---|---|---|
| **Max Length (L)** | 158.5 m | **Max Length (L)** | 520 ft |
| **Max Load** | 537.7 t | **Max Load** | 592.8 t (US) |

* maximum load capacity is dependent on angle and length of the boom.
Maximum load capacity generally decreases as boom extension increases.
See more detailed specifications for more precise load capacities.

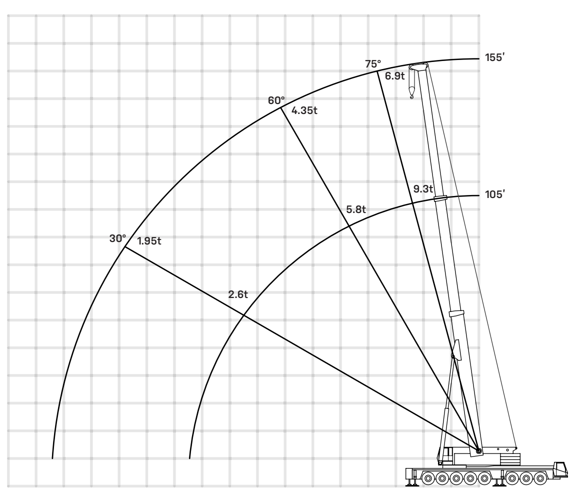


**Fig 11:** *These types of cranes are useful to many job sites due to their relativity small size and good mobility. Mobile cranes are good for moving and staging parts around the job site as well as for a range of low intensity assembly functions,*

# CRAWLER CRANES

Crawler cranes are also in the mobile crane family. However these cranes can be used for much heavier construction types, typically used in industrial or infrastructural settings such as power plant and refinery construction. These cranes are able to navigate rough terrain at slow speeds. Load capacity, hoist height, and maximum radius can be substantially greater than that of wheel mounted mobile cranes. [29]

## Terex (HC165) [30]

| | | | |
|---|---|---|---|
| **Max Length (L)** | 82.2 m | **Max Length (L)** | 270 ft |
| **Max Load** | 149 t | **Max Load** | 165 t (US) |

## Liebherr (LR 13000) [31]

| | | | |
|---|---|---|---|
| **Max Length (L)** | 240 m | **Max Length (L)** | 787 ft |
| **Max Load** | 3,000 t | **Max Load** | 3306 t (US) |

* maximum load capacity is dependent on angle and length of the boom.
Maximum load capacity generally decreases as boom extension increases.
See more detailed specifications for more precise load capacities.

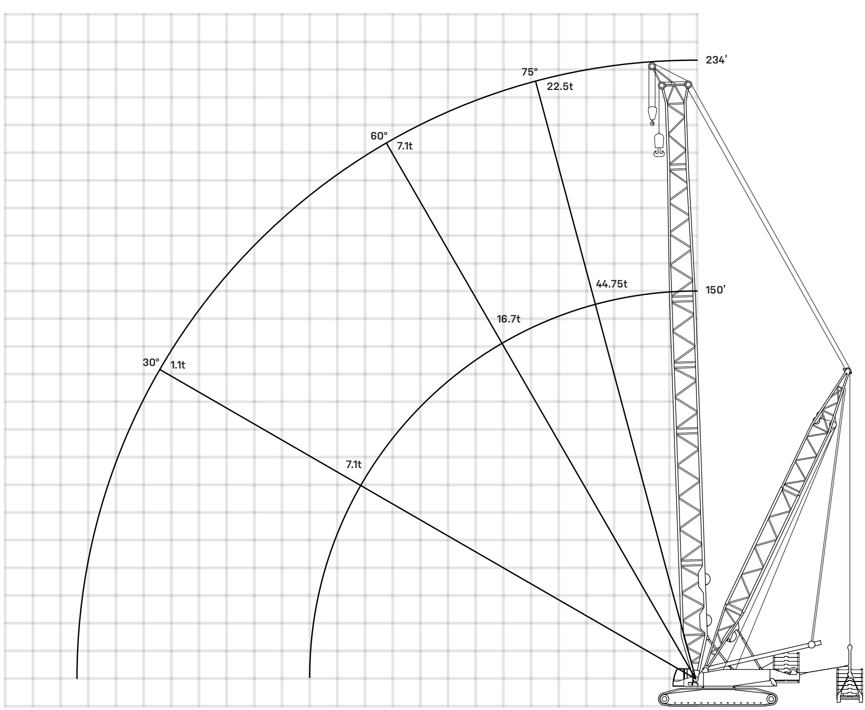


**Fig 12:** *Depending on the scale of the project, crawler cranes have the potential to be used as the primary mode of assembly and construction for pre-fabricated construction projects.*

# TOWER CRANES

Tower Cranes are examples of fixed cranes. Fixed cranes require permanent foundations. The crane cannot be moved around the job site without being completely dismantled and reassembled. The long boom of a tower crane compensates for its lack of mobility by providing lift coverage to a large radius while occupying relatively very little space on site. The tower crane is designed to jack itself up to allow insertion of other tower segments. This process repeats as construction progresses upward. Dismantling proceeds in the reverse order. The tower needs to be braced every 100 to 150 feet by using guys or bracing back to the building structure. [29]

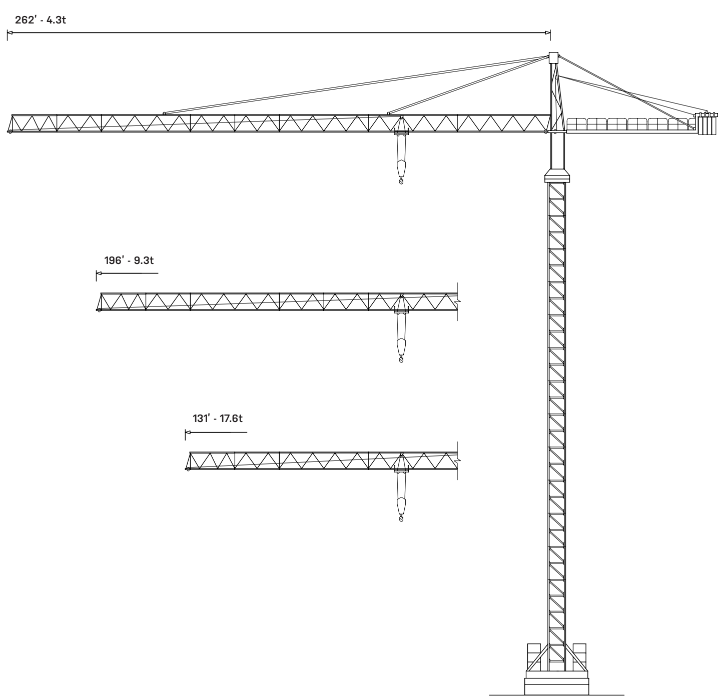
## Terex (SK 575) [30]

| | | | |
|---|---|---|---|
| **Height (h)** | 135 m | **Height (h)** | 444 ft |
| **Max Radius (r)** | 79.8 m | **Max Radius (r)** | 262 ft |
| **Max Load** | 32 t | **Max Load** | 35.2 t (US) |

## 1000 EC-B 125 Litronic [32]

| | | | |
|---|---|---|---|
| **Height (h)** | 110.80 m | **Height (h)** | 363.5 ft |
| **Max Radius (r)** | 36.5 m | **Max Radius (r)** | 120 ft |
| **Max Load** | 125 t | **Max Load** | 137.7 t (US) |

* maximum load capacity is dependent on length of the boom extension. Maximum load capacity decreases as boom extension increases. See more detailed specifications for more precise load capacities.




POTAIN
MANTA

**Fig 13:** *Tower cranes are highly efficient when building on a site of a specified size which falls withing the cranes operational radius. One crucial advantage of the tower crane is that it can be extended upwards limitlessly as long as it is secured to the building structure.*

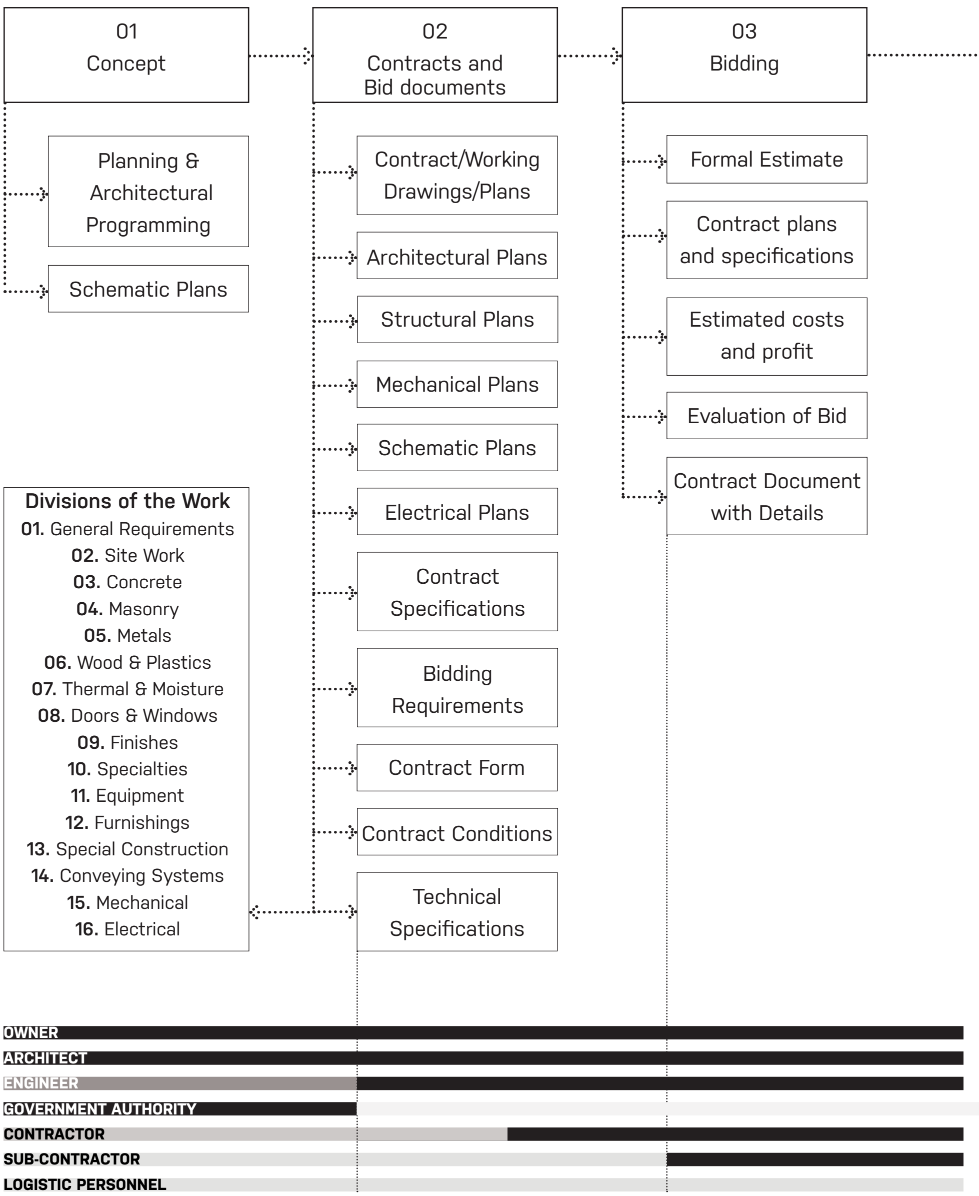
# 04
# Current Building Industry Standards

*Amlin Iqbal Eshita*
*Zhipeng Liu*

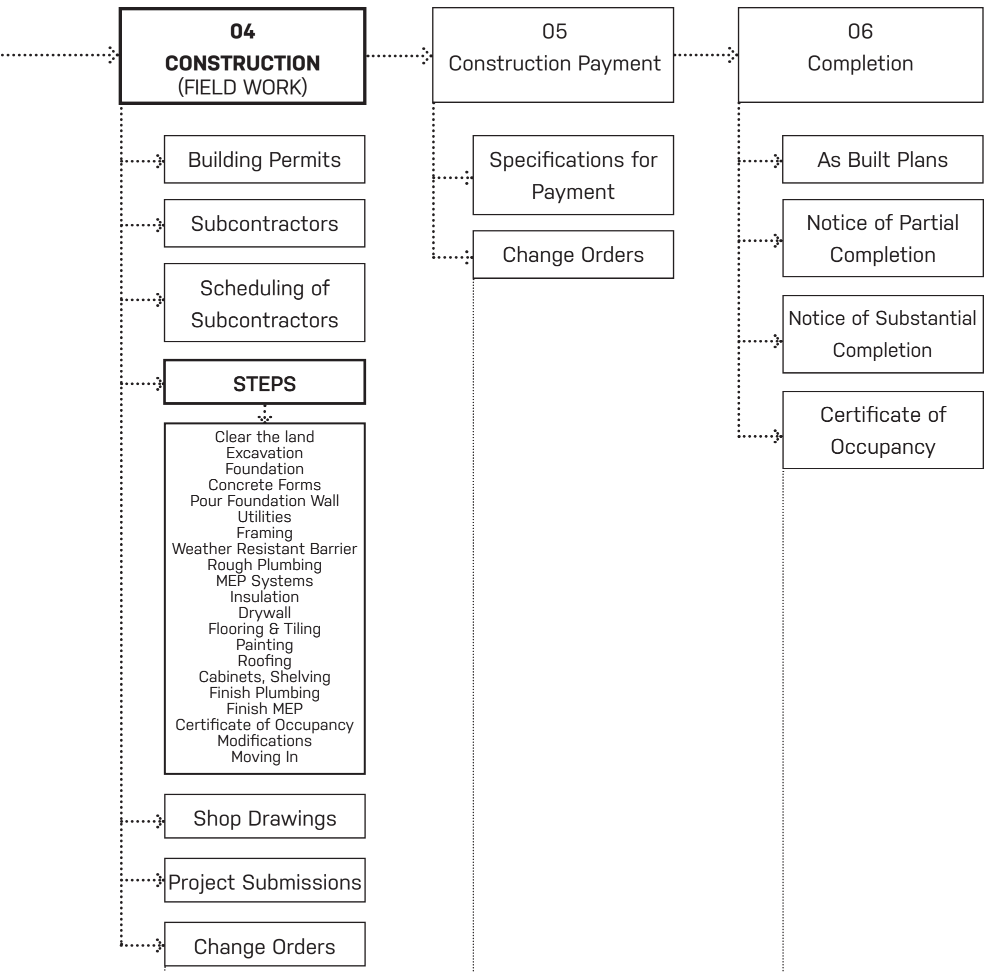
**ABSTRACT**
After analysis of the history, current situation and various logistics related to pre-fabrication, this chapter will highlight on the comparison of conventional on-site construction system. In case of conventional system, the process deals with some pre-made elements, such as- steel beams, doors, windows, furniture etc. that is brought to site and assembled, but the bigger demand does not require for pre-made elements. As a result an analysis of combining pre-fab with on site construction will be discussed as well in terms of elements and components of pre-fab system. Understanding the merits and drawbacks of this conventional process will allow us to perceive what criteria is working for or against the idea of pre-fab construction. With the understanding of different material use in the on-site construction system, it can be compared how this leverages standard material components. Apart from that the risks and limitations of on-site construction system will be analyzed that will give a guideline towards the possible advantages the on-site process offers, that might be lack out in a prefab process. The focus of this chapter leads to a comparison of on-site and pre-fab system that will allow to put forth an argument of possible needs of pre-fab systems.

## STAGES IN CONVENTIONAL CONSTRUCTION PROCESS

The diagram illustrates the six coordinated steps of a construction process from the conceptual stage through the completion stage of a project. Depending on specific facts and circumstances in certain geographic locales, the process might vary in terms of material or locality, the basic construction concepts are similar in all locales.



Construction Process varies in terms of steps, styles and methods while making, considering the site situation, topology, availability of resources, material flexibility and man power. Depending on the weather of a particular locality, the timeline of construction is taken into consideration. Architects, project managers, site engineers and subcontractors are the driving force behind a construction system after confirmation from client.



## 01. CONCEPT

Before construction of a project, good deal of overlapping steps occur centering round the conceptual or design phase. All construction projects begin with conceptualizing the planning and design, which is also called “architectural programming.”
A licensed architect remains in charge of all the design, specifications and finishings. Besides, architects also supervises a good deal of engineers who also have to be licensed, that takes care of structural, mechanical, electrical, lighting and plumbing design of the building.

### Planning & Architectural Programming

In this stage the architects and engineers involved , determines the purpose and objective of the proposed construction with client by producing a list of solutions, alternatives, feasibility studies and costs estimates. In some states/countries, sometimes the government officials has certain preferences that leads the design to a certain direction, prioritizing the material or site context.

### Schematic Plans

After that the preliminary design phases start that gets finalize after a series of revision of requirements both function and aesthetic wise.

## 02. CONTRACTS AND BID DOCUMENTS

To check the feasibility of the projects construction, a estimation is done of the specifications. To prepare that, the bidders need to have a couple of drawing for every part of the design to get the nearest possible cost estimation.
CSI (Construction Specifications Institute) has categorized it in 16 division of works, the load of which will vary depending on the size of the project, which is mentions on the left side of the previous page. This divisions can be sub divided into 3 parts called General, Products, and Execution (Installation).
The sub divisions are explained below:

**General Section**
The scope or the limits of work for a particular divisions. Creates a understanding on the administrative side by mixing the technical specifications and the general conditions of the contract.

**Product Section**
The specification list, it categorizes the list of the materials to be used, by name and model number, and explains the quality of materials and the basis for any substitution.

**Execution Section**
The end result of the construction elements, techniques and workmanship.

## 03. BIDDING

The bidding stage deals with the finalizing of the contract, when a client decides the budget and bids are good to go for construction.

The following sequences are followed to prepare a contract bid:
**i.** The copy of drawings are provided to the contractor from the owner in order to prepare a formal estimation of the construction cost or bid.
**ii.** The contractor overviews the drawings and specifications to determine all the restraints or conditions the owner requires for the project.
**iii.** After considering the over all budget relating to sub-contractors, materials and labour cost, the contractor finalizes an estimated costs and a profit for the construction project.
**iv.** All submitted bid is analyzed by the owner and gets confirmed.

**v.** The contract document contains the timeline for the completion of the project along with necessary information that drives the construction acquirements.

## 04. CONSTRUCTION

Fieldwork is the fourth stage of the construction process, which is the on-site construction of the project. Fieldwork is broken down into building permits, scheduling subcontractors, finish drawings, project submissions, and change orders. It gives a speculative timeline which explains what will happen during the process.
Even though the on-site construction is time consuming and lengthy, it has been established as a very strong process of building livelihood. The differences of this process with a pre-fab process is majorly varied, the only pre-made items used in this system is the windows, doors, floor finish, furnitures, which is part of the contract but the personal items are usually brought by the user or in some case designed for the need of the user.

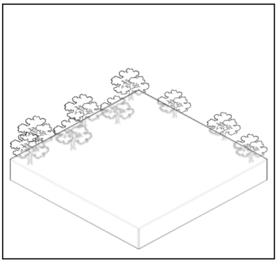
An illustration of the steps of field work for an on-site construction system has been explained on the next page to provide a general overview of the steps to be considered in this system.

## 5. CONSTRUCTION PAYMENTS

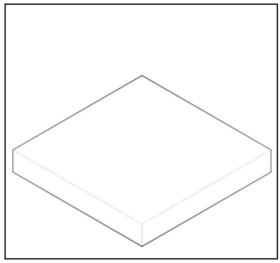
The fifth stage of the construction process is the construction payments stage. All construction contracts extend over a period of time. When a contractor completes a prescribed amount of work, the owner pays either the architect assigned or the contractor for the completed work, depending on what the contract has been made on.

## 06. COMPLETION

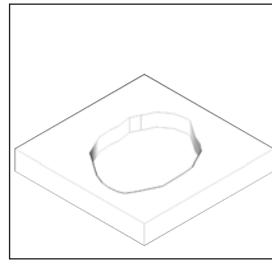
The final phase of the construction process is known as the completion stage, which allows the permission for occupancy.
It follows different steps of completion confirmations that allows the client and the architects to keep a check in the whole process, what is needed and what is not.
After a substantial amount of work completion, the building gets a "Certificate of occupancy" that puts an end to the process.



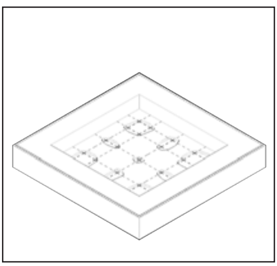
Current Site Situation



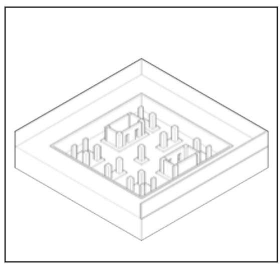
Clearing the land



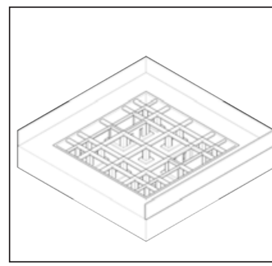
Excavation
(depending on how deep which portion of the site has to go, land excavation is done)



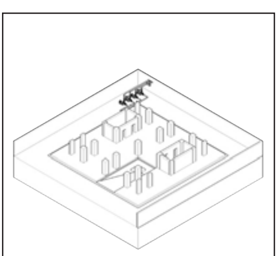
Shore Piling
at the edge of the land ( to protect from land fall from neighbouring land) preparing the position for the foundations



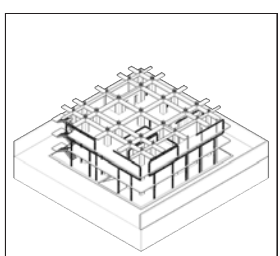
Foundation
(depending on requirement of the building load, Continuous footing, Wall Footing, Strap Footing, Raft Footing is taken into consideration.



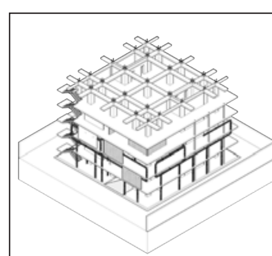
Column layout
concrete pouring floor bed with beam framing.



Ground floor concrete layout



Continuous system of the structure with fitting of the utility wirings, that is the electrical, mechanical and toilet pipes, which gets attached the main line.



The walls and stairs are done simultaneously with each floor. Brick/concrete walls are made step by step,

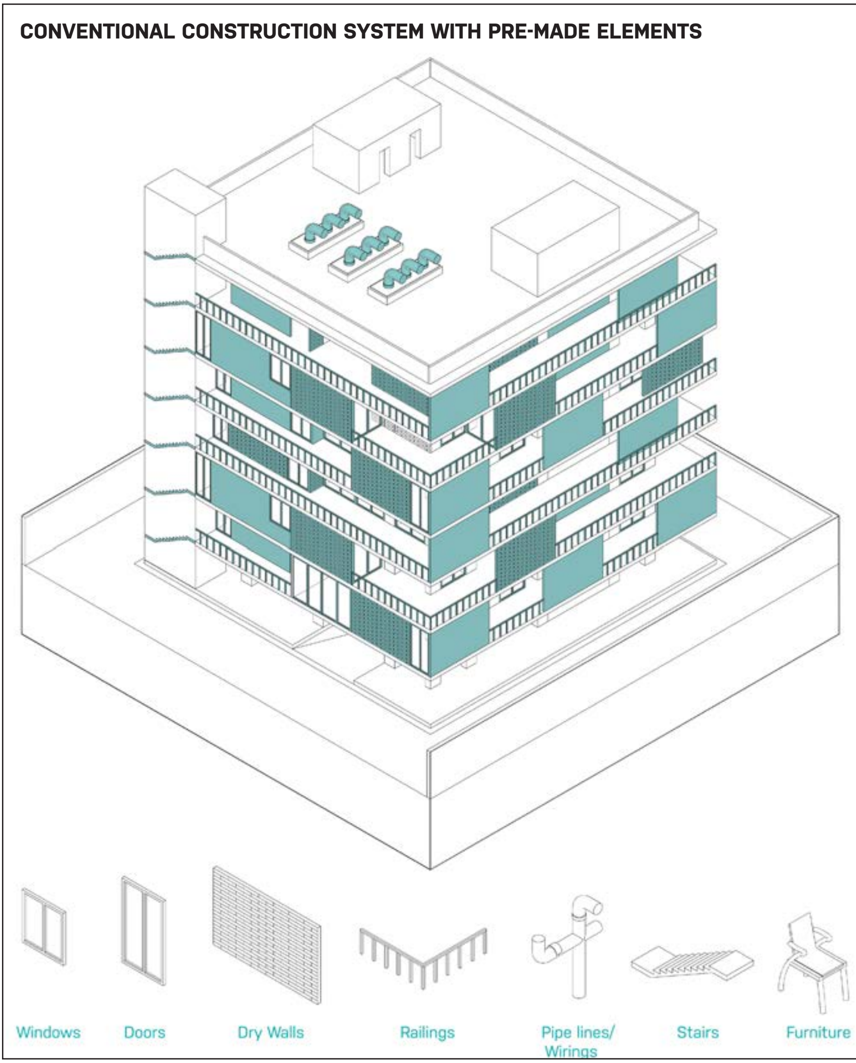



*Fig: Diagram analysis of steps of construction process and identification of possible pre-made elements in the process.*

The pre-made materials used in an on-site construction are the doors, windows, floor finishes, toilet commodities, railing, possibly stairs and furniture, which are the last phase of the on-site construction system. After accommodating those, the painting touches are done for the declaration of completion and handover of the building.

## CONVENTIONAL TECTONIC CONSTRUCTION TO PRE-FAB TECTONICS

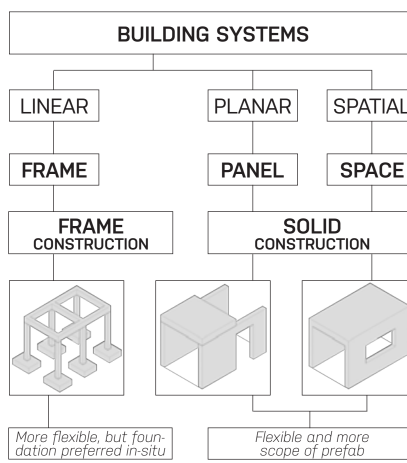
Over the history the origination of building a system for making architecture has a multifaceted relation between architecture, manual skill and industry. The significance of construction the way in which architecture is created has been influenced by those three factors with the course of time. In basic principle, every building is composed of walls, floors and roof, which is follows a certain set of system to generate each element depending on the design. This portion of the chapter focuses on the conventional on-site building elements and components, which is being impacted by the various possible prefabricated tectonics in building systems, and, additionally, analyses what possibilities on-site construction provides that could be taken into consideration for industrial production. Analysis will be made on the importance of industrially manufactured elements but will focus on how the emphasis of architectural design does not merely depends on it.  Building design is a combination of building components but how they are used to fabricate the building systems lies majorly in the hands of the architects and engineers.

On-site building constructions conventionally uses manual skills to create the framing and panel laying which is day by say being influenced by the industrially manufactured building components and systems. The influence of these manufactured components is varying from around 10-60% depending on the requirement of the design. It is implied on both the envelope and the interior fit outs of the structure. As a result, complex approaches are being made with the combination of industrially manufactured building components with elements produced in situ.
A comparison has been given below of the contributions of industrial manufacturing elements in terms of type of building:

| **Type of Building** | **Level of pre-fab[%]** |
|---|---|
| *Rationalized housing* | 25-35 |
| *Industrial building site processes* | 20-30 |
| *Standard ready-built*(rein. conc., steel, timber) | 40-60 |
| *Ready-built housing*(timber panel system) | 50-80 |
| *Modular units / sanitary blocks* (reinf. conc., steel, timber) | 60-90 |
| *Mobile modular units*(steel, timber) | 90-100 |
| *Automobiles*(for purposes of comparison) | 100 |

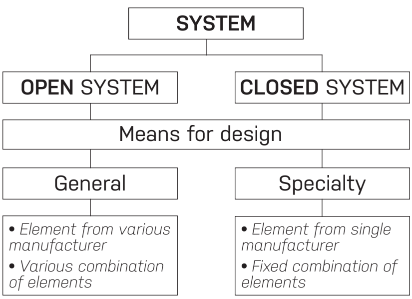
## BUILDING METHODS

Building methods are the standardized idea of how a building system can be categorized and analyze in both the in-situ and industrial perspective.




## SYSTEM – BUILDING SYSTEM

Building system is the geometric organization of the various element and the manner in which they combine that is determined through the design. The coordination of the design system should be made during the design phase mentioned earlier. While making such coordination the decision should be made that whether the design elements as in the shell, interior fit-out and the envelope will be made separately or will be a integrated part of the system, which will guide it in the direction of an in-situ construction or prefab one. This system is categorized into types, open and closed.




## MATERIAL IN SYSTEM BUILDING

Steel, Timber and Concrete is used in three different structural components of the construction process.

**Frame systems**

The linear elements such as column and beam of a building is termed as the frame system which gets a stabilization with bracing system, to withhold the vertical and horizontal loads. These load bearing and non-load bearing elements are clearly detached from the external and internal envelope.

The frame systems have ideally made out of the following the materials to create a solid pre-cast element of a construction system.

**Panel systems**

Paneling system is the major facades of the building that comprises of the wall, floor, and ceiling elements, which allows the building to form a spatial spacing.

The panels can be constructed of steel, timber construction materials, concrete or masonry. Three types of ideal paneling system is followed in a construction system.

- *Small panel construction only used in low-level, multi-story buildings.*
- *Large-panel construction is four edges of a floor slab connected on longitudinal and transverse walls below.*
- *Crosswall construction is transverse walls arranged parallel to the floor slabs above that acts as support.*

**Space systems**

This can be termed as the components of spaces used within a large space to compartmentalize spatial uses and their construction.

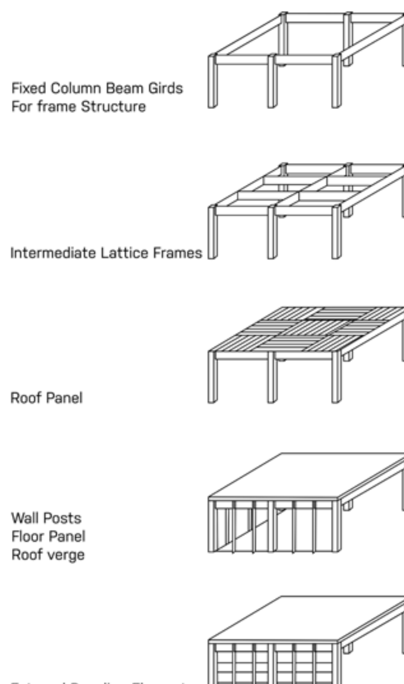



*Fig: Framing, Paneling and Space creation.*

# PRE-FAB ELEMENT TO COMPONENT TO ASSMBLAGE _ON-SITE

## Pre Fab Elements

Apart from foundation construction, starting from the structure to tinniest elements of construction to creating the three planers to form any spatial arrangement of a building, can be pre-made and brought to site for assemblage that can be named as an pre-fab element.

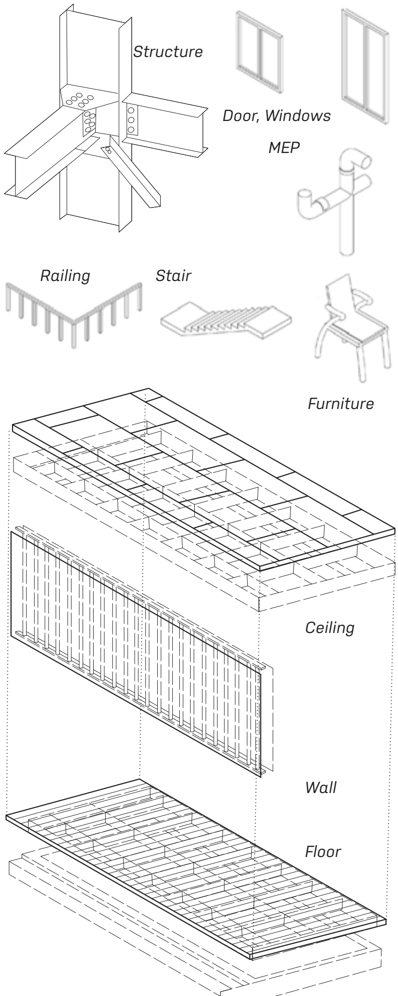



*Fig 3: Possible pre-fab elements.*

## Pre Fab Assembly_On-Site

On-site construction can be also carried out by combining major pre-fab elements of the planar surfaces that is required to build an ideal spatail configuration. The foundation frame structure is preffered to be made on site, over which the compila-

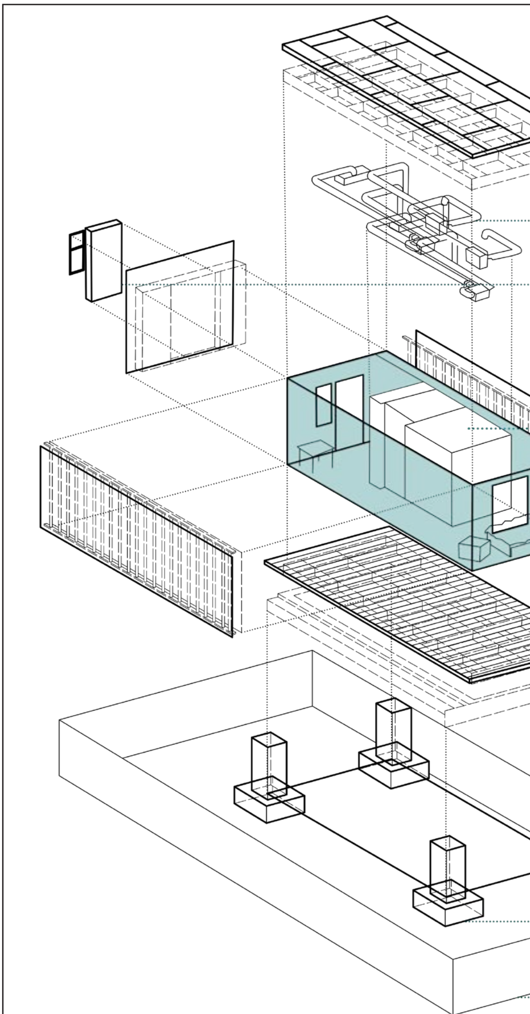
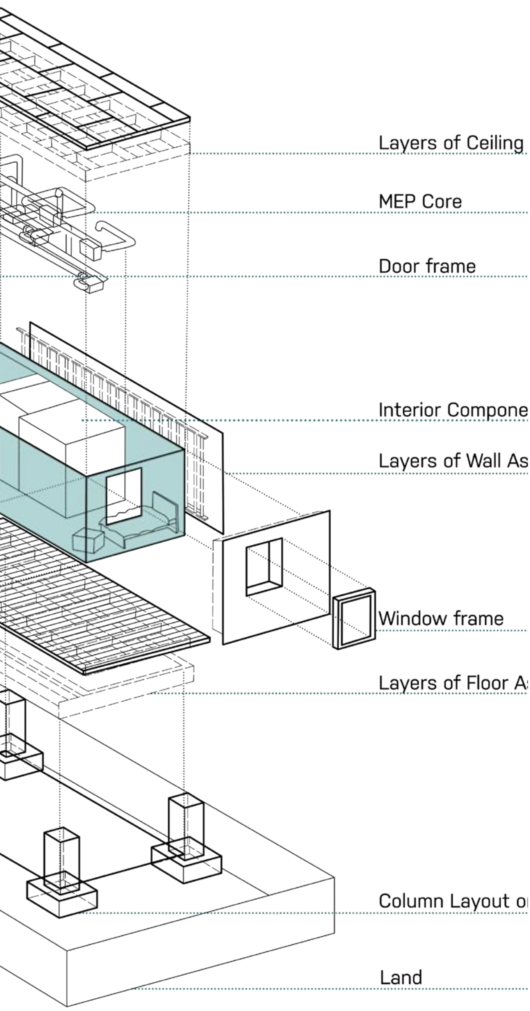


*Fig 4: Pre-fab elements and components to be placed on-site*

tion of the elements gather to give it the shape of one space that contains other components within that space. This one space then can be comnined in different layers of the main frame work to form a compilation of spatial masses on site.




## Pre Fab Components (Spaces)

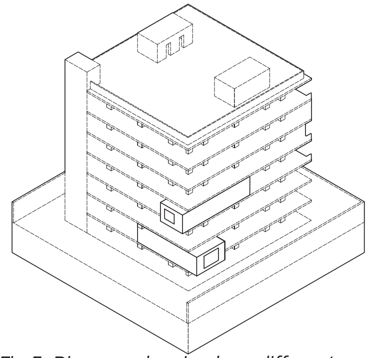


*Fig 5: Diagram showing how different elements can combine to form components and assembled on site.*

Among the spatial components, possible prefab spaces are the toilets and kitchen that can be industrially made and assembled on-site since they act as connecting space and requires uniformity in design.

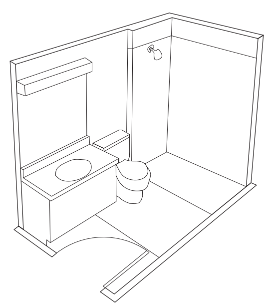
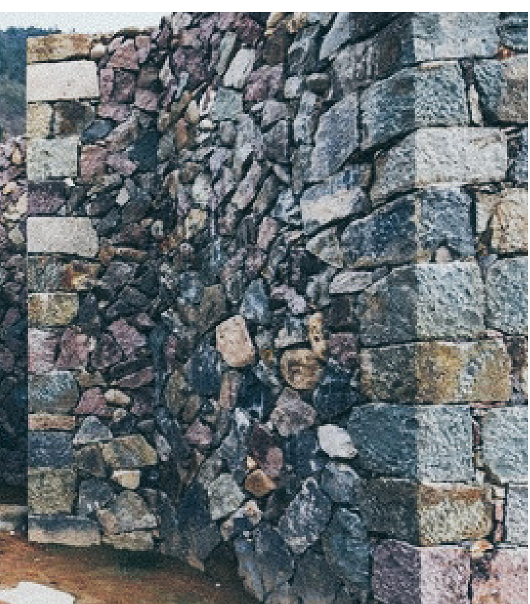


*Fig 6: Diagram of a standard toilet and kitchen*

# MATERIAL DIFFERENCE: US & FRANCE

*Fig.1 Wood frame structure*

*Fig.2 Masonry structure*



Construction of buildings varies significantly between Europe and North America. European houses are typically built with masonry, while North American houses are usually made of wood.[6] Why is this so?

Wood has been the primary construction material used in America due to the vast forests as resource since North America settled. And America still possesses large forests today compared to Europe. On the other hand, most contractors and builders in America get enough training and experience, which are accumulated for several hundred years, of building in an inexpensive and effective way.

On the contrary, most large forests in Europe were cut down clear hundreds of years ago. Those forests never have chance to resume due to the continuous consumption of timber. Today, especially in France, the governments have to enact laws and policy to protect the woods and limit the supply and demand, which increases the price of the wood as well. As a result, we can find less wooden buildings in France than in America.

However, masonry buildings are widespread in France, especially rural areas. The traditional masonry construction in France makes the buildings distinctive from those in America. In this part, we will introduce the timber and masonry construction in France and America.

## TIMBER CONSTRUCTION

In America, **mass timber** construction gradually become the common way for large wooden buildings. Mass timber, a kind of framing styles, is characterized by the use of large solid wood panels for wall, floor, and roof construction.[7] Some special forms of sculptural structures can use mass timber construction as well, formed with solid wood panel or framing systems. Products in the mass timber family include:

**Cross-Laminated Timber (CLT)**.
CLT consists of layers of dimension lumber oriented perpendicularly to one another and then glued to be structural panels.

**Nail-Laminated Timber (NLT)**.
NLT is created from individual dimension lumber members, stacked and fastened with nails or screws to form a thick and solid structural element.

**Glued-Laminated Timber (GLT)**.
GLT consists of individual wood laminations, positioned based on their material properties, and then is fixed tightly with durable, moisture-resistant adhesives. The texture of all laminations runs parallel with the length of the pieces.

**Dowel-Laminated Timber (DLT)**.
DLT panels are made from softwood lumber boards stacked like NLT and bonded together with dowels.

Fig.3 CLT

Fig.4 NLT

Fig.5 GLT

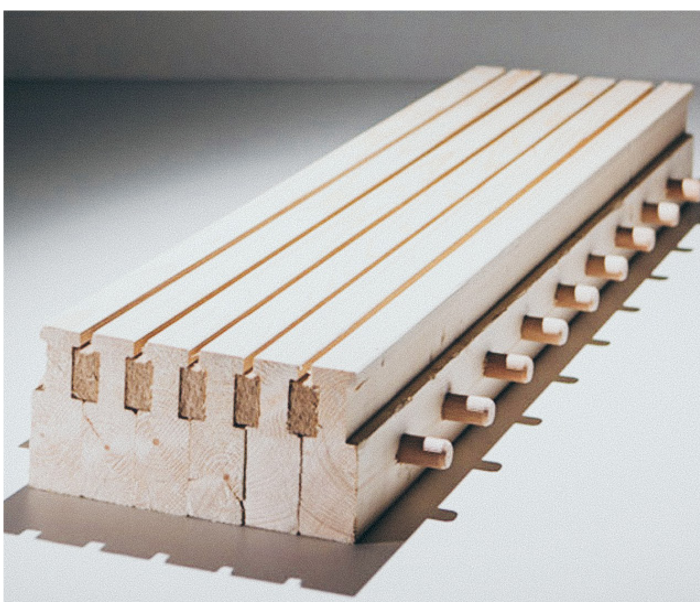


Fig.6 DLT

In France, the modern wooden houses are built less and less with massive woods. Indeed, obtaining dry structural perfect elements with solid wood is technically difficult and expensive.

This is why the new generation of solid wood is used commonly now, whose properties are stable and guaranteed in terms of species, dimensions, strength and preservation. They perform better than normal solid wood in construction. There are three main product types:

**Laminated Veneer Lumber (LVL).**
LVL panels are light and structurally homogeneous. They are resistant and stable while compatible with various construction condition.

**Cross-laminated Timber (CLT).**
CLT consists of layers of dimension lumber oriented perpendicularly to one another and then glued to be structural panels.

**Trussed Wood Floor.** These elements require a semi-industrial process. It consists of an array of compositions on edge in which are drilled at regular intervals holes. In these holes are stuck wooden dowels. The dowels are inflated connecting two consecutive boards, and thus bring a very high stability to the whole structure. This assembly does not require glue.

Fig.7 LVL

Fig.8 CLT

Fig.9 Trussed wood floor

## MASONRY CONSTRUCTION

In America, Reinforced Brick Masonry construction method is used commonly. RBM has greater flexibility in the on-site construction and arrangement than any other comparable materials or methods. Because there is little limitation in selection of masonry materials, patterns, types or size. And it can guarantee the structural safety as well, which means the finishing surface is not served merely as a skin or covering, but a part of the structure as well. This kind of masonry is characterized by elements are bonded together by cement mortar and grout. The types include;

**Stone Masonry.**
It is building with stones set in mortar.

**Reinforced Hollow Unit Masonry.**
The units contain hollow spaces, and with reinforced joints or filled cells.

**Reinforced Solid Masonry.**
Solid Masonry is built with the bars in the bed joint .

**Reinforced Grouted Masonry.**
Wythes are bonded together with grout collar joint between.

**Composite Construction.**
It is similar to reinforced grouted masonry, with hollow units in one wythe and solid in another.

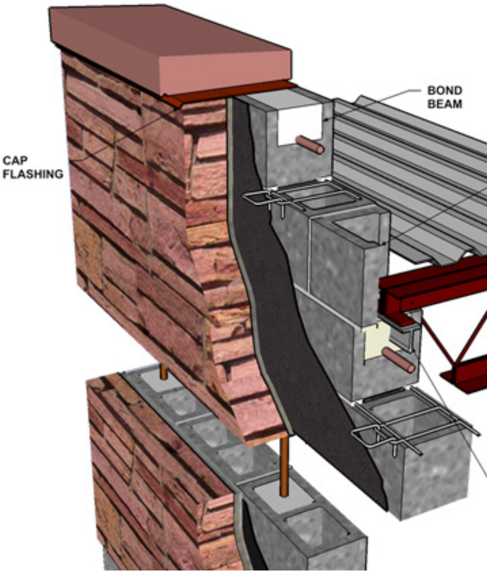


Fig.10 Stone Masonry

Fig.11 Reinforced Hollow Unit Masonry

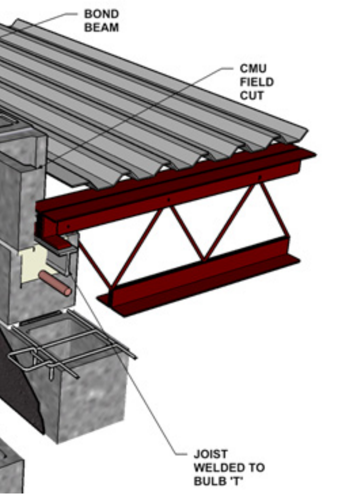



Fig.12 Reinforced Solid Masonry

Fig.13 Reinforced Grouted Masonry

Dry stone walls construction are prevalent in French countryside. Dry stone is a traditional construction method by which structures are built merely from stones without any mortar to bind them together. Although without adhesive, the dry stone structures keep stability because each element for a load-bearing facade is selected interlocking stones.

To keep the dry stone wall sturdy, it's important to use relative large stones to bridge the gaps in the layer below and above. The bottom layers of a wall are always slightly wider than the upper ones to keep the whole structure stable, which makes the wall tapers inward as the wall rises up.[8]

Another significance of applying dry stone walls is that they're usually built from local stones. Using local materials benefits the environment because the construction process won't waste energy on transportation over long distances. It also embodies and maintains the local distinctive architectural features.

*Fig.14 Dry stone wall construction*

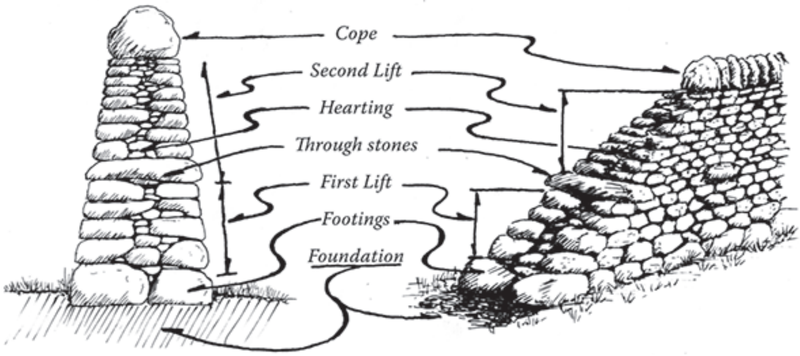



Fig.15 Construction of Dry Stone

Fig.16 Dry stone house, Provence, France

# RISKS IN CONSTRUCTION

Risks in construction can be described as a combination of vulnerability and hazards. Vulnerability is characterized by a physical system which allows a threat to be exploited. While hazards are something with an adverse effect on the activities of an organization.[9] The level of probability of risk occurring is thus determined by the types and frequency of hazards and vulnerability. Due to lack of knowledge or protection within a project, vulnerability comes into being and the construction process will be fraught with potential risks when some hazards occurs. Therefore, it is a priority job that figuring out the risks before working on earth and determine the resolution.

Although the construction risks are interrelated and peculiar to each particular project and each participant, we can still summarize the common risks that almost all the projects share, regardless of regions, types of buildings and construction methods. We categorize the potential risks into two parts: technical risks and external risks; so that we can take consideration of the factors from both inside and outside.

The assessment of the risks can help us decide whether we should use on-site construction or pre-fabrication. Both methods can deal with the risks to different extent, while sometimes neither of them can make it. As a result, in the below chart, we list the better way to response the risks after comparing the on-site construction and prefabrication, which are the subjects we focus on. Obviously, prefabrication has less capacity of deal with certain situations where on-site construction can serve its function, which proves that pre-fabrication has to cooperate with on-site construction.

*Chart: Risks in Construction Analysis*

| Risks | | | How To Response | |
|---|---|---|---|---|
| | | | pre-fab | on-site |
| TECHNICAL RISKS | Design process | Improper structural engineering | | ● |
| | | Wrong selection of materials | | ● |
| | | Lack of site information | | |
| | | Need for design exceptions | | |
| | construction risks | Inaccurate contract time estimates | ● | |
| | | Construction error | | ● |
| | | Construction permissions | | |
| | | Incomplete knowledge of utility information | ● | |
| | | Delayed deliveries and disruptions | | ● |
| | | Worker and site safety | ● | |
| | | Unsuitable equipment and materials | | ● |
| EXTERNAL RISKS | Contractual relations | Landowners unwilling to sell | | |
| | | Priorities change on existing program | | |
| | | Funding changes for fiscal year | ● | |
| | | Consultant or contractor delays | | |
| | | Additional needs requested by stakeholders | | ● |
| | | Inconsistent costs, time, scope, and quality objectives | | |
| | | Permits and licences* | | ● |
| | Environmental factors | Water quality issues | ● | |
| | | waste generation | ● | |
| | | Weather conditions | ● | |
| | Project management risks | Insufficient time to plan | | |
| | | Unanticipated project manager workload | | |
| | | Too many projects | ● | |
| | | Estimating and/or scheduling errors | | |
| | | Inadequate staff / resource availability | | |

* Pre-fabricated buildings needs more permits besides the typical construction permits, including road opening permit, water-sewer taps and fire suppression permit, which are required by *new construction or major renovations.*

# WHY ON-SITE CONSTRUCTION?

As prefabrication getting used extensively in architecture construction field, on-site construction techniques have been superseded to large extent. But on-site construction keeps its own space in many ways. After analyzing the capacity of both methods dealing with risks in last part, we will talk about the advantages of it within architecture design in this part.

Due to the process that produced in a factory and transported to the site, prefabrication limits the design variety, diversity and even quality. Generally, stability, efficiency, aesthetics and functionality are the important principles in architecture design where the on-site construction may serve function.

For stability, on-site construction has a relatively concise workflow compared with prefabrication, as a result, it is the more direct way of constructing the whole building structurally integrated and connecting it with the basement.

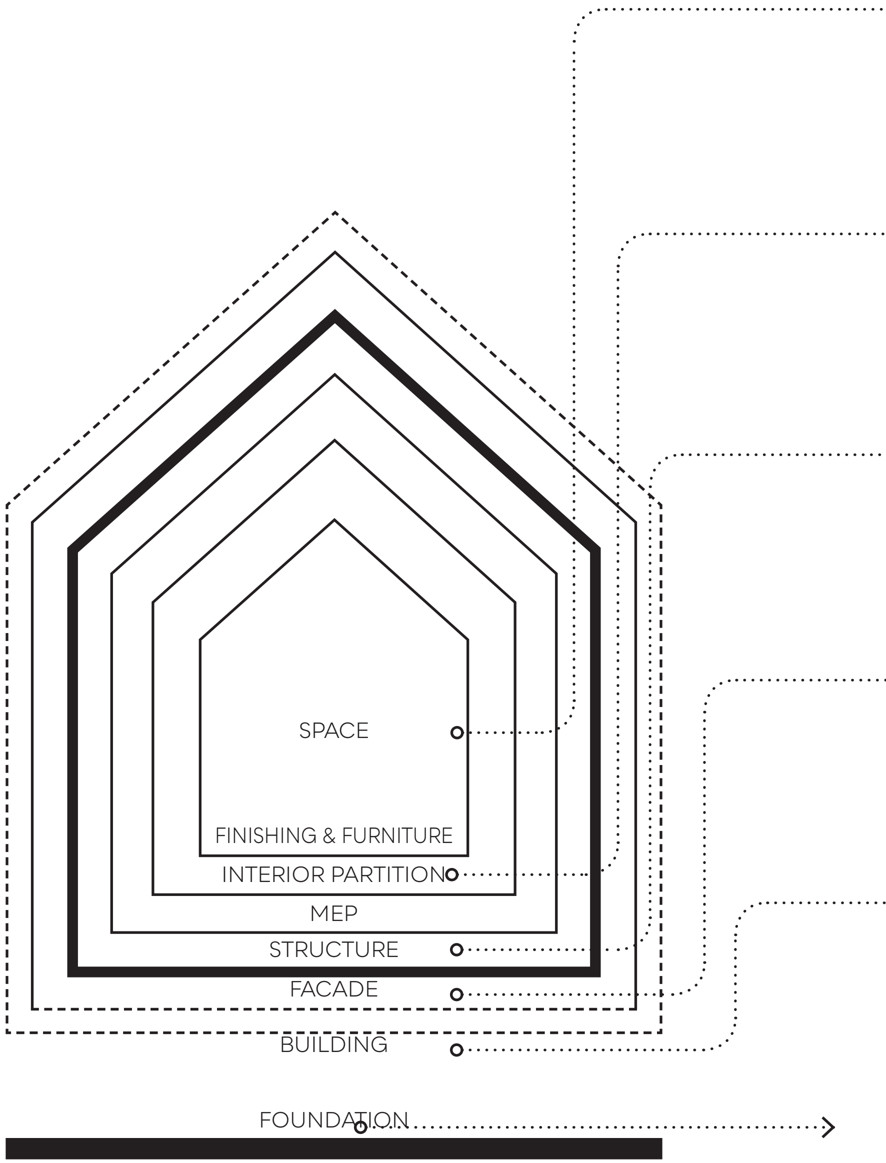
While customers or clients want to change the design plan, a prefabricated product offers no opportunity for altering but on-site construction has more efficiency to do that. The designers and can redesign and reconstruct some certain building parts as they want and at any time without processing in a off-site factory.

Aesthetics includes plenty of catalogues. It is common if the architects would like to keep their own unique preference for the materials and construction methods, such as Tadao Ando and his concrete masterpieces. On the other hand, products from a factory could lose the spirit of the craftsman. Not mention to some certain materials like brick have no chance to be prefabricated in advanced due to its special joints.

The difference in functionality between two construction methods is basically concentrated on the quality of facilities and sealant details. When it comes to the detail construction, on-site techniques stand out. There will be indispensable errors in construction process, which means only on-site construction can compensate the errors without leaving anything unsuitable.

The diagram shows where on-site construction techniques are applied in a typical building. It helps us exclude some certain types of buildings for prefabrication proposal.

Fig.17 On-Site Construction


SPACE
FINISHING & FURNITURE
INTERIOR PARTITION
MEP
STRUCTURE
FACADE
BUILDING
FOUNDATION

### INDIVIDUALITY REQUIREMENT
When the architect pursues architectural spiritual power or uniqueness on a certain site, it'd better to build the structures on-site.


*Fig.18 Bruder Klaus Field Chapel*

### DESIGN FLEXIBILITY
When the building space needs to be changed or restored according to the new condition of the environment, pre-fabricated buildings give no chance of doing that.


*Fig.19 Elbphilharmonie*

### STRUCTURAL REQUIREMENT
When the structure is overly large or the structure needs to be more elastic to resist seismic effect and wind load.


*Fig.20 Weald and Downland Museum*

### MATERIAL REQUIREMENT
Masonry, integral bare concrete, sprayed concrete buildings can't be prefabricated due to the special technical requirement


*Fig.21 Los Manantiales*

### SCALE OF THE BUILDINGS
When the size of the building is over large, the structure components can't be prefabricated or transported. Therefore, such buildings have to be constructed on-site.


*Fig.22 One World Trade Center*

### STABILITY REQUIREMENT
The building should be connected to the earth tightly for seismic resistance or wind load.


*Fig.23 Basement*

*Fig.24, 25 On-site Construction: Weald and Downland Museum*

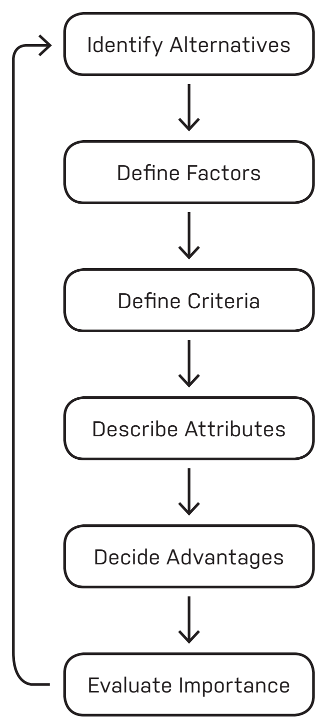
*Fig.26, 27 On-site Construction: Los Manantiales*

# ON-SITE CONSTRUCTION OR PRE-FAB?

We can compare the advantages of both on-site construction and prefabrication to choose which way we will apply, which is called Choosing By Advantages. The Choosing by advantages (CBA) strategy is a decision-making strategy created by Jim Suhr. It serves the purpose of helping people reach objective decisions when having to compare mutually exclusive solutions.[10] CBA introduces a new idea that can potentially lead to better decisions. In construction field, the factors of CBA derive from the consideration of location, transportation, time, safety prevention, quality, weather condition, etc. In the chart, we list the criteria of each principle and attitude of each construction method can do, and finally, the comparison result in each item.

At first, we need to clarify some definitions. ***Alternation*** is two or more items of construction methods from which one of them must be chosen. ***Factor*** is the element of a decision. For assessing sustainability, the factors should represent economic, social, and environmental consideration. Besides, CBA considers the cost after evaluation of attributes of alternatives based on factors and criteria. ***Criteria*** is a decision rule, or a guideline. A criterion can represent what conditions and prerequisites each alternative should satisfy or avoid, or the preferences each alternative may fulfill to some extent. ***Attribute*** is the data showing the characteristic, quality, or consequence of choosing one alternative. ***Advantage*** is benefit or improvement that certain alternative can bring about after comparing the difference between the attributes of two alternatives.

For the assessment of prefabrication, the factors taken into consideration can be categorized as location/ transportation, time considerations, safety/accident prevention, quality and weather conditions. The chart is an example for application of CBA and it can offer the reference for the final decision.




*CBA steps*

*Chart: Choosing By Advantages Strategy (example)*

| | FACTORS | PRE-FAB | ON-SITE |
|---|---|---|---|
| 1 | **Number of material suppliers** | | |
| Criteria | fewer is better | | |
| Attribute | | 1 | 15 |
| Advantage | | ● | |
| 2 | **Location of suppliers** | | |
| Criteria | closer is better | | |
| Attribute | | 350 miles away | within 100 miles |
| Advantage | | | ● |
| 3 | **Local labor cost** | | |
| Criteria | less is better | | |
| Attribute | | 35$/hr | 65$/hr |
| Advantage | | ● | |
| 4 | **Time to insall a unit** | | |
| Criteria | less is better | | |
| Attribute | | 5 days | 6.5 days |
| Advantage | | ● | |
| 5 | **Overall quality** | | |
| Criteria | Perfectly robust | | |
| Attribute | | less robust | perfectly robust |
| Advantage | | | ● |
| 6 | **Quality of finishes** | | |
| Criteria | Perfect finishes | | |
| Attribute | | consistent quality | less consistent |
| Advantage | | ● | |
| 7 | **Percentage of work steps done above-head / in dim lighting** | | |
| Criteria | Less than 15% of total activities | | |
| Attribute | | 0% | 15% |
| Advantage | | ● | |
| 8 | **Overall construction time** | | |
| Criteria | faster is better | | |
| Attribute | | 31 | 33 |
| Advantage | | ● | |
| 9 | **Design flexibility** | | |
| Criteria | Allow for change at a large stage | | |
| Attribute | | no flexibility | can be modified |
| Advantage | | | ● |
| 10 | **Solid waste generation** | | |
| Criteria | less is better | | |
| Attribute | | less waste | more waste |
| Advantage | | ● | |
| 11 | **Weather** | | |
| Criteria | No delays due to weather | | |
| Attribute | | not affected | affected |
| Advantage | | ● | |

# 05

# The Future of Pre-fabrication

*Lovejeet Gehlot*
*Shahryar Beyzavi*

**ABSTRACT**

Pre-fabrication in architecture is perhaps in the top tier of the most sought after industries in terms of making the leap into the future. Prefabrication allows for pre-planning to reduce time, costs and increase overall accuracy. But equipped with pre-existing tools, the pace of such goals will remain steady. The future of pre-fabrication will be based on modifying the existing steps through digitization, means of assembly, and upgrading existing materials that will allow pre-planning during the very beginning of the process.

The future of Pre-fabrication incorporates Digital Design, 3D printing, Robotics, and Sustainability to launch the next level of performance. This new era of integrating calculation will provide an environment that is thought-out from manufacturing to assembly, and finalize with a cycle of re-fabrication that would reduce waste. Such process, and knowledge have to be integrated into growth in population and changes in urbanization in the future of the social context. The Future of Pre-fabrication will be extending hands to an array of industries that will form a mesh, and move from one another seamlessly to be able to continue a parallel level of improvement and grow in harmony, so the future will achieve new levels of innovation.

# ROLE OF PRE-FABRICATION IN CONSTRUCTION

Through standardization of modules and pre-fabrication, the construction industry can achieve better productivity resulting in better construction costs , higher quality, and fewer interface problems leading  to fewer maintenance costs and higher scopes for re-using and recycling.

The degree of prefabrication in a given system can be distinguished by three scales of components
•Planar components such as walls, ceilings or trusses.
•Enclosed modular components.
•Stand-alone pre-fabricated structures.
The degree of Pre-fabrication however, is not just based on physical dimensions, but various other factors such as integration on MEPs (Mechanical, electrical, and plumbing).

Acceptance of pre-fabrication in construction industry relies on each country. Countries like Sweden and Germany engaged pre-fabricated residential projects, while it is most commonly used in larger industries such as offshore oil and gas facilities, road bridges and elevated highways.

Current obstacles to acceptance of pre-fabricated structures are:
Misconceptions of poor quality and


*Fig. 1: Sikorsky Aircraft Home Transport*

higher costs.

Client demands of individualization, discouraging the usage of standardized components.

Limited market exposure of Pre-fab in high-rise construction.

Monopoly in Pre-fab component prices by individual suppliers.

Higher costs of transportation from factory to site, especially with limitations and hindrances in transporting large-scale components.

Problems faced in moving and handling large-scale components in space-constrained sites of construction.

Restrictive government regulations and client specifications. (For example, using prefabricated bridge foundations is banned in Spain.)

Once these problems are identified, various mitigation strategies are applicable to each problem. For example, risks in having to rely on one fabricator for the pre-fab components can be resolved in two ways-

Imposing universal industry standards for each type of component across the world, also bringing down the prices due to higher competition.

Future reliance on 3D printers will not only saves significant time on material transportation to site, but also save significant costs on construction and transportation of materials.[1]

*Fig. 2: Node Covered with Sheaths. British architect Adrian Priestman claims to have designed and installed the first 3D-printed components to be approved for use in the construction industry.*

# NEED FOR ADVANCEMENT IN PRE-FABRICATION

The construction industry alone accounts for 6% of Global GDP. With the largest share in raw material usage, construction of buildings alone accounts for up to 40% of global carbon emissions.

Major factors shaping the future of the construction industry include sustainability issues raised globally. With about 30% of global greenhouse gas emissions attributable to construction industry, and with countries like UK targeting to reduce more than 50% of their total greenhouse gas emissions by 2025, there exists a challenge as well as opportunity for the 'Pre-fabrication industry' to respond to these urgent issues by coming up with a more sustainable method.

When compared with other industries, construction industry has relatively grown at a slower pace in terms of technological development. In fact, both labor and multi-factor productivity in construction industry has declined in most countries around the world (Abdel-Wahab and Vogl, 2011), United States alone, has shown a continuous fall in labor productivity over the past 40 years.

**Role of government towards the future of Pre-fabrication**
Government across all countries need to standardize their codes and construction standard policies to improve the productivity of Pre-fabrication industry. With countries like Britain specifying targets to reduce construction and life-cycle cost of future buildings by 33%, there lies immense opportunities for the industry by proposing faster and cost effective approach of Pre-fabrication.

**Possibilities within a private company**
Through innovation and implication of new technologies, materials and tools, companies themselves can not only improvise the productivity, but also improve the quality of buildings, and environmental impact.

Although these innovations are being applied on a smaller scale by few advanced countries, they have the capacity to radically change the construction industry, if applied on a global scale. As an example, mere 2% of upfront costs on a project to support design optimization can help reduce 20% of the total life-cycle cost of the building.[2]

**Factors Influencing Pre-fabrication Industry**
Various factors (both direct and indirect) affect the construction industry and must be taken into consideration for the pre-fabrication industry as well. Even small shift in any of these factors could bring substantial changes to the industry. World Economic Forum, in collaboration with Boston Consulting Group in 2016, prepared a framework with a list of 30 major factors, that can help improve the industry. (Figure on the right)

## (Future) Best Practices

Actors

**Company level**

### Technology, materials and tools

| | | |
|---|---|---|
| *Advanced building and finishing materials* | *Standardized, modularized and prefabricated components* | *(Semi-)automated construction equipments* |
| *New construction technologies e.g. 3D printing* | *Smart life-cycle optimizing equipment* | *Digital technologies and big data along the value chain* |

### Processes and operations

| | | |
|---|---|---|
| *Front loaded and cost-conscious design and project planning* | *Innovative contracting models with balanced risk-sharing* | *A common and appropriate framework for project management* |
| *Enhanced management of subcontractors and suppliers* | *Lean and safe construction management and operations* | *Rigorous project monitoring (scope, time and cost)* |

### Strategy and business model innovation

| | | |
|---|---|---|
| *Differentiated and business model and targeted consolidation and partnerships* | *Sustainable produces with optimal life-cycle value* | *Internationalization strategy to increase scale* |

### People, organization and culture

| | | |
|---|---|---|
| *Strategic workforce planning, smart hiring, enhanced retention* | *Continuous training and knowledge management* | *High performance organization, culture and incentive schemes* |

**Sector level**

### Industry collaboration

| | | |
|---|---|---|
| *Mutual consent on standards across the industry* | *More data exchange, benchmarking and best practice sharing* | *Cross industry collaboration along the value chain* |

### Joint industry marketing

| | | |
|---|---|---|
| *Industry-wide collaboration on employer marketing* | *Coordinated communication with civil society* | *Effective interaction with the public sector* |

**Government**

### Regulation and policies

| | | |
|---|---|---|
| *Harmonized building codes/ standards and efficient permit processes* | *Market openness to international firms and SMEs* | *Promotion and funding of R&D, technol, adoption and education* |

### Public procurement

| | | |
|---|---|---|
| *Actively managed and staged project pipelines with reliable funding* | *Strict implementation of transparency and anti-corruption standards* | *Innovation-friendly and whole-life-cycle-oriented procurement* |

*Fig. 3: Industry Transformation Framework*

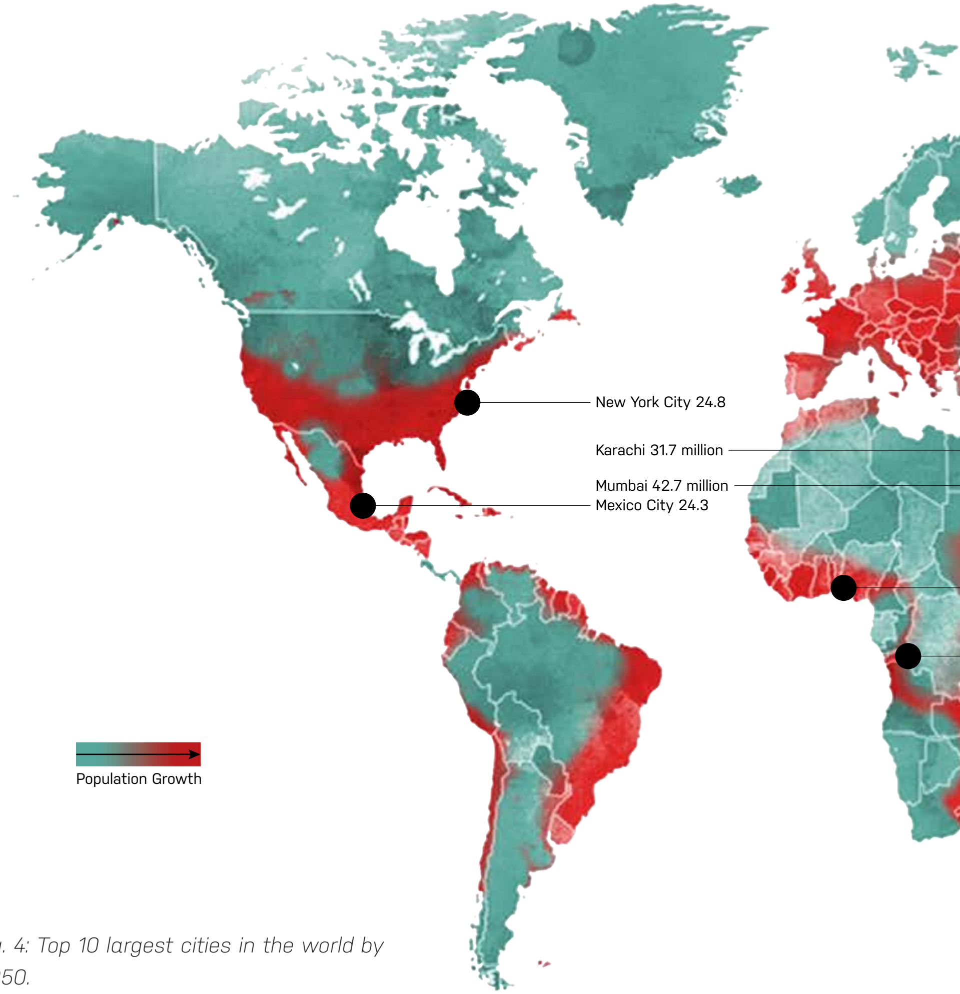
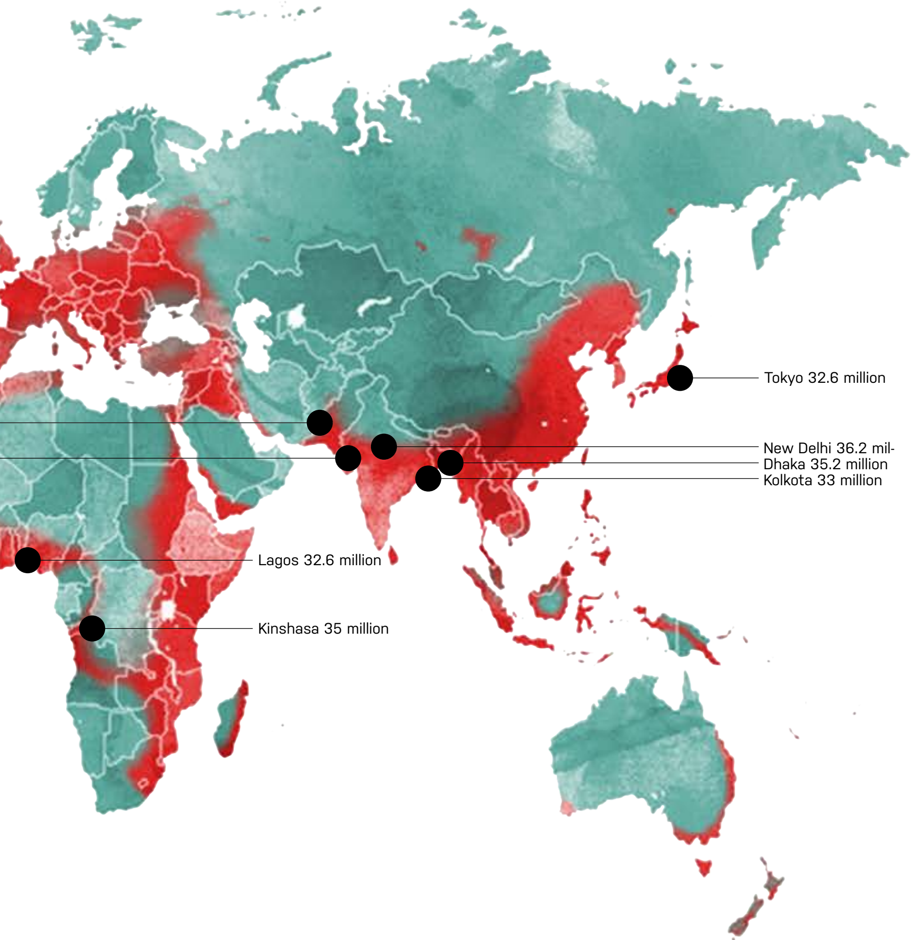



*Fig. 4: Top 10 largest cities in the world by 2050.*

**POPULATION GROWTH AND URBANIZATION**

The world of construction is strongly dependant upon the environment, economy, and the society as a whole. This correlation affects other industries, as construction reaches out to other forms of service to be able to perform. However, its biggest driving factor is population growth, which is heavily shifted towards urban growth more than anything else. The population of urban areas is increased globally by 200,000 per day; therefore, in terms of infrastructure, there needs to be a massive upgrade in affordable housing, social utilities, and transportation.[3] The World Resource Institute has




projected that by 2030, cities will have tripled their population, and by 2050, the world population will reach 10 billion, with 2/3 living in urban areas. This growth can benefit from the advantages of pre-fabrication, but in addition, it will certainly require new strategies in social structure, transportation and sustainability.[4] With the youngest of millennials in higher education, and the rest well within their careers and in family settings, the future of housing, and construction for that matter, will be shaped differently.[5] Companies such as wework or Regus are new concepts that have changed the platform of occupying buildings. Similar to apps like Uber or task apps, the future of consumerism is moving outside a paradigm ownership and towards access. Both wework and Regus provide access to an office desk or conference room by receiving a membership fee that is more affordable than renting an office space for a full year, especially for today's start-up type businesses.[6] But given that Regus covers a larger area of square footage than wework, the latter has a valuation 10 times Regus. That is because wework is advertising directly to millennials. In addition to attracting younger demographic by offering perks, wework sells a lifestyle that its competitors lack.[7] They offer gym, living space, school for kids and adults. Wework has access to very valuable data that allows them to know where people work and when they are most productive, which allows them to customize their buildings and their structure as closely as knowing how many conference rooms they require and how many hours a day they are going to be used for. This allows them to take advantage of their space as efficiently as possible. This is certainly a big portion of the future of urban living, which will certainly affect pre-fabrication's trajectory.[8]

**Talent Distribution**

As population grows, one important challenge will be uneven distribution of skilled labor. Driven by the shift in careers in developed countries such as the United States, there has been an increase in the average age of construction workers, from 43 in 2014, as opposed to 36 in 1985 (the overall median age of the world population will increase annually, from 31 in 2020, to 36 in 2050). At the same time, the rate of soon-to-be retirees went from 25% to 40%. This is of course accompanied by the progress in technology that requires higher levels of skill and additional knowledge. Therefore, in order for the future of pre-fabrication to prosper, by identifying risks, smart long term hiring, and reviewing data for future planning, one can invest now to guarantee enough labor force for a future that can handle rise in population growth, and perform

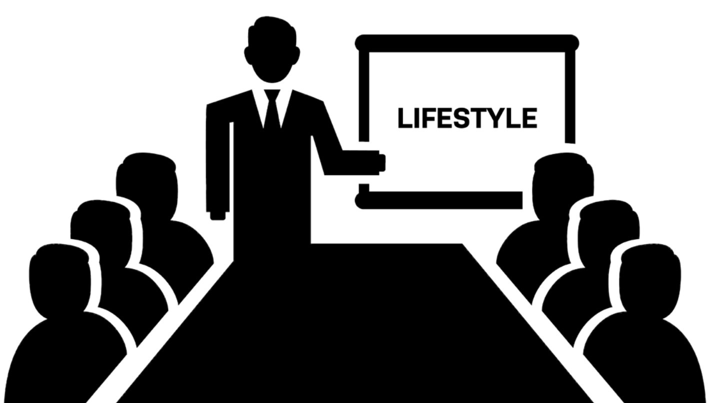



*Fig. 5: Wework's Product Pitch*

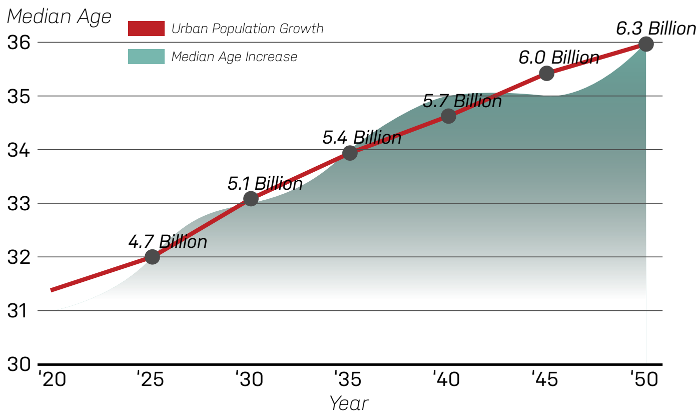



*Fig. 6: Median Age increase from 2020-2050. (overlaid by Urban Population growth)*

in correlation with advancements in technology.[9]

**TRANSPORT**

The future of fabrication is certainly related to the future of transportation and autonomous vehicles; therefore, the questions that arise are related to strategy, technology, and urbanization growth. Building material require time and fuel to be delivered; therefore, there will always be an issue for areas with condensed traffic, and inadequate material storage space. The future of transportation certainly needs to take into account such constraints.[10]

In addition, there should be a consumer oriented system in place. A system that will integrate processes directly from what is preferred by the consumer. The main reason for private companies such as Uber and Lyft's market dominance over the government is their attention in curating a consumer oriented experience based on valuable data.[11]

It appears that a sizable missing link within the world of transportation is the intercommunication of the private side with the public side. By integrating consumers' data within the public infrastructure, it would be easy to predict 'needs' for goods that will be delivered in advance, which will result in a highly integrated and convenient system of multi-modal transportation.[12]

The biggest challenge to figure out for construction is the capability of providing transportation to an array of consumers with a wide range of distance-- this is certainly an ambitious goal, but with the integration of all private systems and public, we could envision a multifaceted transportation system. Crucial to this goal is to break up the concept of having one main warehouse that everything is shipped from. With the right data, high density areas with the highest likelihood of construction can be marked to have

smaller warehouses in the close vicinity. This will create multiple nodes of distribution that will allow for a strategic approach towards transportation.
This will increase access to construction material that might otherwise take much longer time to deliver. And as mentioned earlier, it appears that 'access' is the key word for most of the innovation that has occurred recently-- access to cars, bikes, places to stay, tasks/errands, and so on. Today, much like borrowing books from a library, one can rent someone's apartment via AirBNB, or ask a task grabber to put IKEA furniture together for them.[13] Therefore, by the addition of Autonomous Vehicles in the future, which will highly likely include the same 'access' platform culture, what is going to happen to the urban context? Currently a number of those who use ride sharing apps, do not own a car, or have sold their car. If this trend continues, there would be no need for insurance, parking, and maintenance cost. By Users, Autonomous Vehicles perhaps will be helpful for construction in terms of delivering material in trucks. But as far as the city, are driveways going to disappear? are highways going to get smaller? Or the exact opposite?[14]

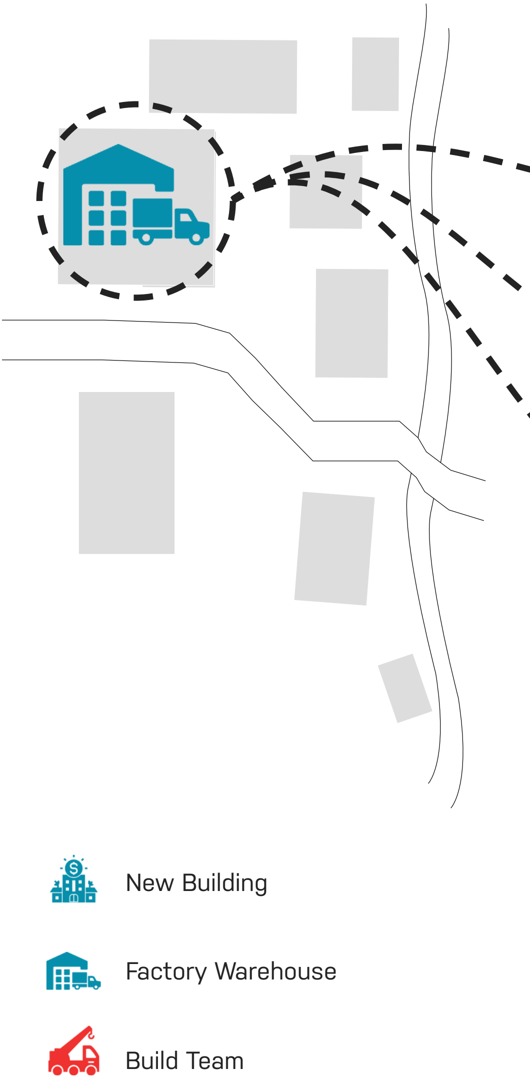



*Fig. 7: Warehouse - Transportation nodes in urban vicinity*

# FUTURE TRENDS IN PRE-FABRICATION

Pre-fabrication industry as a part of the construction industry, gets effected by the same trends from four major domains:

- Consumer Market
- Environmental sustainability
- Society & workforce
- Politics and regulations

It is important that the industry identifies these mega-trends and responds optimally facing challenges and opportunities they possess.

**Consumer Market**

Unlike developed countries like USA, emerging countries like China and India, are rapidly growing in population and GDP. Hence, the needs for future infrastructure in these countries shall remain highest. It is important that these countries get benefited by technological advancements in pre-fabrication that otherwise remains utilized by developed countries only.

Another particular challenge lies in maintaining the aging infrastructure of developed countries. Their demands for maintaining/upgrading or replacing shall always remain, which makes it even more challenging to comply with updated building codes.

**Environmental Sustainability**

Sustainability is no merely a desire, but a requirement in today's construction industry. In US alone, 548 million tons of construction material waste was generated in the year 2015, which is more than twice the amount of municipal solid waste generated at the same time.[15]

With rapid urbanization of popular cities and limited land area, new priorities such as space optimization are emerging. Natural hazards such as floods and earthquakes are major concerns, hence risk-mitigating solutions are needed.

**Society & Workforce**

With the world's population expected to be 6 billion by 2045, the expected population living in slums will be 1.5 billion if the ratio of 1:4 remains unchanged. Hence, it should be of utmost priority to both industry leaders and government to provide affordable housing for the upcoming population.

Another important factor to be considered is changing demographic trends in different countries. Developed countries like Japan, Italy and Germany, have a median age above 45 years, while developing countries like India, have the youngest population with an average of around 29 years. It hence becomes important to understand the current and future needs of the population catering to solutions like reduction in supply of construction workers and providing accessible facilities to the aging population.

Although new technologies help take over the current low-skilled work force, the need for upcoming high skilled operators to use those technologies will be a challenge as the industry is not glamorous as other industries. With growing concerns of global warming and high pollution across the world, it is now also the responsibility of the construction industry to come up with solutions that could help reduce overall carbon emissions and utilize safer materials for construction that are more environment friendly. Ban of asbestos in most countries is a perfect example of increased motivation to ensure better health of people.

Currently, almost every industry is highly focused on research to understand the needs of local communities and predict their future trends and lifestyle. A comparison of wework to Regus[16] is a perfect example of how valuable 'data-collection' has become to predict future needs of users. It is still a challenge untouched by the construction industry to predict the concerns of a community while designing spaces using pre-fabricated structures.

**Politics and regulations**

Challenges in pre-fabrication also include political and regulatory factors related to bureaucracy and corruption.

A global survey by KPMG [17], revealed that building regulations have the most important factor when it comes to increasing complexity in construction. New code regulations affected by factors like health and safety requirements, can affect the complete business operations of pre-fab structures(For ex., ban of river sand in India caused major disruption in construction industry).

Bureaucracy is another factor, where construction permits and compliance to codes and standards are subjected to other factors like environmental concerns and social impacts. Political instability causes further problems as the new government in power will disrupt the existing interests to its own priorities as opposed to its predecessor.[5]

**Future Trends**

Upcoming examples identifies current trends in fabrication industry, that holds potential to change the future of pre-fabrication industry. The precedents shall reveal that technological innovations are not too far from reach of pre-fabrication industries and there lies an immense opportunity to improvise by utilizing these resources and unlocking its potential on a larger production scale.

*Fig. 8: WeGrow school designed by BIG architects*

Figure: Trends shaping the future of construction industry

| Market and Customers | Environmental Sustainability |
|---|---|
| Construction will outpace GDP<br>*57% of the worldwide construction will be accounted by US, China and India alone for next 15 years*[18] | Resource scarcity<br>*1500 Mt of $CO_2$ emissions every year are produced from cement production globally*[19] |
| Globalized markets<br>*50% of the construction industries plan to move to new states or countries with favorable policies* | Sustainability requirements<br>*1.68 kg/capital/day was the global average construction waste generation in 2018*[22] |
| Faster ,more complex projects<br>*57 story, 800 apartment building built by Broad Sustainable Building in just 19 days*[24] | Energy and climate change<br>*30% of global greenhouse gas emissions are attributable to buildings* |
| Aging infrastructure<br>*D+ ASCE rates the US infrastructure as below standard with significant deterioration*[27] | Resilience challenges<br>*$85 billion total losses by Hurricane Harvey in Texas in 2017*[28] |
| Massive financial needs<br>*$1.5tn annual investments are needed to close the global infrastructure by 2025 in US alone*[27] | Cyber threats<br>*60% of small businesses that are hacked go out of business within the following 6 months* |

*Fig. 9: World Economic Forum*

| Society and Workforce | Politics and Regulations |
|---|---|
| Urbanization and housing crisis<br>*6.6 billion people are projected to live in urban areas by 2050 and shall need affordable and healthy housing*[20] | Complex regulations<br>*22 different procedures and 137 days on average, are required for construction permit in China -Beijing*[21] |
| Health needs of citizens<br>*2-5 times higher than outside levels of VOC are found inside US homes*[23] | Stricter HSE and labor laws<br>*10% of the workforce in a public project in California reserved only for "otherwise unemployable" category* |
| Talent and aging workforce<br>*70% of general contractors are concerned about finding experienced craft workers for their workforces*[25] | Geopolitical uncertainty<br>*175k EU workers may lose there jobs in UK, with Brexit and potential restrictions*[26] |
| Stakeholder pressure organization<br>*650k deaths per year are reported from diseases related to hazardous construction materials*[29] | Slow permit and approvals<br>*$1.2tn of infrastructure can be added by 2030 if time limits are fixed in all countries* |
| Politicization of construction<br>*In 2011 the Portuguese government canceled a 165km high-speed train line project as austerity measure* | Corruption<br>*49% of survey respondents believe construction in Western industry is corrupted*[30] |

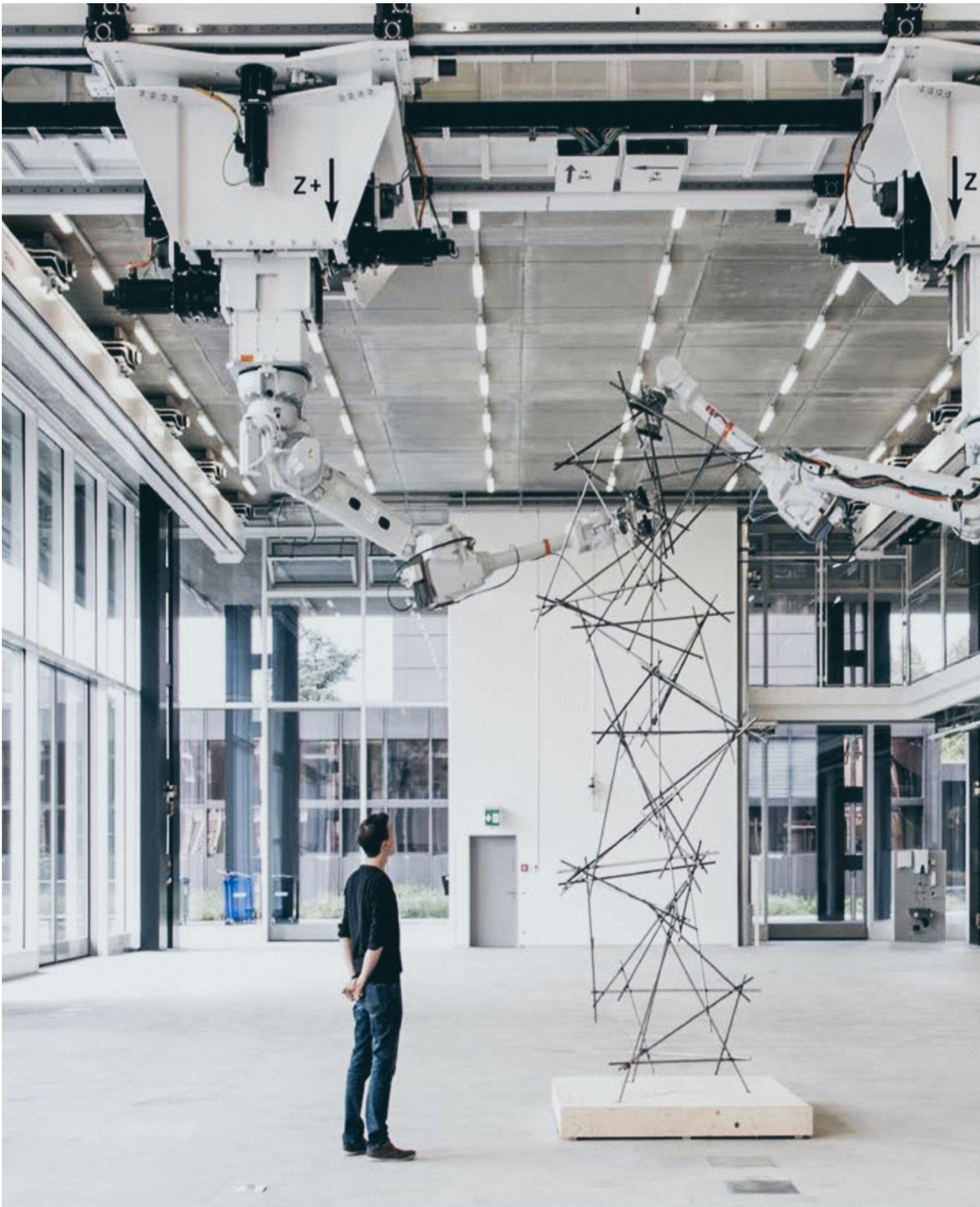



Fig. 10: Cooperative robotic assembly of a spatial metal structure


# ROBOTIC COORDINATION IN FABRICATION

Robotic Fabrication Lab (RFL) at ETH Zürich developed a novel construction approach to build a 4.2m tall structure comprising of 72 steel tubes of 16mm diameter. [31]

The project was a successful demonstration of robot's ability to build complex spatial structures by holding building materials in space, that could not otherwise be accomplished by humans without a reference point. The robotic trajectories were set up digitally through CAD to replicate in real-world, avoiding collisions while moving. Once positioned, robotic arms held the rods with nodes interlocked in space, allowing manual welding at the joints.

Currently, simulation parameters for robotic movement requires complex manual inputs. Hence, further automation can help simplify user interaction by understanding algorithmic function for robotic movements.

Other scopes lie in automating welding process and sensing spatial arrangement of the surrounding by robots to avoid collision and compensating tolerances (such as bent tubes).

*Fig. 11: Olafur Eliason's first completed building project. Kirk Kapital Headquarters in Denmark, completed in June 2018*

Another example of robotic coordination is **Robotic hot-wire-cutting** (RHWC) . It is a technique performed by controlling the curvature of hot-wire held by two six-axis robotic arms. This technique helps to create double-curved surfaces on objects by a single cutting procedure.[31]

Odico Formworks Robotics, founded in 2012, manufactures complex formworks for construction industry  cost-effectively with the help of robotics. Odico explored the implications of Robotic hot-wire-cutting (RHWC) of expanded polystyrene (EPS) form-work for concrete casting after a paper was published finding that RHWC reduced the machine time by a factor of 10-100 folds as compared to CNC robot milling.[32] (McGee,2012)

After continuous R&D and small scale installations, Odico's first milestone was achieved in 2013 when it received a commission to produce 4500m$^2$ of form-work for Kirk Kapital Headquarters in Denmark, designed by Olafur Eliason.

In test mock-up, Odico's EPS mold outperformed traditional wooden molds by staying true to its form under casting pressures, whereas the traditional form-work failed by deforming.

Commercially, Zaha Hadid Computation and Design Group got engaged with Odico to explore the potential of RHWC concrete. As a result, the team came up with a design for **Ultra High performance concrete** (UHPC) benches, installed at Winton Gallery of Mathematics at the Science Museum, London. Odico to explore the potential of RHWC concrete. As a result, the team came up with a design for **Ultra High performance concrete** (UHPC) benches, installed at Winton Gallery of Mathematics at the Science Museum, London. [33]

*Fig. 12: Benches, installed at Winton Gallery of Mathematics, Science Museum, London*

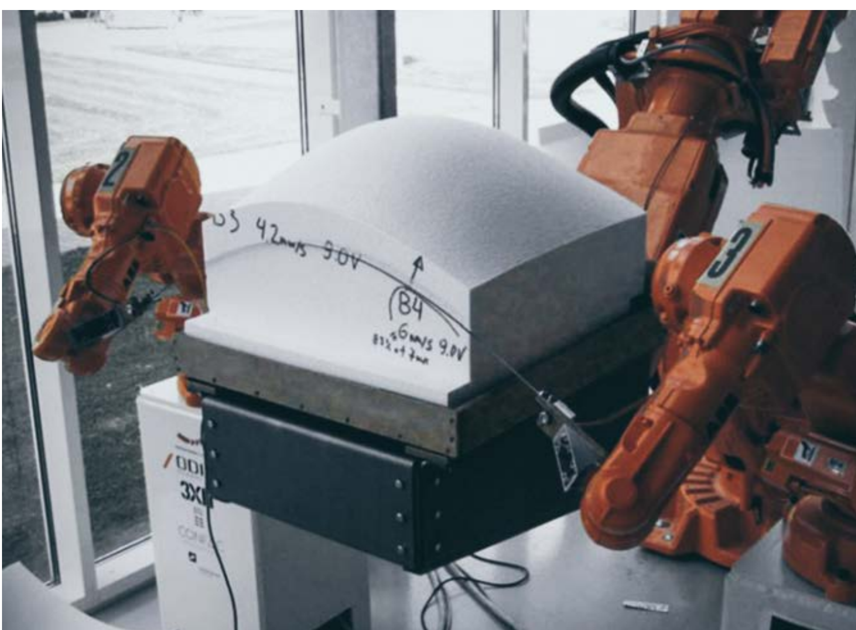


*Fig. 13: Experimental multi-robot cell deploying 3 ABB multi-move manipulators for production of doubly-curved geometries via sweeping of a flexible, heated blade along a surface.*

# CONCRETE AND METAL RE-IMAGINED

For numbers of decades, concrete and metal have been at the top of most used material in construction. And due to their abundance and easy process of form creation they have been used in an array of different roles from structure to facade, making them great candidates for the future of pre-fabrication. But in order to take a leap into the future with such material, they need to be elevated to what the future demands. In order for them to take on bigger roles, and more, they need to be re-defined, first in terms of material property; an upgrade on a molecular level, and second, they need to be manufactured with methods that are capable of double-curved production.[34]

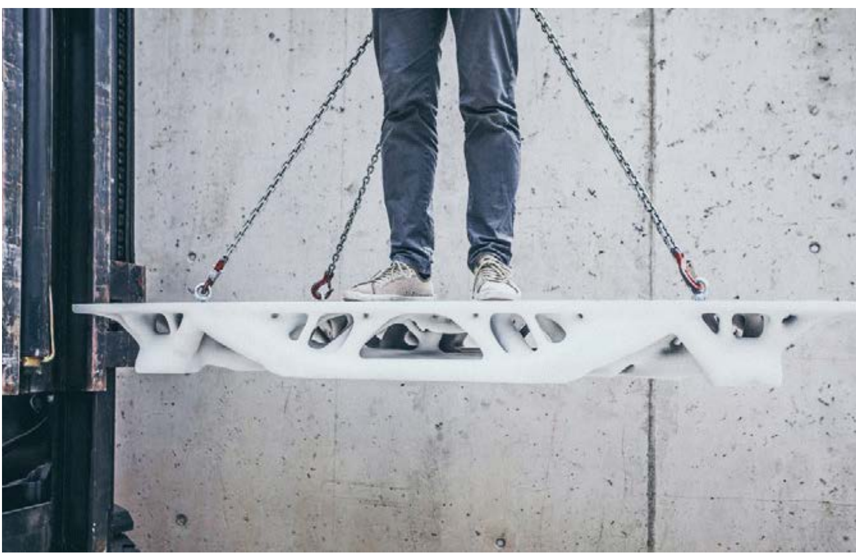


*Fig. 14: Composite building element with load-bearing, ETH Zürich*

**Strength**
Compressive: 17,000 to 22,000 psi, (120 to 150 MPa)
Flexural: 2200 to 3600 psi, (15 to 25 MPa)
Modulus of Elasticity: 6500 to 7300 ksi, (45 to 50 GPa)

**Durability**
Freeze/thaw (after 300 cycles): 100%
Salt-scaling (loss of residue): < 0.013 lb/ft3, (< 60 g/m2)
Abrasion (relative volume loss index): 1.7
Oxygen permeability: < 10-19 ft2, (<10-20 m2

*Americas Cement Manufacturers*[11]

*Fig. 15: Composite building element with load-bearing, ETH Zürich*

*Fig. 16: Steel Micro-Reinforcement*

# FUTURE OF CONCRETE

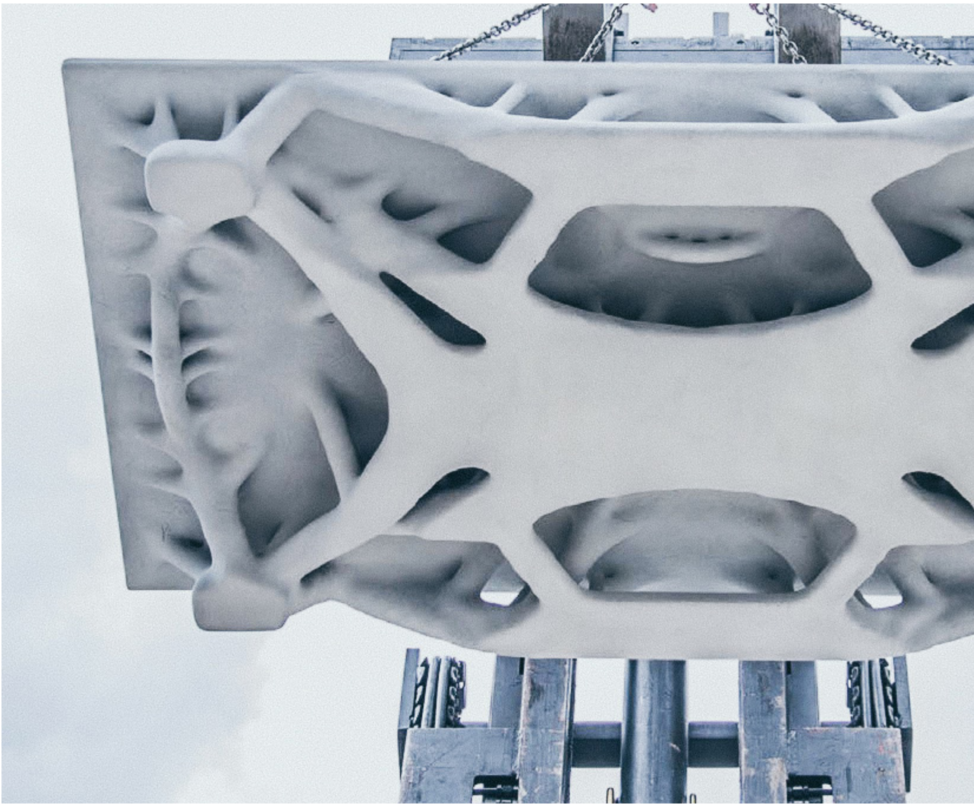
**Micro-Reinforced Ultra-High Performance Concrete (UHPC) Shell Structure**

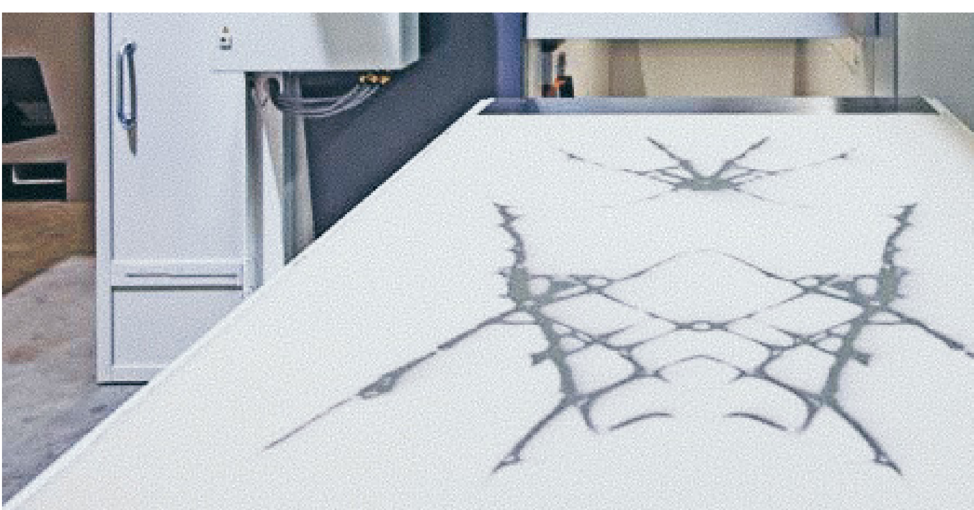
A cementitious composite material consisting of granular components, with a high percentage of internal fiber reinforcement, and water-to-cement ratio below 1:4 This is an excellent material to use for thin and double curved structures that could also have long spans; however, it is with the development of appropriate joining method that it becomes efficient. Futurist ideologies in digital manufacturing and computational design inspire alternative methods to achieve high efficiency by using different shapes. UHPC is one of a kind due its non-porous and compressive behavior, and the ability to join with press fitting and mechanical screws, it becomes a more desirable element to use as opposed to traditional concrete. Fiber-steel reinforced UHPC can transfer loads solely as a membrane force; therefore, slender elements can get the job done without the need of thousands of hours of form-work in traditional flexural concrete structures. The comparison of cheap materials used to produce concrete do not correlate with the high cost consisted of producing complex form-work; therefore, a re-examination of the building method is the key to a re-evaluation of concrete shell production. Due to the possibility of form-work made via hot-wire cutting, double curved elements can be more efficiently and precisely produced than traditional methods . Concrete shell structures will be assembled by joining elements that have been accurately prefabricated; therefore, the double curved space must get divided into a number of individual elements based on transportation constraints. The current process for making double-curved molds is to CNC-route the molds, which means long milling time for smooth

*Fig. 17: Final mock-up and steel connectors, Graz University of Technology*

*Fig. 18: Pixel/Pin field mold*

concrete results, and repeating the same process for each piece is extremely time-consuming and expensive as each mold is only used once. However, the use of a pin/pixel field type mold will allow for robot-controlled surface adjustment that can be changed after each use.[33]





**Additive Manufacturing (AM)**
In order to pre-fabricate large scale building components with highly detailed and complex geometry, AM is incorporated. By reducing material use and integrating technical infrastructure, AM appears to be an efficient futurist pre-fabrication method.
Through the use of sandstone substrate, AM can cast concrete in the most complex shapes imaginable. The more flexible the 3D printed sandstone form-work is, the more complicated the concrete shape can be. Using the method of binder jetting, an AM process for which a bonding agent in liquid form is dropped on thin layers of powder material (cement, plastic, ceramic, metals, sand, sugar, plaster,..) via a controlled path, in order to commence the pre-fabrication process. Furthermore, within a set bounding box (the size of the bed) increasing complexity in geometric shapes will not increase the cost or production time; at the same time, the powder beds acts as an auxiliary support for forms that cantilever or include interior structure. Tubular structures, undercuts, internal voids, and recesses are possible within the wide range of geometric flexibilities of 3D printed sandstone form-work. Such methods improve the idea of using 3D printing as a fabrication method for producing such intensely complex building components, this relates to both mass production components, and unique pieces for custom purposes. In order to

*Fig. 19: Composite building element with load-bearing capacity. Physical testing of the integrity of a ceiling prototype*

*Fig. 20: Final 3D stainless steel print connector*

scale this process up to larger masses such as a whole ceiling, there needs to be structures assembled from multiple pre-fabricated parts that can be bolted together.[35]

**3D Metal Printing as Structure**
A rapidly growing field, mostly for the benefit of structural technology for architectural purpose, is 3D metal printing. Metal has high performing strength , and the ability to form into desired shapes, and via computational design, such shapes could be structurally designed in a way that will minimize the risk of unnecessary overload. In addition, by understanding metallurgical processes, the material properties can be controlled to desired performance.

There are two methods of metal 3D printing; powder-bed fusion, and the deposition-based approach. In powder-bed fusion, the metal powder is sintered one layer at a time through methods such as electron beam melting and direct metal laser sintering, which are high energy methods in terms combustion resources. The deposition approach refers to a manner similar to continuous welding in air. Powder-bed fusion results in high-quality control and incorporation of powdered alloys with particle sizes as small as 45 microns, which can easily allow for high levels of customization. In contrast, the deposition approach results in a coarser finish, but allows for a larger building environment in comparison to the former approach. Metals such as titanium, stainless steel, and aluminum, are much more preferred for this purpose, as opposed to softer metals such as copper or bronze, and given titanium is a more expensive than stainless steel, it is more cost effective for this purpose, as cost in metal 3D printing is driven by the energy to melt, rather than gathering, the raw material.[36]

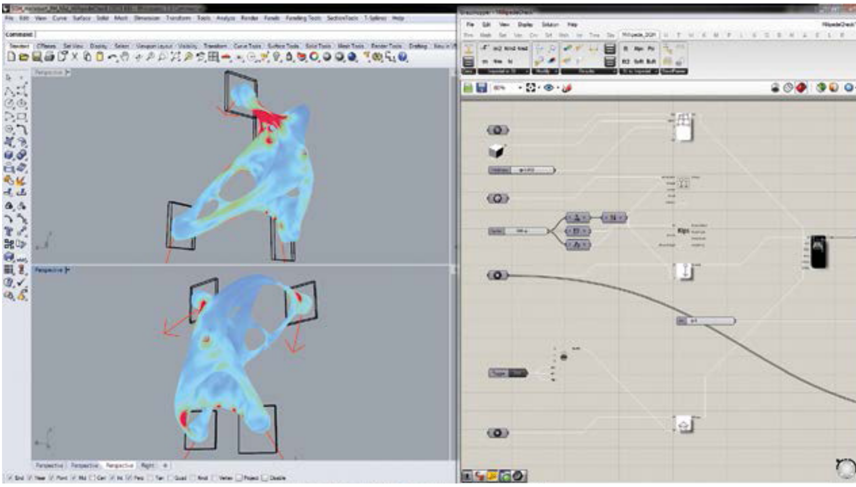


Fig 21: Wind forces and stresses on optimized model14

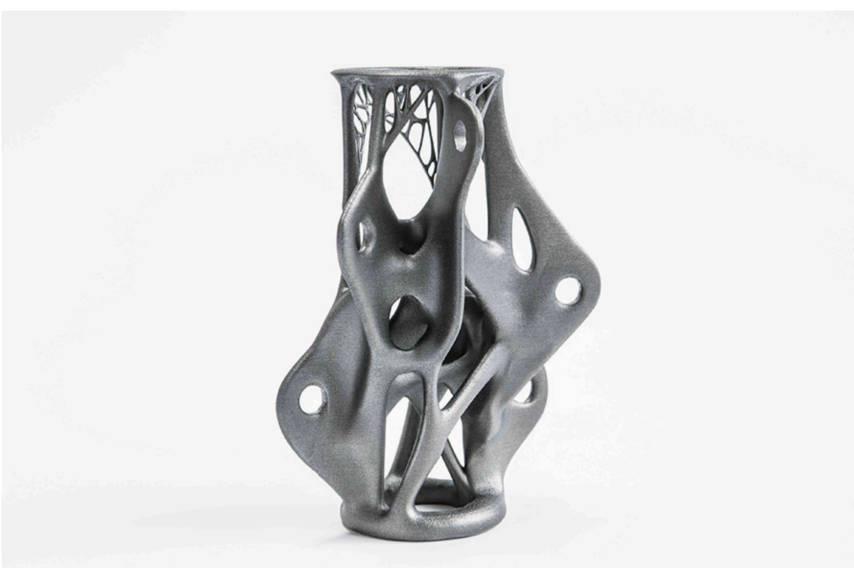


Fig. 22: Structurally designed metal piece

Fig. 23: NFL stadium featuring double-curved cladding system. courtesy, HKS Architects

# AUTOMATION IN FABRICATION WORKFLOW

This literature case study is based on an ongoing construction of an American football stadium called Los Angeles Rams Stadium in Inglewood, California. Designed by HKS architects for 'Kroenke Sports and Entertainment', the project is scheduled for completion by the end of 2019.[37]

The roof structure comprises of 70,000 unique panels, covering an area of 50,000sqft. of surface area.

These panels are fabricated through Zahner's proprietary ZEPPS' process using titanium anodized aluminum, cut by a 3-axis CNC die-punch machine.

Conventionally, a fabricator would be given a set of drawings by the designer with individual drawings for each panel. In this case however, in order to minimize file conversion and documentation of CNC fabrication of 70,000 different panels, an alternative approach was developed to avoid shop-drawings. A direct design - to - production method was adapted that helped avoiding exchange of CAD drawings as a form of communication, also eliminating chances of errors in the process.

Instead of having to rely on 70,000 different drawings of panels, a text-base file format would be adopted. Proper coordination was established by following a nomenclature and formatting of texts such that they could be automatically be translated into CNC

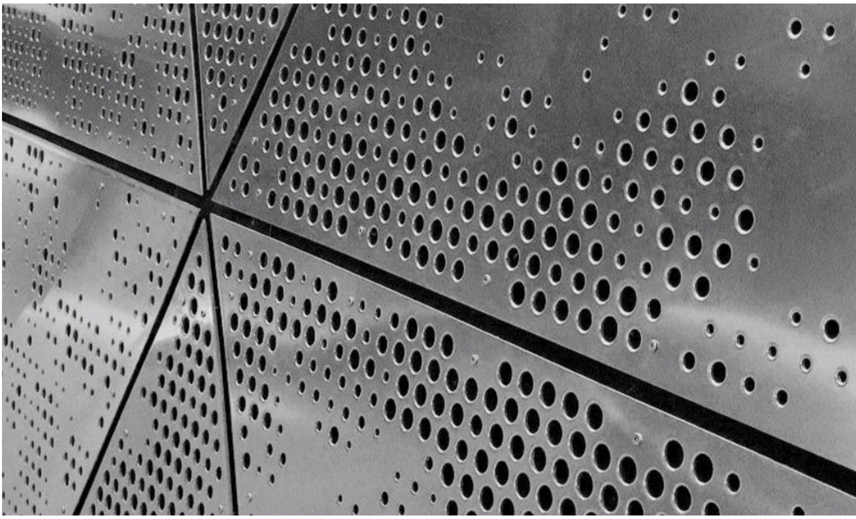


Fig. 24: Close up of aluminum panels showing coined die-punch perforation.

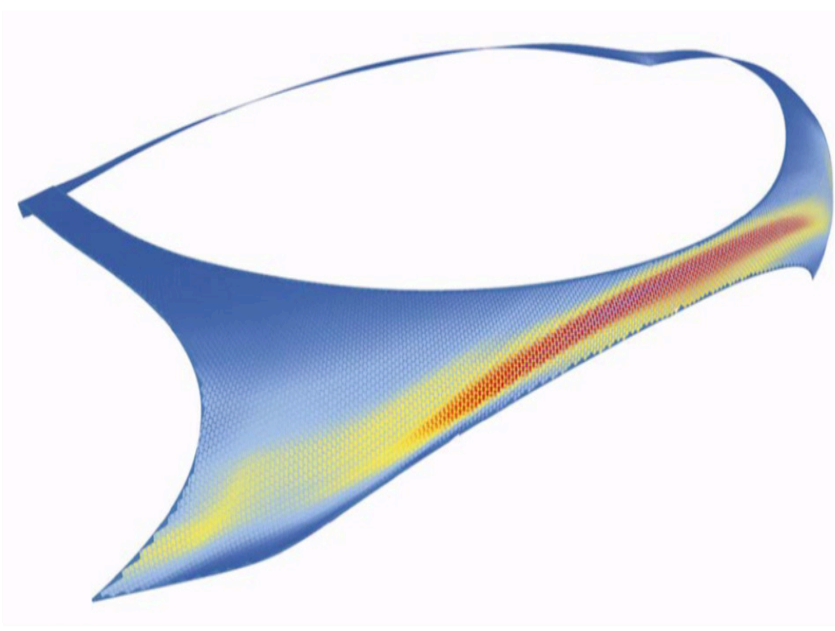


Fig 25: 274,962 square foot outer region of the stadium envelope comprised of approximately 35,000 panels. Heat map indicates deviation between panel normal and surface normal of design surface at node

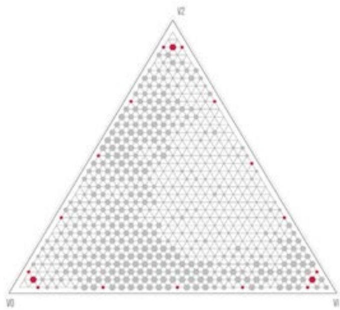



Fig. 26: Panel layout showing subdivision grid and image mapped perforations. Fixation points for ZEPPS framing vs. AM node with six branches are delineated in small and large red dots respectively.

machine instructions, without having to feed data manually.

The adopted work-flow was based on a customized C++ framework which implemented open source libraries such as Armadillo and Array-fire for GPU-based matrix operations and image processing.
This project successful demonstrated the effectiveness over visual based programming approaches such as Grasshopper for Rhino.

As computational design tools become more advanced, greater degrees of complexity in architectural fabrication are observed.

Fig. 27: Isolated structural bay showing substructure and framing strategy with continuous rolled extrusions along primary grid line and segmented straight framing members between

Fig. 28: View of SFMoMA east façade

# FRP COMPOSITE PANELS IN FABRICATION

Fiber-reinforced polymer (FRP) is widely used in European construction. San Fransisco Museum of Modern Art (SFMoMA), currently the largest museum of modern art in the US, was the first building to use FRP for exterior cladding in US. With the need for 710 unique panels for the building, FRP's primary advantages over alternatives such as metal, UHPC or GFRC was its cost effectiveness, high strength-to-weight ratio and its flexibility to mold into any shape.

The panels used in SFMoMA, weighed 3lbs/sqft., making them light enough to fix on aluminum unitized panels that were used as waterproof barriers. This allowed the FRP screens to be prefixed on the aluminum panels off-site, which made the on-site installation more convenient and faster. This method also helped in eliminating other factors such as installation of support system for rain-screens, reduced construction time, and reduced overall cost. Life-cycle studies by Stanford University also suggests that FRP had lesser environmental impact as compared to its alternatives, GFRC or UHPC.[38]

Fig. 29: A large CNC machine cuts blocks of EPS foam into the unique geometry of each SFMoMA panel.

Fig. 31: FRP being attached to unit at Mare Island.

Fig. 30: Mold surface being prepped prior to composite lamination

**Future of FRP**

FRP has been a reliable engineering material for decades, and is widely used by Aerospace, marine and military. Its ability to consolidate as one single monocoque material, as an alternative to assemblies of materials, (such as wood or metal) helped the Boeing 787 aircraft to reduced part count. Such composite structures are commonly used in industries where monocoque structures are routine.

FRP holds a possibility of bringing a new approach to construction industry by being able to create entire buildings by itself.

There has been recent updates by International Building Code (IBC) , recognizing FRP as a combustible material under section 2612. This bought a significant reduction of FRP in building construction. For one to use FRP, there shall be additional requirements of submitting various test certificates to the authority complying to IBC standards and wait for approval. However, successful completion of SFMoMA proves that going through this lengthy procedure does not have any negative impact on the project's cost and schedule. Also, using FRP systems helped save costs by eliminating the entire steel support frame (1,000,000 lbs).

Further studies to explore the structural possibilities for FRP composites in construction are required.

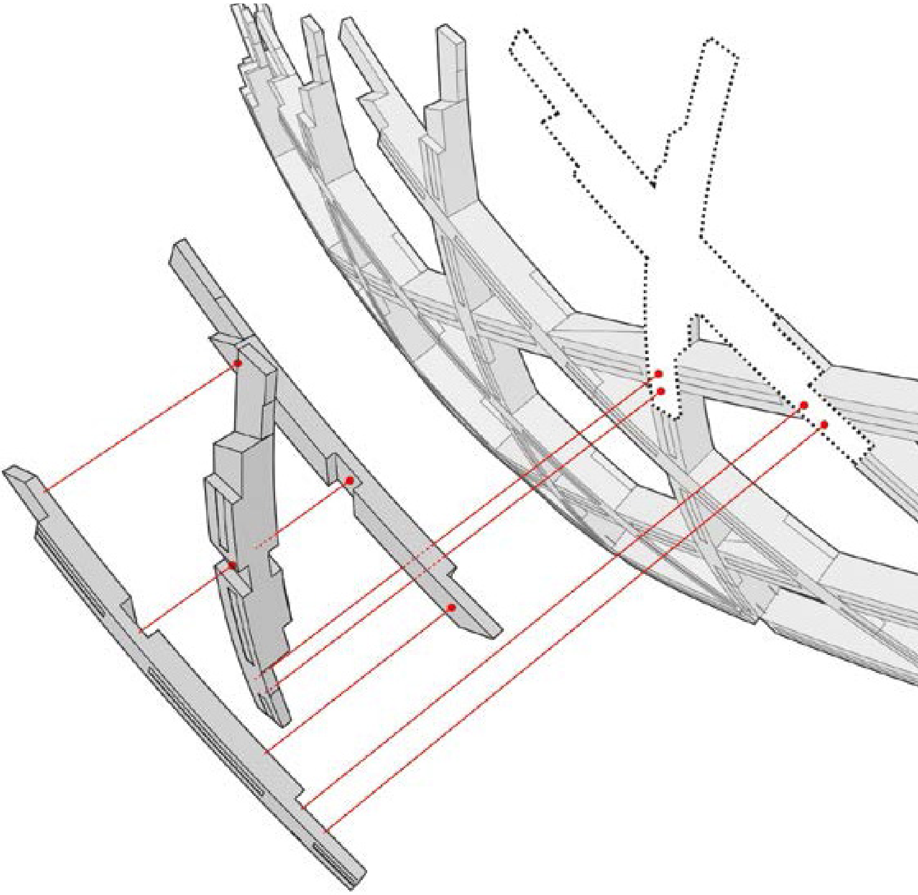

HELI

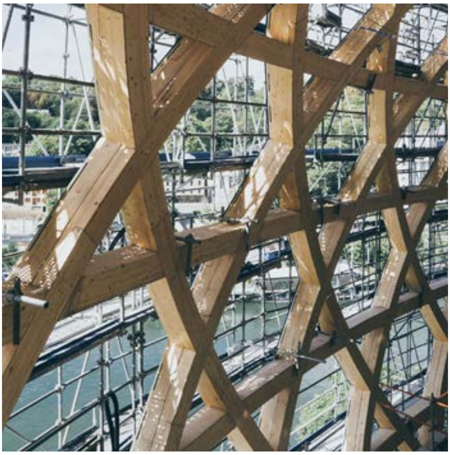
## STRATEGIES

**From Design to Assembly**

Using the capabilities of CNC routing, computational design software such as wood-pecker plug-in for grasshopper, and lamination techniques, an all wooden structure is possible for sizes larger than before, with higher efficiency in time and cost for a fully pre-fabricated process. With the option of creating doubly-curved components, in order for efficiency, double laminated timber could be allocated to structurally sensitive parts, and the material cut-off in addition to single laminated timber could be used for less tensile parts, hence following the exact geometry put together via the computational design software. Currently such work is possible, but due to high levels of customization by incorporating a free-form design, the conversion of formats and processes become too specialized to manufacture that exact project only, but with improved software integration, and trial and error, there could be an optimal balance between machine automation and manual control for such projects in the future. In order for such process to occur at the moment, there is need for integration of multiple software out-put for cutting in desired forms with or without curve with joinery undulation and finally assembly points where the components would be fastened together.[39]

*Fig. 32: The Seine Musicale by Shigeru Ban with diagonal segments during finishing after milling., Île Seguin, Paris, France*





Such integration causes loss of data since the fastening points are transferred from a flat environment to a 3D environment. But with additional progress in computational software such as wood-pecker the process could be done all in one, and fine-tuned for ease of use in the future.[18]

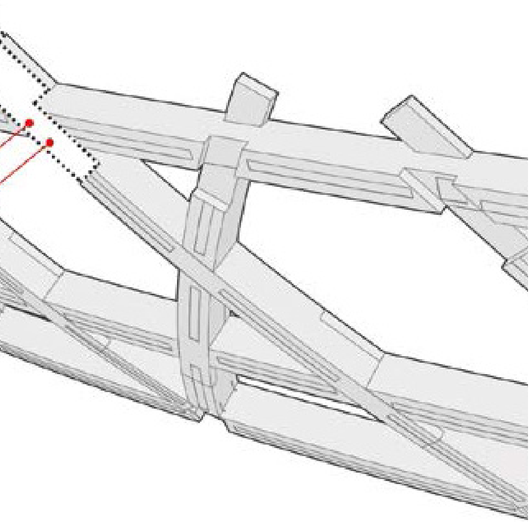


*Fig. 33: Assembly concept for the diagonals. To facilitate the central crossing, one of the legs forming the X has to be subdivided into two layers.18*

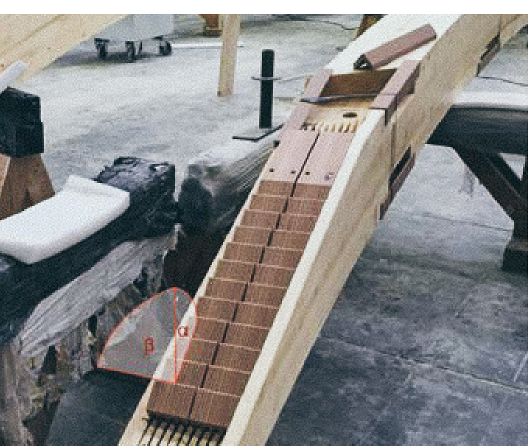



*Fig. 34: The longitudinal tension joint features toothed beech plywood inlays instead of steel plates. The joint can be engaged within the opening of the teeth.*

# CLT WITH ROBOTICS AND DIGITAL DESIGN

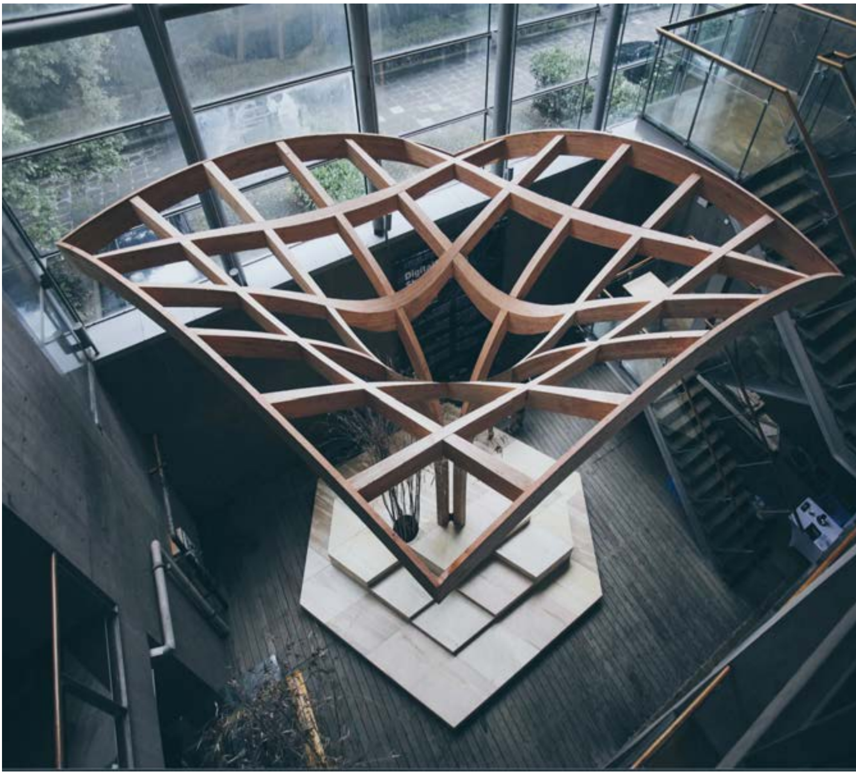


*Fig. 35: Final full-scale pavilion*

'Robotic wood tectonics', a 2016 project by DigitalFUTURE Shanghai, successfully produced complex geometries in wood with the help of robotic band saw machines, inspired by robot wire-cutting technology. This project was able to explore the extent at which this novel technology could be utilized in a large scale through mass customization.[40]

Recent building projects (such as 2010 completed Centre Pompidou Metz by Shigeru Ban) used CNC milling for their material production with immense support from Swiss consultants, 'Designtoproduction' . This required heavy technical support and complex data processing from design to production. Also, the amount of time and material invested was significantly higher. Robotic band saw fabrication however, allows direct design to production data transformation, which allows significant time reduction in the production stage,  also producing less wastes in material as compared to conventional CNC milling.

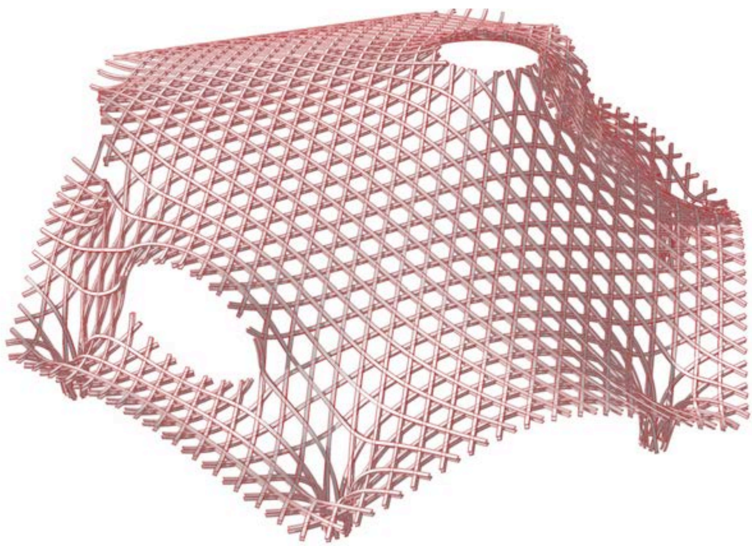


*Fig. 36: Digital design Assembly of Pompidou Metz structure.*

*Fig. 37: Pre-fab wooden elements, ready for assembly*

**Researched Projects**

Researchers from Greyshed and Princeton University (Johns & Foley, 2014), were first ones to write a paper, 'Bandsawn Bands: Feature-Based Design and Fabrication of Nested Free-form Surfaces in Wood',[41] that used robotic band saw machines. The machine cut curved strips to with double curved surfaces produced digitally. RMIT University (Williams & Cherrey, 2016) in a paper, 'Crafting Robustness: Rapidly Fabricating Ruled Surface Acoustic Panels',[42] studied the robustness in speed, accuracy and finish of robotic band saw cutting and demonstrates the feasibility of approach for the double curved wood surfaces.


*Fig. 38: Robotic band sawing of irregular flitch*

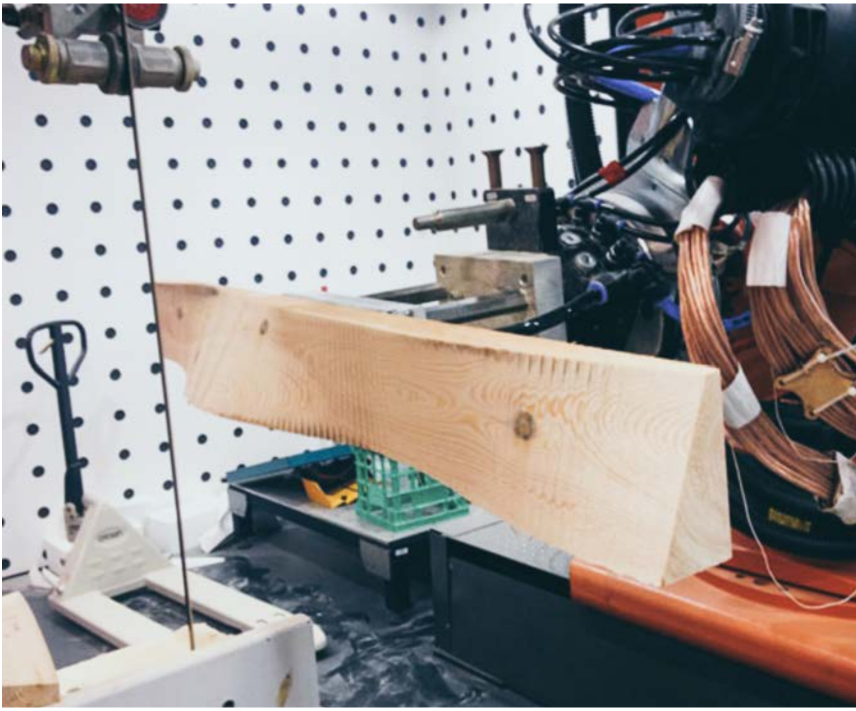


*Fig. 39: Robot and band saw pairing to cut laminated blanks*

*Fig. 40: Prototype panel showing 'wash boarding' from controlled deflection of the blade*


*Fig. 41 Site assembly. Image: Xie Zhenyu.*

Tonji University (Philip F. Yuan & Hua Chai ,2017)[43] questioned on the 'crisis of scale', as previous projects only worked on smaller scale constructions. They were able to fabricate a full-scale wooden pavilion by integrating material properties, structural constraints, digital design and robotics into fabrication process, and proved its feasibility with speed, accuracy and robustness on a larger scale.

A compression only structural form was developed in Rhinoceros plug-in Rhino-vault (Rippmann et al., 2012). While the Grasshopper plug-in Millipede (Michalatos & Kaijima, 2007) was used for form-finding and size optimization of wooden elements. Robotic movements were simulated in Rhino with the help

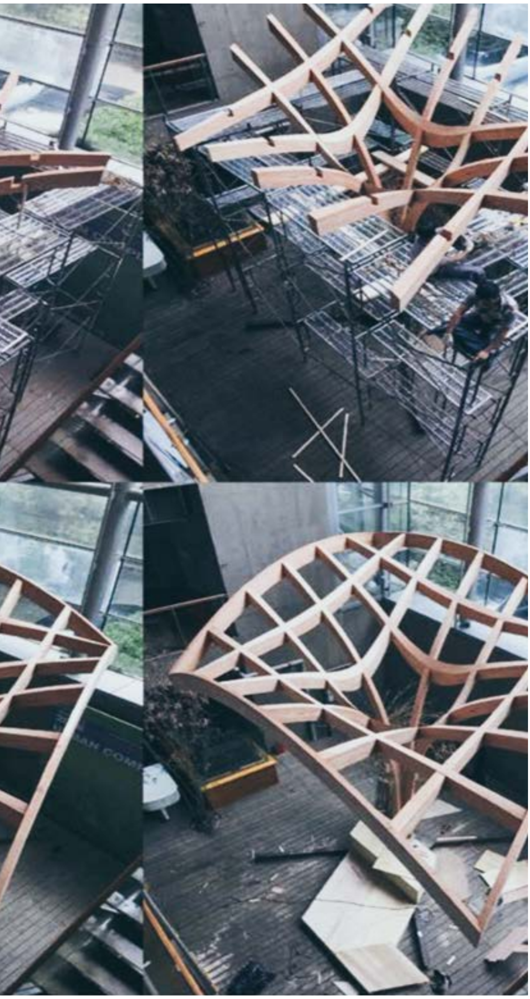
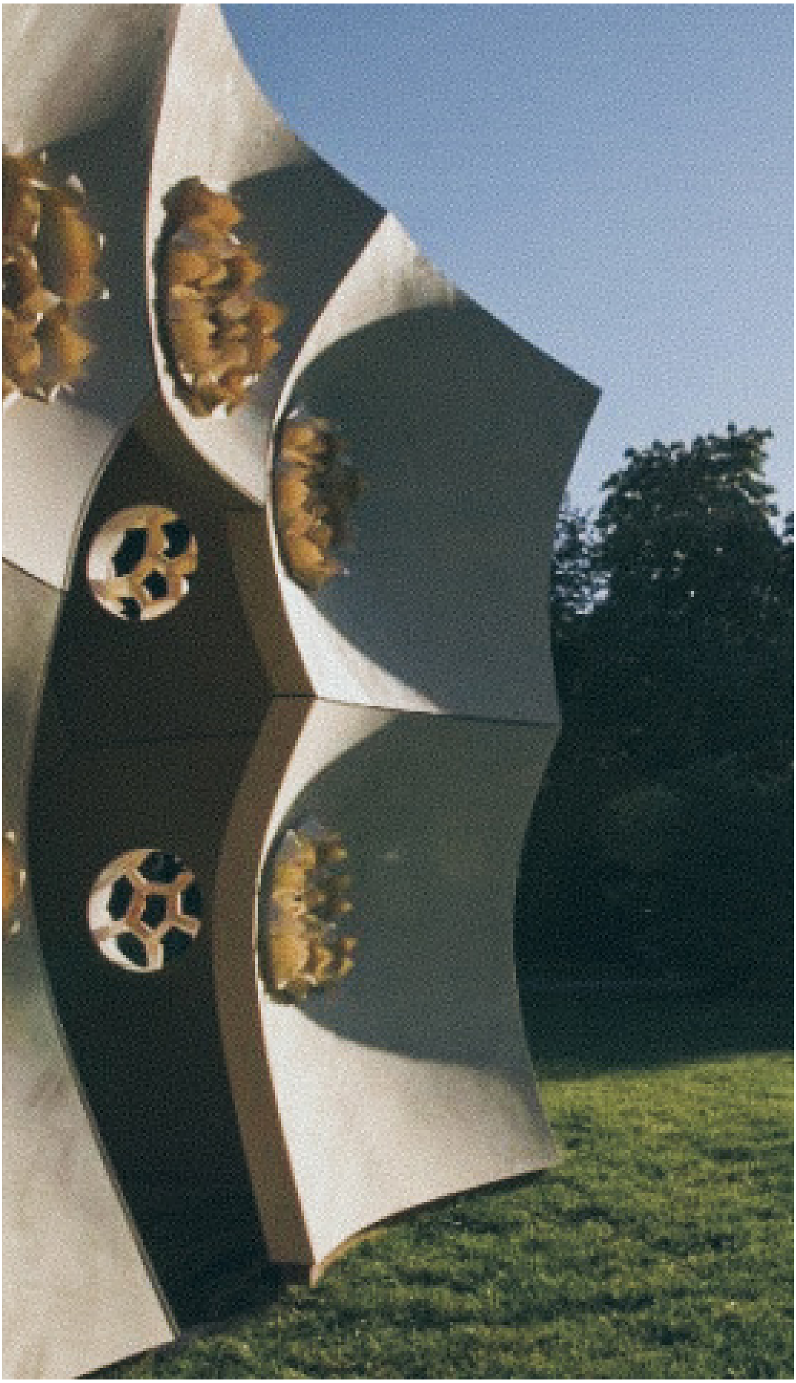
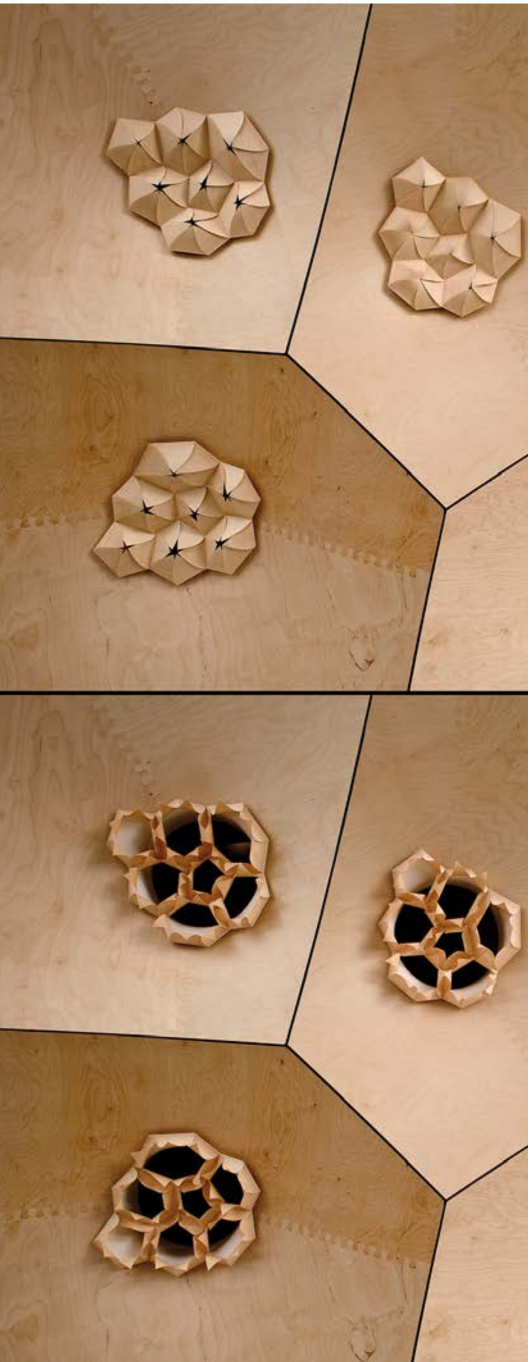


*Fig. 42: Robotic fabrication simulation*

of grasshopper plug-in KUKA PRC (Braumann & Brell- Cokcan, 2011). The robot covered 5-8m per hour on a beam, that proved to be significantly lesser than the conventional milling method.

Through integrating mortise-tenon joinery system, site assembly became easier. A team of five workers were able to assemble the structure in two days.





# FUSED FILAMENT FABRICATION

With the process of 3D printed prototypes and simultaneous material development, the future of Fused Filament Fabrication is on the rise. This concept studies manipulation of new composite materials to create architectural components capable of complex kinematic deformations in response to environmental conditions.

Currently, fused filament fabrication, with use of timber composites, multi-materials, and bi-metals, has gone through multiple processes of fabrication to be able to reach doubly-curved, shape-changing hygroscopic apertures capable of autonomous climate-adaptive kinematic response. But by using fibrous fillers, which will add to anisotropic properties in the structure of the material, there can be a design-oriented and computational method that allows for 3D printing stimulus-responsive materials(SRM) that are composite polymers and bio based, result in a multi-directional curvature with precise kinematic geometry. The main concept that allows SRM to shape change is to allow small expansion forces over a non-SRM substrate, and via the direction of expansion forces along a single axis, single curvature shape deformations become possible, but to achieve double curvature, the material needs to negotiate the interaction forces in multiple directions.

*Fig. 43: Hygroskin Pavilion*

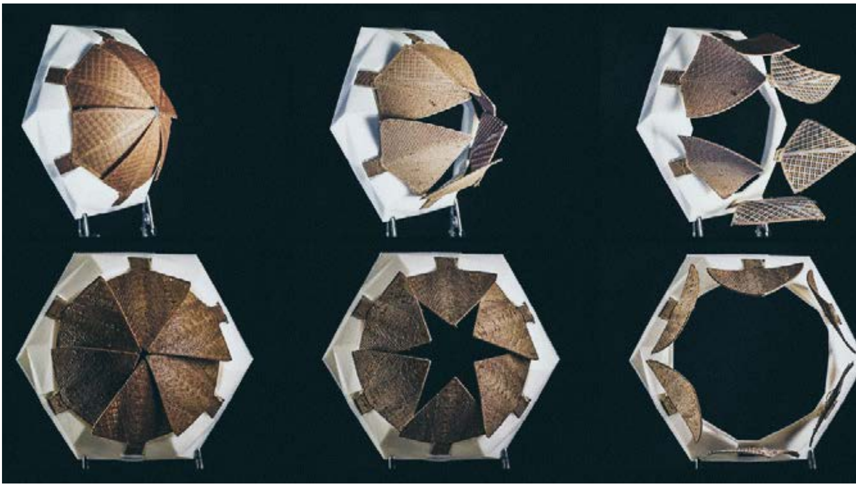


*Fig. 44: Multi-kinematic-state climate-responsive aperture time lapse shape change*

In order to achieve the double curvature in the hygroscopic-responsive SRM flap, a customized additive manufacturing process can be used consisting of two fused together components; the 3D printed SRM flaps with fastening support attachment, and the 3D printed non-responsive understructure that positions the flaps into the aperture. Eventually, the purpose is to have a dominant and secondary curling axis, for which the primary axis is responsible for the opening of the aperture, and the secondary axis facilitates the lateral expansion, concluding a double-curved shape.

When the aperture is closed, the double curvature deformation allows for a segmented dome geometry, and when the aperture is open, the flaps push each other further into a wider diameter. While there are several FF plastics available with some moisture expansion, acrylonitrile-butadiene-styrene appears to perform the best as a fusing element. Wood composite polymer and custom developed cellulose composite polymer can be used as SRM subjects, which are both dependent on fibrous cellulose or wood fillers for hygroscopic expansion. Such material construct allows for an increase in response pace and higher sensitivity, as there is increase in moisture absorption and desorption with two material involved rather than one.

The combination of wood composite and the polymer to bond the wood particles allowed for the pre-fabrication of a traditional primary material in a controlled and directed manner. Cellulose is currently the active hygroscopic component of wood, and this process basically replaces it with a new customized cellulose that allows for selectivity in performance properties, hence allowing for adaptive buildings where material is programmable.[43]

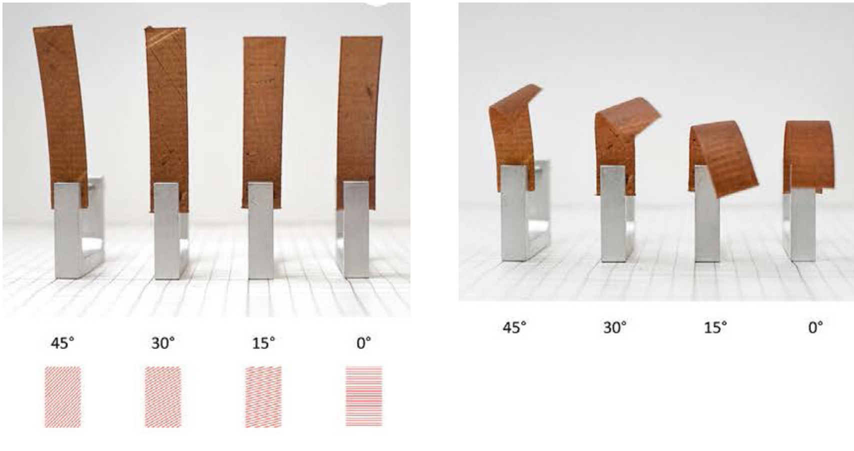




*Fig 45: Top, 3DP shape change curling direction in relation to material deposition angles (Correa, 2015)*

*Fig 46: Bottom, pine actuation and veneer bilayer system (Reichert, 2015)*

# 06

# Matrices of Evaluation

*Mackenzie Bruce*
*Marco Nieto*

**ABSTRACT**

The aim of this chapter is to evaluate the previous precedents and related materials under a variety of lenses. This chapter is to act as a reference for the future of pre-fabrication, evaluating systems and materials in existence as a way to continue to develop pre-fabrication. Specific precedents have been chosen and examined in further detail to assess their success as a pre-fabricated system or component.

The intent is to use this information moving forward in the design process as a way to inform the design. By evaluating the systems at hand, one can learn of the successes and failures of the past.

# CRYSTAL PALACE

JOSEPH PAXTON
HYDE PARK, LONDON, ENGLAND
1851

**Design Intentions**
Already renowned at the time the competition prompt was released for his aesthetically pleasing and pure glasshouses, Joseph Paxton proposed an enormous building made of pre-fabricated glass and iron components for the great exhibition hall.  Constructed in less than ten months due to its network of supporting structural systems that were derivative of the smaller and repetitive panels, the building would go on to host over six million visitors during its lifetime.

*Fig. 01 - Exterior elevation*

## EVALUATION CRITERIA

| | | | |
|---|---|---|---|
| TOTAL COMPONENT COST:<br>2 Million Euro | MATERIALS:<br>Iron and glass. | CONSTRUCTION TIME:<br>Less than ten months. | PROGRAM:<br>Great exhibition hall. |

| | |
|---|---|
| SUSTAINABILITY:<br>Since the building was covered almost entirely in glass, no artificial lighting was needed during the day, reducing the exhibitions running costs and energy usage. | MODULARITY:<br>Panels of glass allow for the building to be designed around a specific dimension. |
| TRANSPORT:<br>Pieces of glass were transported and assembled on site. | MASS:<br>The structure measured 456 ft by 1,848 ft, with a height of 62.25 ft to the nave and 108 ft to the top of the barrel vault. The entire area encompassed over 750,000 SF.[1] |

SYSTEMS:
Millions of glass panels (10" x 49") comprised the facade and the building was scaled around those dimensions. This reduced the production cost and time needed to install them. The issue with the design was leaks, as the sealant used was permeable. Another challenge was maintaining the temperature inside the Palace. Canvas shade cloths were installed and stretched across the roof ridges reducing heat transmission, moderate and soften light, and acted as a primitive evaporative cooling system when water was sprayed on them. Each of the modules that formed the outer walls of the building was fitted with a prefabricated set of louvers that could be opened and closed using a gear mechanism, allowing hot stale air to escape.

CONCLUSION:
The economies of scale allowed for the success of the project being cheap and easy, as each module was identical, prefabricated, self supporting and fast and easy to construct. Paxton hits all the marks for success of a pre-fabricated building. The module was simple, cheap and easy to produce. The building was designed with the manufacturing in mind. The module allows for buildings using this technique to be constructed at all scales. Issues for the building come with their energy efficiency and comfort as this has to be constantly maintained. Overall, the building was a successful form of pre-fabrication and a great exhibition of the technologies of the day allowing for advances in construction.

| CUSTOMIZABLE: | ECONOMIC SUCCESS: | DESIGN: | SUSTAINABILITY: |
|---|---|---|---|
| ●●●○○ | ●●●○○ | ●●●●● | ●●●●○ |

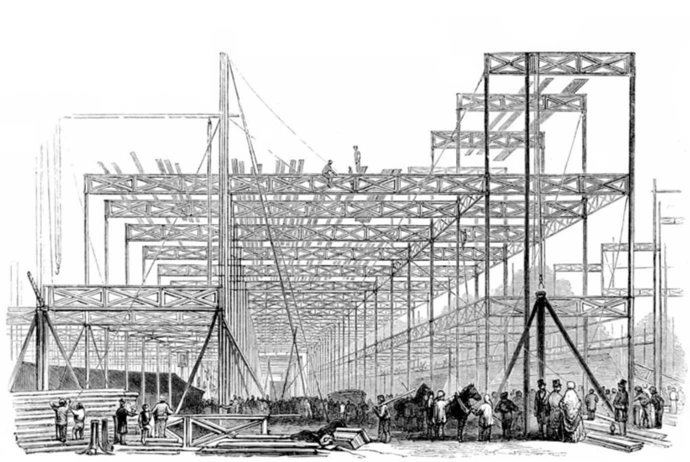


*Fig. 02 - Construction of the pre-fabricated structural elements*

# SEARS CATALOG HOMES

SEARS, ROEBUCK AND COMPANY
NORTH AMERICA
1908 - 1940

**Design Intentions**

Sears' Modern Homes were state of the art and revolutionary in the way that they could be purchased by consumers and delivered straight to them so that they could be self-assembled. Assembly was taken care of by the very homeowner without the need for a specifically trained crew of contractors. The houses also pushed towards normalizing advancements in new technology, such as central heating, indoor plumbing, and electricity. As a result, they became incredibly popular over the span of a few decades and could arguably be considered the best example of pre-fabricated architecture.

*Fig. 03 - Exterior elevation of  a Sears Magnolia*

| EVALUATION CRITERIA | | | |
|---|---|---|---|
| TOTAL COMPONENT COST: $360 – $2,890 (1908)[2] | MATERIALS: Precut framing timber + lumber, asphalt, plaster, etc. | TRANSPORT: Shipped in boxcars and then transported to site by truck. | PROGRAM: Residential houses. |
| MODULARITY: Various models were offered with varying levels of customizability. Sears offered both single-family residences and multi-family units. | | SYSTEMS: Sears homes featured typical systems, often introducing families to their first residence with HVAC, electricity, etc. | |
| CONCLUSION: Sears Homes were incredibly popular because of their revolutionary package that allowed consumers to take part in the assembly process. They offered an incredibly wide range of diverse models and the balloon framing of construction decreased the time of assembly by over 40%. | | | |
| CUSTOMIZABLE: ●●●●○ | ECONOMIC SUCCESS: ●●●●● | DESIGN: ●●●●○ | SUSTAINABILITY: ●●●○○ |

Fig. 04 - The Woodland House model


Fig. 05 - Modern Home model

# QUONSET HUT

GEORGE A. FULLER
RHODE ISLAND, USA
1941

**Design Intentions**

"In the early days of World War II, the United States Navy required all-purpose buildings that could be shipped anywhere and assembled without skilled labor. They also needed buildings that were lightweight for long distance portability reasons. Thus was born the Quonset hut. The practicality and convenience inherent in these buildings came into play in the early days of Future Buildings as the owner recognized that this same arch format Quonset design would transport well across Canada to service the First Nations reserves, loggers, fishermen and farmers with steel buildings."[3]

*Fig. 06 - Quonset Hut exterior*

**EVALUATION CRITERIA**

| | | | |
|---|---|---|---|
| TOTAL COMPONENT COST: 24ft x 24ft = $5,760 - $7,900 | MATERIALS: Corrugated galvanized steel. | MASS: 690 SQ FT | CLIMATE: Variable, all throughout the world. |
| ACCESSIBILITY: First used for military bases, the huts have to be accessible to house injured soldiers and various equipment. | | MODULARITY: Quonset Huts are easy to assemble since they come pre-punched and are easy to bolt together. Once assembled, they are also easy to expand if the need ever arises. | |
| TRANSPORT: Quonset Huts were usually put in place by a larger mechanical system, such as a crane. | | CONSTRUCTION TIME: Takes a very short amount of time to assemble, usually a day. | PROGRAM: Military base/single family home. |
| SYSTEMS: Quonset Huts are extremely bare bones, only structural. | | | |
| CONCLUSION: Quonset Huts prove to be both cost-effective and easy to assemble. The absence of obtrusive structural elements on the inside allow for the interior inside to be utilizes. It can also be designed with openings on either end for future additions. | | | |
| CUSTOMIZABLE: ●○○○○ | ECONOMIC SUCCESS: ●●○○○ | DESIGN: ●○○○○ | SUSTAINABILITY: ●●◐○○ |


*Fig. 07 - Quonset Hut installation*

# 8X8 DEMOUNTABLE HOUSE

JEAN PROUVÉ
BÉDARIEUX, FRANCE
1945

**Design Intentions**

"A visionary creator, Jean Prouvé came to architecture indirectly: the production of technically innovative housing components led him to overall building design and the honing of construction methods. The resulting principles were put to work in response to France's postwar reconstruction drive and the need for affordable, mass-produced housing. Commitment to reconstruction and research into the potential of the axial portal frame system had in fact begun in 1938, when the Ateliers Jean Prouvé patented a "demountable metal-frame structure" using an 8 sq meter module. The size was based on the capacity of the big bending press in the workshop, which machined 4-meter sheets of steel."[4]

*Fig. 08 - Exterior view*

<table>
<tr><th colspan="4">EVALUATION CRITERIA</th></tr>
<tr><td colspan="2">MATERIALS:<br>Metal and wood were primarily utilized to create a stable and easily manufactured structure.</td><td colspan="2">UPCYCLABLE:<br>The house could be used as tables or to repair machines.</td></tr>
<tr><td colspan="2">SUSTAINABILITY:<br>A majority, if not all, of Jean Prouve's work is pre-engineered and efficient in its material process.</td><td colspan="2">MODULARITY:<br>There are 6x6 meter versions all the way up to 24x8 meters. Wood panels can be substituted for glass. Examples of the pre-fabricated structure include timber panels mounted on a freestanding axial portal frame made of folded steel.</td></tr>
<tr><td rowspan="2">ACCESSIBILITY:<br>The building is lifted up what seems to be the height of a step or two, and there are no findings on a ramp, making it inaccessible.</td><td>MASS:<br>689 SF (8x8 meters)</td><td>CONSTRUCTION TIME:<br>Three people could assemble the house in one day.</td><td>PROGRAM:<br>One- room house.</td></tr>
<tr><td>CLIMATE:<br>Western European oceanic climate, which is overall mild and moderately wet throughout the year.</td><td colspan="2">TRANSPORT:<br>A single truck was all it took to transport the parts of the house.</td></tr>
<tr><td colspan="4">CONCLUSION:<br>The project is a great example of a small-scale single residence project that is easily made, easily transported, and could be assembled in a timely fashion to provide those in need of a home with one as fast as possible. The project truly represents Jean Prouvé's ideology that architecture should leave no trace on the landscape.</td></tr>
<tr><td>CUSTOMIZABLE:<br>● ○ ○ ○ ○</td><td>ECONOMIC SUCCESS:<br>● ○ ○ ○ ○</td><td>DESIGN:<br>● ● ● ● ●</td><td>SUSTAINABILITY:<br>● ● ● ● ●</td></tr>
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*Fig. 09 - Interior view*

*Fig. 10 - Interior view*

# DYMAXION HOUSE

BUCKMINSTER FULLER
WICHITA, KANSAS, UNITED STATES
1946

**Design Intentions**

The Dymaxion House was designed as a machine for living by Buckminster Fuller which was completed in 1945. The idea was that this modular house was inexpensive and could be built in only a few days with no special skills required. It came at a time post WWII where many young men were coming back from the war with no land, home or money. This design came because of the demand for housing. Everything inside this machine was automated. The design allowed for flexibility with the possibility for adding multiple units together for a variety of family sizes.

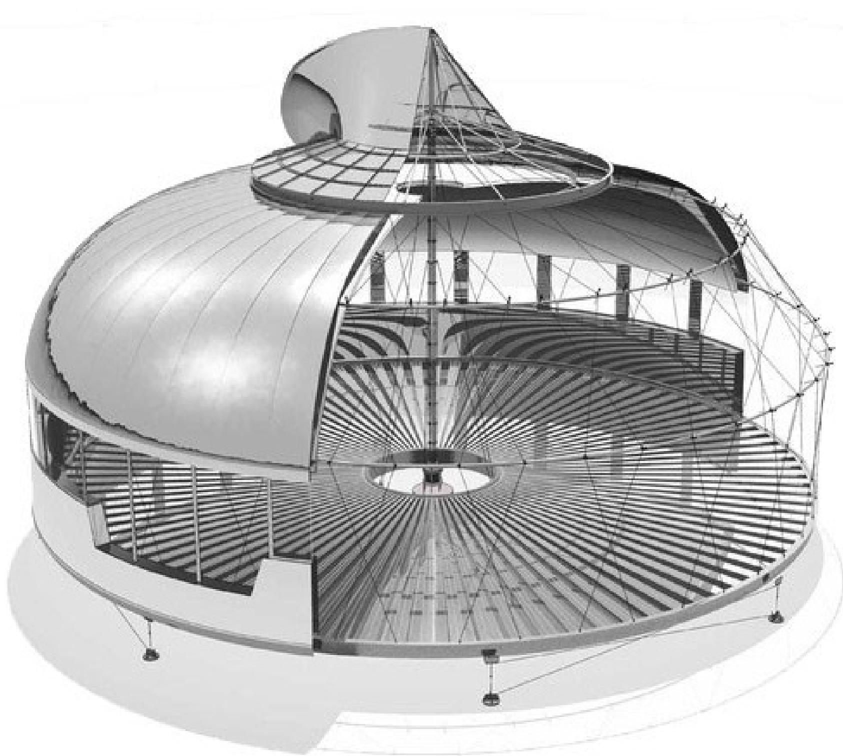

*Fig. 11 - Section perspective of structural system*

| **EVALUATION CRITERIA** | | | |
|---|---|---|---|
| TOTAL COMPONENT COST:<br>$6,500 per unit (1945) | MATERIALS:<br>Aluminum, lucite, plexiglass, metal alloys, plywood. | UPCYCLABLE:<br>Aluminum is easily recyclable and reusable. | |
| SUSTAINABILITY:<br>While aluminum is resource intensive to produce, it is recyclable and has little environmental effects once produced.[5] The design of the ventilation system allows for natural airflow through the home, reducing the energy demand. | | MODULARITY:<br>Combination of units is possible for large families. The single home itself is not custom, but specifically designed for the needs of the average user. | |
| ACCESSIBILITY:<br>The home is not accessible as it is raised off the ground with no ramp. | MASS:<br>3.75 lbs/SF<br>1600 SF<br>3 tons | CONSTRUCTION TIME:<br>Once delivered, the home can be built in 2 - 3 days by the buyer. | SCALE:<br>Single family home. |
| | CLIMATE:<br>All thermal climate types. | TRANSPORT:<br>Homes would be shipped in pieces weighing no more than 10lbs that homeowners could pieces together on site in a couple of days. | |
| SYSTEMS:<br>The central core housed all systems of the home leaving the facade free and open.[6] The home revolved around these systems. 18 ft wide hooded sheet metal ventilator controlled air flow within the building through air flow patterns. Plexiglass windows were inoperable because airflow allowed for natural ventilation. | | | |
| CONCLUSION:<br>The design allowed for families to purchase this relatively inexpensive home and assemble with ease on-site. The modularity allowed for young people to purchase the home and add additional units as their family expanded. Did not catch on because tradition ultimately prevailed. Homes began to be developed at a rapid rate, dramatically reducing the need for these homes.[7] | | | |
| CUSTOMIZABLE:<br>● ○ ○ ○ ○ | ECONOMIC SUCCESS:<br>● ○ ○ ○ ○ | DESIGN:<br>● ● ● ● ○ | SUSTAINABILITY:<br>● ● ● ○ ○ |

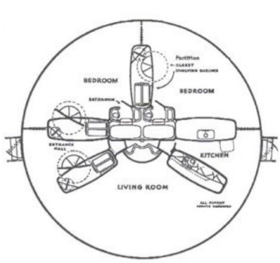


*Fig. 12- Plan view*

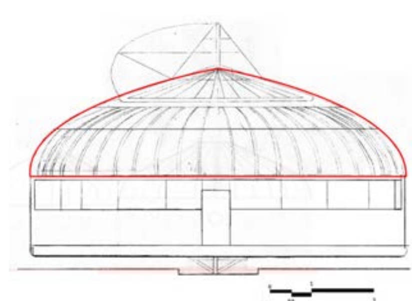

*Fig. 13 - Section*

# LEVITTOWN

LEVITT & SONS
UNITED STATES AND PUERTO RICO
1947 - 1970

**Design Intentions**

Levitt's idea was to build essentially identical houses to leverage the power of the assembly line. Each contracting job was standardized, so specialized labor efficiently moved from house to house completing their respective jobs. At the height of production, workers were finishing some 20 houses per day. Levittown put the American Dream within reach by bringing the assembly line to the site.[pg. 8-11]

*Fig. 14 - Aerial view of one of the seven Levittowns, specifically in New York*

| EVALUATION CRITERIA | | | |
|---|---|---|---|
| TOTAL COMPONENT COST: First sold for $7,990 with a 5% down payment.[8] | MATERIALS: Wood framing, drywall, etc. | MASS: Traditional single and double story homes. | CLIMATE: Mostly on the East coast with a few in Puerto Rico. |
| TRANSPORT: Precut parts were shipping on-site where they were then assembled. | | MODULARITY: Various models were offered with varying styles, some which were contemporary and West coast inspired.[9] | |
| CONSTRUCTION TIME: Multiple houses could be built in a single day. | PROGRAM: Residential houses. | SYSTEMS: Levitt houses came included with modern appliances and accessories which were meant to make daily life easier. | |
| CONCLUSION: Levitt provided mass housing at a low price, and gave thousands their slice of the American Dream. Those who were able to purchase their own home in such a development that they could not have otherwise are no doubt grateful to Levitt's ingenuity. Yet, taken to its logical extreme, mass production results in the monotony of the most efficient product repeated endlessly. Levittown is anti-architecture, drumming out creativity in favor of profitability.[pg. 13] | | | |
| CUSTOMIZABLE: ●○○○○ | ECONOMIC SUCCESS: ●●●●○ | DESIGN: ●●○○○ | SUSTAINABILITY: ●●◐○○ |


Fig. 15 - Variety of Levitt House models

# MOBILE HOME

VARIOUS DESIGNERS
UNITED STATES
1950

**Design Intentions**

"Originally meant to provide a shelter for those who are constantly on the move, the mobile home features a chassis with wheels attached that allow it to be moved freely, either from the factory to the site, or from location to location. The idea is that the mobile home can become either permanent of semi-permanent, and can be relocated as necessary according to codes and laws, giving the owner flexibility in their options."[10]

*Fig. 16 - Exterior elevation*

<table>
<tr><th colspan="4">EVALUATION CRITERIA</th></tr>
<tr><td>TOTAL COMPONENT COST:<br>$4,000 (1950).</td><td>MATERIALS:<br>Pre-painted aluminum panels.</td><td colspan="2">UPCYCLABLE:<br>Possible to recycle and reuse, but takes more effort.</td></tr>
<tr><td colspan="2" rowspan="2">SUSTAINABILITY:<br>"Some variations of the mobile home can claim a high degree of sustainability, which incorporate photo-voltaic arrays, passive solar water heating systems, tank-less water heaters, formaldehyde-free cabinets and insulation, qualified appliances, and natural linoleum flooring."[11]</td><td>CONSTRUCTION TIME:<br>Can be finished in 2 - 7 days.</td><td>PROGRAM:<br>Often designed for single-family situations.</td></tr>
<tr><td colspan="2">TRANSPORT:<br>Can be simply moved with a car or sometimes a larger professional truck service.</td></tr>
<tr><td rowspan="2">ACCESSIBILITY:<br>While mobile homes are typically lifted off the earth, there are accessible plans and arrangements available. These homes have wider doors, more open spaces, and they also feature ADA ramps for the entrance.</td><td>MASS:<br>Single-wides - < 18' x 90'<br>Double-wides - > 20' x 90'</td><td rowspan="2">SYSTEMS:<br>Mobile homes are loaded with similar, albeit smaller and more compact, HVAC and other systems. Either inside or directly connected outside.</td><td rowspan="2">MODULARITY:<br>Parts of the home are built in a facility to satisfy codes that are necessary for final assembly and placement.</td></tr>
<tr><td>CLIMATE:<br>Can be placed anywhere, regardless of climate.</td></tr>
<tr><td colspan="4">CONCLUSION:<br>Commonly seen as a symbol for the impoverished, the mobile homes stands as a great representation of the pre-fabrication model that provides all of the services and programs necessary for the user while offering a fast time frame and cost-efficient package.</td></tr>
<tr><td>CUSTOMIZABLE:<br>●●●○○</td><td>ECONOMIC SUCCESS:<br>●●●●●</td><td>DESIGN:<br>●○○○○</td><td>SUSTAINABILITY:<br>●◐○○○</td></tr>
</table>

*Fig. 17 - Mobile home park*

# CAPSULE TOWER

KISHO KUROKAWA
SHINBASHI, TOKYO, JAPAN
1972

**Design Intentions**

The Capsule Tower is a proud structure representative of the Japanese Metabolist movement, which became culturally popular after the war. Kisho Kurokawa designed the building with the intent of becoming a home for the traveling businessman who worked and came repeatedly to central Tokyo. The function informed the form, which is a sustainable and reusable module that locks into the main vertical core and can be replaced or moved by demand. The units are highly customizable to suit the needs of each user, and provide easy installation due to 4 high-tension bolts that provide the connection to the core.

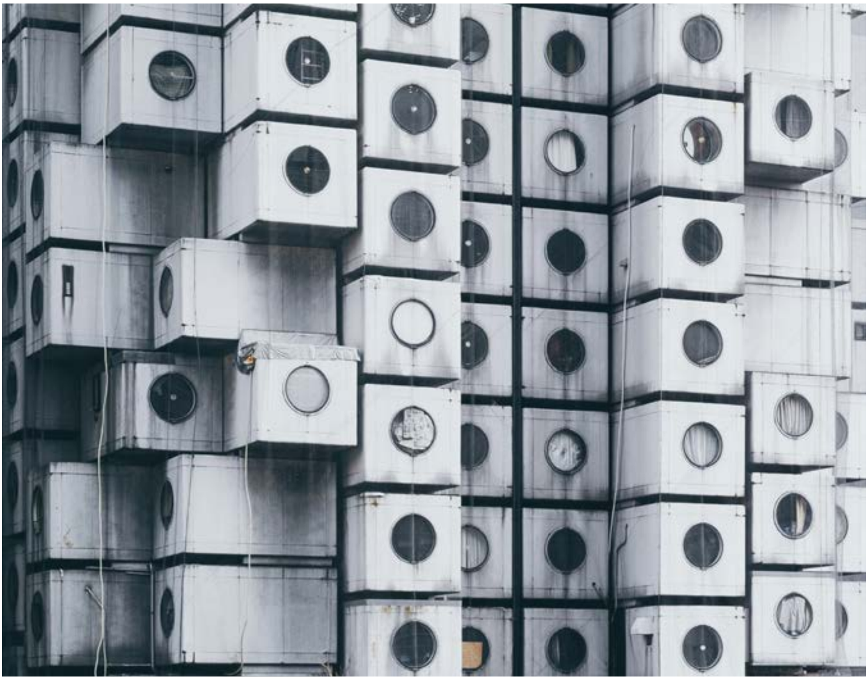

*Fig. 18 - Exterior elevation*

<table>
<tr><th colspan="4">EVALUATION CRITERIA</th></tr>
<tr><td colspan="2">MASS:<br>Each capsule measures 8.2 ft by 13.1 ft with a 4.3 ft diameter window at one end.</td><td>MATERIALS:<br>Steel frame and reinforced concrete.</td><td>CLIMATE:<br>Humid climate with hot summers and cool winters.</td></tr>
<tr><td colspan="4">MODULARITY:<br>The interior of the capsule reflects the exterior form. They all appear to be derivative of a box of varying dimensions and scales. They're free to be re-arranged and adjust to the users needs. Because of this simplified design, cost does not change proportionately to the amount of units.[12]</td></tr>
<tr><td rowspan="2">ACCESSIBILITY:<br>While nothing is directly stated about ADA and dimensions of the spaces, the building does feature two cores with elevators and straight-forward access to the individual units.</td><td rowspan="2">SUSTAINABILITY:<br>Each module can be plugged in to the central core and replaced or exchanged when necessary.</td><td>CONSTRUCTION TIME:<br>The entire building was completed in only 30 years.[13]</td><td>PROGRAM:<br>Two interconnected apartment towers, 11 and 13 floors tall, with 140 pre-fabricated capsules.</td></tr>
<tr><td colspan="2">TRANSPORT:<br>The modules were constructed in a nearby facility in the Shiga Prefecture and then moved to the site by truck.[14]</td></tr>
<tr><td colspan="4">CONCLUSION:<br>While a successful project that represents the Japanese metabolist style of architecture, the Capsule Tower has both potential and problems. The capsules haven't been maintained in over 30 years and only a percentage of them are being used today since so many are at risk, opening up discussions about its demolition. However, it's modular design that was easily replicated and fast to assemble and move was an impressive feat on its own, providing a good example of apartment units that can stylized to each individual.</td></tr>
<tr><td>CUSTOMIZABLE:<br>● ○ ○ ○ ○</td><td>ECONOMIC SUCCESS:<br>● ● ○ ○ ○</td><td>DESIGN:<br>● ● ● ● ○</td><td>SUSTAINABILITY:<br>● ● ◐ ○ ○</td></tr>
</table>

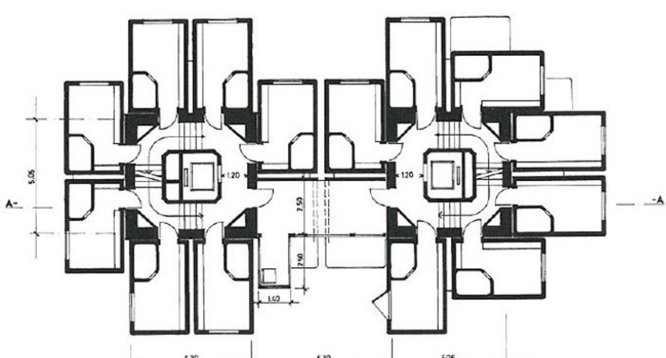


*Fig. 19 - Floor plan*

# MANUFACTURED HOME

VARIOUS DESIGNERS
UNITED STATES + AUSTRALIA
1976

**Design Intentions**

"Manufactured homes are at least 320 SF in size with a permanent chassis to assure transportability of the home. The original focus of this form of housing was its ability to relocate easily. Units were initially marketed primarily to people whose lifestyle required mobility. Beginning in the 1950s, these homes began to be marketed primarily as an inexpensive form of housing designed to be set up and left in a location for long periods of time, or even permanently installed with a masonry foundation. Since then, they became even longer and wider than the original 10 ft wide model, restricting the mobility of the units. Now, it is usually kept there permanently."[15]

*Fig. 20 - Exterior elevation of a manufactured home*

<table>
<tr><th colspan="4">EVALUATION CRITERIA</th></tr>
<tr><td>TOTAL COMPONENT COST:<br>~$50,000 for a single.</td><td>MATERIALS:<br>Steel chassis, wood structure, siding, wheels, etc.</td><td>MASS:<br>320 SF <</td><td>PROGRAM:<br>Typically a single family residence.</td></tr>
<tr><td colspan="2">SUSTAINABILITY:<br>"High-performance manufactured home models are functional, water-efficient, resilient to wind, seismic forces, and moisture penetration, and have healthy indoor environmental quality. Achieving high-performance involves integrated building design, involving many components, not just one."[16]</td><td>TRANSPORT:<br>Like the mobile home, wheels attached to the house's chassis allow for easy transport.</td><td>CLIMATE:<br>Can be placed anywhere, regardless of climate.</td></tr>
<tr><td colspan="4">CONCLUSION:<br>As a result of being held to a high standard and forced to go under several inspections, the manufactured home is a successful example of a pre-fabricated structure that checks nearly every box. It can also cost $0.10 - $0.30 less per SQ FT than on-site construction.</td></tr>
<tr><td>CUSTOMIZABLE:<br>● ● ● ○ ○</td><td>ECONOMIC SUCCESS:<br>● ● ● ● ●</td><td>DESIGN:<br>● ○ ○ ○ ○</td><td>SUSTAINABILITY:<br>● ● ● ○ ○</td></tr>
</table>

*Fig. 21 - Example of a modern manufactured home*

# BLU HOMES

BILL HANEY + MAURA MCCARTHY
SAN FRANCISCO, CA
2007

**Design Intentions**

"Blu Homes was started as a two-year research study at Massachusetts Institute of Technology and Rhode Island School of Design on how to use technology to revolutionize the way we build green homes. I tested this on my own ecologically protected property with our first homes, which were designed online in 3-D and precision-built with steel, installed in one inspiring day and each finished in a week. Since then Blu has been building high-quality, green homes for families across North America. Our goal is to make it easier and more fun for our clients to design and build beautiful, spacious, light-filled homes that bring the outside in."
—Bill Haney, Founder and President[17]

*Fig. 22 - Breezehouse project*

**EVALUATION CRITERIA[18]**

| | | | |
|---|---|---|---|
| TOTAL COMPONENT COST:<br>Base Price: 185-285($/SF)<br>$155K-665K per home. | MATERIALS:<br>Steel frame. | UPCYCLABLE:<br>Steel frame is recyclable. | |
| SUSTAINABILITY:<br>Energy efficient and eco-friendly materials used. The compact size of the units allows for less energy consumption post construction. Factory construction enables a greener building process protected from the elements. | | MODULARITY:<br>Modularity allows for bedroom number expansion and additional pods to site. Multiple models to choose from (Breezehouse, Sidebreeze, Origin, Glidehouse, Lofthouse, Balance, Breeze Aire, Element). Custom built in factory, allows buyer to choose features specific to their needs. | |
| ACCESSIBILITY:<br>Most modules are single level homes making the main areas wheelchair accessible, although narrow corridors and compact rooms make the rest of the home inaccessible. | MASS:<br>Varies dependent on module. Breezehouse: 2,871 - 3,002 SF, 67'-9" x 64'-7" | CONSTRUCTION TIME:<br>6 - 8 weeks. | SCALE:<br>Typically single family homes. |
| | CLIMATE:<br>All, designed for extreme weather conditions; winds, snow, seismic, challenging soil and marine moisture. | TRANSPORT:<br>Components of the home are able to fold onto a standard truck for shipping to the site. | |
| SYSTEMS:<br>Steel framing technology provides incredible strength, quality and durability. High efficiency forced air, radiant heating, and mini split HVAC systems with high seasonal energy efficient ratings (SEER). Low flow fixtures for water efficiency. Steel frame has highest strength to weight ratio, produces less waste (2% vs. 20% for lumber) and is recyclable. Energy efficient CFL and LED lighting options available. Rigid foam provides a tight air seal and radiant barrier. Bamboo, Cradle to Cradle certified engineering hardwood and reclaimed wood flooring options. Oriented passive solar siting. Overall, Blu homes are typically 50% more efficient than average existing homes. | | | |
| CONCLUSION:<br>Blu homes have an abundance of energy efficient features, an important factor in both saving costs and having a low environmental impact. The modularity allows buyers to customize their homes to their specific needs and style through an online 3-D configurator. Blu homes are upfront about the total cost of building as well as a more exact timeline for construction as weather considerations are almost non-existent with in-factory construction. Where Blu homes lack is in their affordability. The price of these homes does not include transportation, site foundation, utility hook-up or land cost, making them an expensive alternative to the traditional on-site home. The Blu home has built over 300 homes to date. | | | |
| CUSTOMIZABLE:<br>●●●●● | ECONOMIC SUCCESS:<br>●●○○○ | DESIGN:<br>●●●●○ | SUSTAINABILITY:<br>●●●●○ |

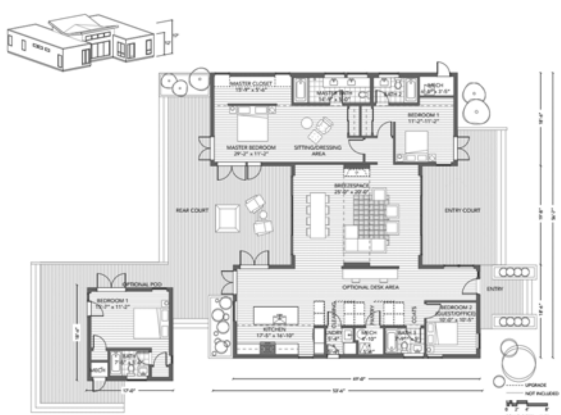

*Fig. 23 - Breezehouse 3 bedroom and library plus optional pod plan*

# AXE QUATRE ARRONDISSEMENTS

POST-OFFICE ARCHITECTS
PARIS, FRANCE
2016

**Design Intentions**

The 900 SF single barrel-vaulted volume was laid out along the building's axis. The space is supported by four pre-assembled wooden arcs that allow for large open ends with views to the Boulevard de La Villete and the other across the city with the Eiffel Tower in sight. The barrel-vaulted ceiling is clad in insulated wooden panels while the exterior is clad with corrugated metal that blend in with the Parisian sky. The building was pre-fabricated and assembled in a factory, including the interior wood and exterior metal cladding, the insulated wooden panels, and the timber terrace floor. The design includes operable glass sections that allow for natural ventilation and solar panels on the roof.[pg. 88]

*Fig. 24 - Interior view*

**EVALUATION CRITERIA**

| | | | |
|---|---|---|---|
| TOTAL COMPONENT COST:<br>$220,000. | MATERIALS:<br>Insulated wood, metal cladding, and terrace floor. | MODULARITY:<br>All parts of the building were prefabricated and assembled in a factory. | |
| ACCESSIBILITY:<br>There is one single staircase that leads from the third floor apartment to the roof addition. | MASS:<br>900 SF. | CONSTRUCTION TIME:<br>The total on-site assembly took only 15 days. | PROGRAM:<br>Photographic studio + living room. |
| | CLIMATE:<br>Western European oceanic climate, which is overall mild and moderately wet throughout the year. | TRANSPORT:<br>Shipped on a truck to the site. | |
| CONCLUSION:<br>Although it took roughly five years from the planning phase to completion[19], Axe Quatre Arrondissements is an example of a successful small scale program that isn't a residential typology. The solution to creating more space on a roof is also an interesting solution that could potentially be applied to high density urban fabrics with limited square footage. | | | |
| CUSTOMIZABLE:<br>● ○ ○ ○ ○ | ECONOMIC SUCCESS:<br>● ○ ○ ○ ○ | DESIGN:<br>● ● ● ○ ○ | SUSTAINABILITY:<br>● ● ● ◐ ○ |

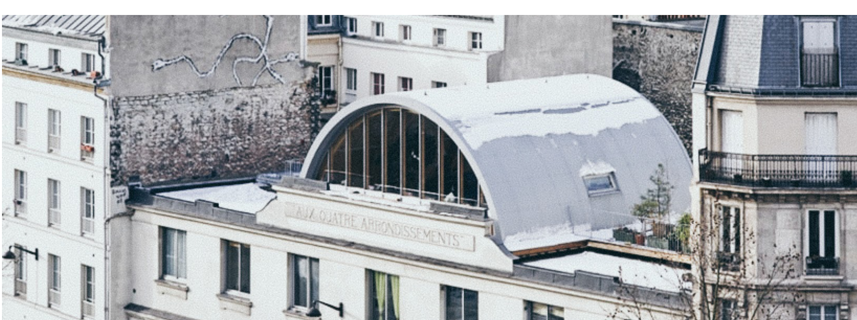


*Fig. 25 - Exterior view*

# TRUE NORTH - QUONSET HUT

EC3
DETROIT, MICHIGAN
2017

**Design Intentions**

"Open to the neighborhood and without fencing, the community is accessible from the street via three pathways. The strategic placement of the huts is driven by a need for openness and security, views and privacy, socializing and solitude. Within the community, pathways connect visitors to the eight huts, the communal pavilion, gardens and eight parking spots (alongside the back alley). Each pre-fabricated steel Quonset Hut is assembled on top of a four-inch radiant heat, which is also the finished floor. The end walls feature custom steel framing around polycarbonate panels that provide a higher level of security, natural light and high thermal volume."[20]

*Fig. 26 - True North Neighborhood of Detroit, MI*

## EVALUATION CRITERIA

| | | | |
|---|---|---|---|
| TOTAL COMPONENT COST: $1.6 million. | MATERIALS: Corrugated galvanized steel, polycarbonate, plywood. | MASS: 10 units at 475 - 1,600 SF each, 25,117 SF site.[21] | CLIMATE: Located in a heating dominated climate. |
| ACCESSIBILITY: Multi-floor units do not have an accessible route to all spaces. The compact size of the unit does not allow for the space to have the turning radius required for a wheelchair. | | MODULARITY: Variety of layouts available to accommodate a greater diversity of lifestyles to exist within the community. | |
| TRANSPORT: Steel arches prefabricated and constructed on-site. | | CONSTRUCTION TIME: The entire development was built in less than a year. | PROGRAM: Multiple single family homes in a single development as well as two flexible event spaces. |
| SYSTEMS: Corrugated galvanized steel forms a semi-circular barrel-vaulted volume. Polycarbonate 'island' contains a kitchen, bathroom and mechanical/storage space. | | | |
| CONCLUSION: The entire site creates a sense of community through pre-fabrication, even though it may appear minimal. Each hut is a standard residential unit, but through the carefully thought out layout and considerations, they begin to create secondary and tertiary spaces, such as community gardens, play zones, and event space. The galvanized steel arches are factory made, yet individually pieced together on site. | | | |
| CUSTOMIZABLE: ●●●○○ | ECONOMIC SUCCESS: ●●○○○ | DESIGN: ●●○○○ | SUSTAINABILITY: ●●●○○ |


*Fig. 27 - Variety of units in True North*

# MARKET SUCCESS

| | DATE | NUMBER MANUFACTURED | CONSTRUCTION TIME | COST (USD 2018) | CO SQUA |
|---|---|---|---|---|---|
| CRYSTAL PALACE<br>London, England | 1851 | 1 | 1 YEAR | 68.7 M | 89 C |
| SEARS CATALOG HOMES<br>United States | 1908-1940 | 70,000+ | KIT SELF BUILT BY HOMEOWNER | $26,670 (MODEL 125) | $26 (MOI |
| QUONSET HUT<br>Rhode Island, USA | 1941 | 150,000 - 170,000 | 100% PRE-FABRICATED | $5,760 - $7,900 | $8 |
| 8X8 DEMOUNTABLE HOUSE<br>Bedarieux, France | 1945 | 1 | 1 Day | N/A | |
| DYMAXION HOUSE<br>Wichita, Kansas, USA | 1946 | 1 | SELF BUILT IN 2 - 3 DAYS | $91,700 | $5 |
| LEVITTOWN<br>Levittown, NY, USA | 1947 | 17,447 | 20 HOUSES IN ONE DAY | $84,503 | $11 |
| MOBILE HOME<br>USA | 1950 | 3 MILLION+ | 2-7 DAYS | $40,000 | $30 |
| CAPSULE TOWER<br>Tokyo, Japan | 1972 | 160 CAPSULES | 30 DAYS | $54,200 PER UNIT | $5 |
| MANUFACTURED HOME<br>USA | 1976 | N/A | 2 DAYS | $53,900 | $ |
| BLU HOMES<br>San Francisco, CA, USA | 2007 | 300 | 6-8 WEEKS | $155K - 665K | $185 - |
| AXE QUATRE ARRONDISSEMENTS<br>Paris, France | 2016 | 1 | ON SITE ASSEMBLY: 15 DAYS | $220,000 | $2 |
| TRUE NORTH QUONSET HUT | 2017 | 150,000-170,000 | LESS THAN 1 YEAR | 1.6 MILLION | $1 |

| T 018) | COST PER SQUARE FOOT | MEDIAN HOUSEHOLD INCOME (USD 2018) | PROGRAM | ECONOMIC SUCCESS | OTHER FACTORS |
|---|---|---|---|---|---|
| M | 89 CENTS/FT$^2$ | N/A | EXHIBITION HALL | ●●●○○ | The singular module expedited construction, reducing labor cost. |
| 70 125) | \$26.70/FT$^2$ (MODEL 125) | \$19,400 | SINGLE FAMILY HOME | ●●●●● | Over 370 home designs were offered. They were inexpensive in a time of economic prosperity. |
| $7,900 | \$8.34/FT$^2$ | \$35,300 | MILITARY BASE/SINGLE FAMILY HOME | ●●○○○ | The huts were designed and manufactured for the US Navy. Surplus were sold as homes after the war. |
| A | N/A | N/A | SINGLE FAMILY HOME | ●○○○○ | |
| 00 | \$57.31/FT$^2$ | \$33,800 | SINGLE FAMILY HOME | ●○○○○ | The design went against cultural norms and soon after the mobile home was introduced to the market. |
| 03 | \$112.67/FT$^2$ | N/A | SINGLE FAMILY HOME | ●●●●○ | Town funded by developer, not reliant on individuals to buy then build. |
| 00 | \$30 - \$67/FT$^2$ | \$34,800 | SINGLE FAMILY HOME | ●●●●● | After WWII, many young men came back from the war with little money and starting families. |
| ) PER T | \$504/FT$^2$ | \$58,800 | MULTIFAMILY TOWER | ●●○○○ | The tower is currently facing occupancy issues due to high prices and faces the risk of demolition. |
| 00 | \$23/FT$^2$ | \$60,500 | SINGLE FAMILY HOME | ●●●●● | The term manufactured home came about in 1976 and encompassed the mobile home in definition. |
| 665K | \$185 - \$285/FT$^2$ | \$60,500 | SINGLE FAMILY HOME | ●●○○○ | Lack infrastructure for expansion, currently only operating in CA and are not significantly more affordable. |
| 000 | \$244/FT$^2$ | N/A | ARTIST STUDIO + RESIDENCE | ●○○○○ | High prices per square foot as well as it being a specific design for expansion. |
| LION | \$160/FT$^2$ | N/A | SINGLE FAMILY HOMES + EVENT SPACES | ●●○○○ | Government funded by the city with subsidized rent for artists. |

# SUSTAINABILITY

| | DATE | MATERIALS | EM EN |
|---|---|---|---|
| **CRYSTAL PALACE** London, England | 1851 | IRON, GLASS | ● ● |
| **SEARS CATALOG HOMES** United States | 1908-1940 | LUMBER, DRYWALL, PLYWOOD | ● ○ |
| **QUONSET HUT** Rhode Island, USA | 1941 | CORRUGATED GALVANIZED STEEL | ● ● |
| **8X8 DEMOUNTABLE HOUSE** Bedarieux, France | 1945 | METAL AND WOOD | ● ● |
| **DYMAXION HOUSE** Wichita, Kansas, USA | 1946 | ALUMINUM | ● ● |
| **LEVITTOWN** Levittown, NY, USA | 1947 | WOOD, DRYWALL, PLYWOOD | ● ○ |
| **MOBILE HOME** USA | 1950 | PRE-PAINTED ALUMINUM PANELS AND WOOD | ● ● |
| **CAPSULE TOWER** Tokyo, Japan | 1972 | STEEL FRAME AND REINFORCED CONCRETE | ● ○ |
| **MANUFACTURED HOME** USA | 1976 | STEEL CHASSIS, WOOD STRUCTURE, SIDING | ● ○ |
| **BLU HOMES** San Francisco, CA, USA | 2007 | STEEL FRAME, WOOD, SIDING | ● ○ |
| **AXE QUATRE ARRONDISSEMENTS** Paris, France | 2016 | INSULATED WOOD, METAL CLADDING, TERRACE FLOOR | ● ○ |
| **TRUE NORTH** Detroit, MI, USA | 2017 | CORRUGATED GALVANIZED STEEL, PLYWOOD | ● ○ |

| | EMBODIED ENERGY | RECYCLE POTENTIAL | ENERGY EFFICIENCY | SUSTAINABILITY SUCCESS |
|---|---|---|---|---|
| | ●●●○○ | ●●●●● | ●○○○○ | ●●●○○ |
| | ●○○○○ | ●●○○○ | ●●●○○ | ●●●○○ |
| | ●●●○○ | ●●●●● | ●○○○○ | ●●◐○○ |
| | ●●○○○ | ●●●○○ | ●●●●○ | ●●●○○ |
| | ●●●●● | ●●●●● | ●●●●○ | ●●●○○ |
| | ●○○○○ | ●●○○○ | ●●○○○ | ●●◐○○ |
| | ●●●●● | ●●●○○ | ●○○○○ | ●◐○○○ |
| | ●○○○○ | ●○○○○ | ●●●○○ | ●●◐○○ |
| | ●○○○○ | ●●●○○ | ●●○○○ | ●●●○○ |
| | ●○○○○ | ●●○○○ | ●●●●● | ●●●●○ |
| OR | ●○○○○ | ●●○○○ | ●●●●○ | ●●●◐○ |
| | ●○○○○ | ●●●●○ | ●●●○○ | ●●●○○ |

# 3D PRINTED MATERIALS

| | PRINT SIZE | STRENGTH | AVAILABILITY | TYP CUR |
|---|---|---|---|---|
| PLA | Largest is 6096 x 2133 x 1829 mm | High strength and stiffness, but low durability. | One of the most commonly available materials on the market. | Test i deco |
| RESIN | Largest is 2100 x 700 x 800 mm | High yield strength, chains and tools can often be printed. | Easily available on the market, but more expensive. | Can pr mo r |
| CARBON FIBER | Largest printer is 4 x 2 x 1.5 m | Much stronger and stiffer than regular plastic prints. | There's a growing selection of carbon fiber filament and printers. | Func mech |
| CLAY | Largest printer is 3 x 3 x 3 m | New powders are coming out that increase strength of the brittle prints. | Available on the market, but more expensive than a typical printer. | P prot |
| CONCRETE | Largest can print up to 16 x 9 x 2.5 m | One of the strongest materials, can hold the load of several people. | Available on the market, but at varying levels of prices and function. | Protot of vario |
| METAL | Largest printer is 9 x 3 x 1.5 m | Incredibly high strength, but not comparable to the real thing. | Commercially available, but expensive. | Large in |

| | TYPES OF PROJECTS CURRENTLY USED FOR | POTENTIAL ARCHITECTURAL USE | PRE-FAB POTENTIAL | NOTES |
|---|---|---|---|---|
| monly n the | Test items, cosplay parts, decorative parts, scale models. | Making unique mass production items at scale. | ●●●●○ | |
| the e | Can print from fragile scale models to durable, resistant tools. | Continuous printing without layers or structure necessary. | ●●●●○ | |
| lection ment | Functional prototypes, mechanical components. | Printing large components with incredible durability and longevity. | ●●●●○ | |
| rket, than a | Pottery, ceramic prototypes, decorative pieces. | The advent of rise of new diverse products and sculptural forms. | ●●●○○ | |
| rket, ls of on. | Prototypes and structures of various scales and uses. | Can potentially make housing and other projects more affordable. | ●●●●● | |
| le, but | Large structures, medical implants, jewelry, components. | Multiple alloys and forms can soon become available. | ●●●●○ | |

# STRUCTURAL MATERIALS

| | COST | STRENGTH | AVAILABILITY | S |
|---|---|---|---|---|
| GLULAM | ~$24 per ft | High strength and stiffness. | AITC manufacturing plants throughout the U.S. | Lowes for |
| PLASTER | ~$5.00 per sq ft | Strength can be increased depending on materials mixed into it. | Very commonly found and used for various reasons. | Exoth be tox |
| STAINLESS STEEL | $1.38 per lb | Incredibly strong and not likely to warp. | Wide range of steel grades that are not difficult to source. | Steel be witho |
| ALUMINUM | $1.60 per lb | Can be just as strong if not stronger than steel. | Third most abundant material on the planet, making it easy to source. | Manuf has hig |
| CORRUGATED IRON | 8' x 4' sheet = $10 | Corrugated shape adds strength to materials, making it last for longer. | Easy to find in local hardware stores. | Long-li get d and |
| PORTLAND CEMENT | Less than 4 cents per pound. | High compressive strength as it cures. | Used common generally around the world. | U enviro |
| 3D PRINTING | $100 - $2,000 (printer) | Typically high strength and stiffness with various levels of durability. | Widely available in today's market. | Ma beco mer |

| | SUSTAINABILITY | MODULARITY | PRE-FAB POTENTIAL | NOTES |
|---|---|---|---|---|
| plants .S. | Lowest energy requirement for its manufacture. | Glulam can be used for various uses, mainly structural. | ●●●●○ | |
| d and sons. | Exothermic reactions can be toxic and cause burns. | Depending on the mold and mix, plaster can take almost any form. | ●●○○○ | |
| grades lt to | Steel is recyclable, able to be used and reused without losing durability. | Depends on the grade and manufacturer available specs. | ●●●●○ | |
| ant net, ource. | Manufacturing is easy and has high recycling potential and efficiency. | Depends on the grade and manufacturer available specs. | ●●●●○ | |
| cal s. | Long-lived (it doesn't rot or get damaged by insects) and easily recyclable. | As a thin planar material, it can be used for many flat applications. | ●●●●○ | |
| erally d. | Unhealthy to the environment in all phases. | Different types of portland cement are manufactured to meet various criteria. | ●●●○○ | |
| oday's | Materials are slowly becoming more environmentally sustainable. | Can be used for various applications depending on the material/printer. | ●●●●○ | |

# FINISH MATERIALS[22]

| CHARACTERISTICS OF ENVIRONMENTALLY PREFERABLE MATERIALS | |
|---|---|
| CATEGORY | CHARACTERISTIC |
| MATERIAL COST (MC) | Relative cost to equivalent products that do not possess sustainable characteristics. |
| LIFE CYCLE COST IMPACT (LCCI) | Relative impact on life cycle cost of building operations (not to be confused with environmental life cycle assessment, which measures environmental burdens, not financial impact). |
| ENERGY EFFICIENCY (EE) | Construction materials that directly influence building energy use. |
| WATER EFFICIENCY (WE) | Construction materials that directly influence building water use. |
| MATERIAL REDUCTION (MR) | Products or materials that serve a defined function using less material than is typically used. |
| NON-TOXIC (NT) | Construction materials that release relatively low levels of emissions of odorous, irritating, toxic, or hazardous substances. Volatile organic compounds (VOCs), formaldehydes, and particulates and fibers are examples of substances emitted from construction materials that can adversely impact human health (allergens, carcinogens, irritants). |
| RECYCLED CONTENT (RC) | Amount of reprocessed material contained within a construction product that originated from post-consumer use and/or post-industrial processes that would otherwise have been disposed of in a landfill. |
| SALVAGED (S) | Construction materials that are reused as-is (or with minor refurbishing) without having undergone any type of reprocessing to change the intended use. This includes the reuse of existing building structures, equipment, and furnishings at LANL. |
| RAPIDLY RENEWABLE (RR) | Construction materials that replenish themselves faster (within 10 years) than traditional extraction demand; and do not result in adverse environmental impacts. |
| CERTIFIED WOOD (CW) | Construction materials manufactured all or in part from wood that has been certified to the standards of the Forest Stewardship Council as originating from a well-managed forest. |

| |
|---|
| CARP |
| FABR |
| RESIL |
| PAIN |
| SEAL |
| STEE |
| CEME |
| INSU |
| BATH |
| WOO |
| GYPS |
| BRIC |
| ROOF |
| WIND |
| DOOF |
| CERA |
| INSUL |
| SIPS |
| AERAT |
| EXTE |
| PERM |

| SUSTAINABLE DESIGN EVALUATIONS FOR MATERIALS AND RESOURCES | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MATERIAL | MC | LCCI | EE | WE | MR | NT | RC | S | RR | CW |
| CARPET | = | = | | | ● | ● | ● | | | |
| FABRICS | = + | = - | | | | ● | ● | | | |
| RESILIENT FLOORING | = + | = - | | | | ● | ● | | ● | |
| PAINTS | = | = | | | | ● | ● | | | |
| SEALANTS AND ADHESIVE | = | = | | | | ● | | | | |
| STEEL | = | = | | | ● | | ● | | | |
| CEMENT/CONCRETE | = | = | ● | | ● | | ● | | | |
| INSULATION | = | - | ● | | | ● | ● | | | |
| BATHROOM PARTITIONS | = | = | | | | | ● | | | |
| WOOD PRODUCTS | = + | = | | | ● | ● | | | ● | ● |
| GYPSUM WALLBOARD | = | = | | | | | ● | ● | | |
| BRICK/CMU | = | = | | | | | | | | |
| ROOFING | = | = | ● | | | | ● | | | |
| WINDOWS | + | - | ● | | | | | | | |
| DOORS | = + | - | ● | | | | ● | | | ● |
| CERAMIC TILE | = | = | | | | ● | | | ● | ● |
| INSULATING CONCRETE FORMS | + | - | ● | | | | ● | | | |
| SIPS PANELS | + | - | ● | | | | ● | | | |
| AERATED AUTOCLAVE CONCRETE | + | - | | | | | ● | | | |
| EXTERTION FINISHES | | | | | | | | | | |
| PERMEABLE PAVING | + | - | | ● | | | ● | | | |

(=) Equivalent, (-) Generally less expensive, (+) Generally more expensive

# EVALUATING FINISH MATERIALS USE IN BUILDING

| | STANDARD PRACTICE | |
|---|---|---|
| MATERIAL REDUCTION | Alternate low-mass, low volume materials | Alterna |
| LOCALLY MANUFACTURED | 10% of building materials | 20% of |
| LOCALLY DERIVED RAW MATERIALS | 5% of building materials | 10% of |
| NON-TOXIC | CRI-compliant | CRI-cor |
| RECYCLED CONTENT | Meet EPA Comprehensive Procurement Guideline requirements | 10% of |
| SALVAGED MATERIAL | None | 5% of l |
| SALVAGED BUILDING REUSE (IF APPLICABLE) | Maintain 75% of existing building structure and shell | Maintai |
| RAPIDLY RENEWABLE | None | 5% of l |
| CERTIFIED WOOD | None | 50% of |

| | BETTER | HIGH PERFORMANCE |
|---|---|---|
| | Alternate low-mass, low volume materials | Materials that serve multiple functions, and allow for omission of layers |
| | 20% of building materials | 30% of building materials |
| | 10% of building materials | 15% of building materials |
| | CRI-compliant carpet and GS-compliant paint | CRI-compliant carpet, GS-compliant paint, California AQMD-compliant adhesives and sealants |
| ne | 10% of building materials by weighted average | 20% of building materials by weighted average |
| | 5% of building materials | 10% of building materials |
| d | Maintain 100% of existing building and shell | Maintain 100% of existing structure and shell AND 50% of non-shell (walls, floor coverings, ceiling systems) |
| | 5% of building materials | 10% of building materials |
| | 50% of wood-based materials | 75% of wood-based materials |

# MATERIAL EMBODIED ENERGY[23]

| MATERIAL | EMBODIED ENERGY (MJ/Kg) |
|---|---|
| **WOOD AND DERIVATIVES** | |
| Wood from temperate climates | 3.00 |
| Tropical Wood | 3.00 |
| Laminated Wood | 7.69 |
| Wood, formaldehyde-free particle board | 14.00 |
| Wood, particle board containing formaldehyde | 14.00 |
| Wood, plywood | 5.00 |
| Wood Strand Board | 8.86 |
| Paper | 929 |
| **STONE** | |
| Granite-compact stone | 3.58 |
| Porous Stone | 1.64 |
| Sand | 0.10 |
| Gravel | 0.10 |
| | |
| **MINERAL BINDERS** | |
| Cement | 7.00 |
| Mortar M-40/a | 1.00 |
| Mortar M-80/a | 1.34 |
| Lime and bastards mortars | 1.78 |
| Concrete H-150 | 0.99 |
| Concrete H-175 | 1.03 |
| Concrete H-200 | 1.10 |
| Reinforced concrete 2% steel quality | 1.64 |
| Lightweight concrete 600 Kg/m$^3$ | 1.31 |
| Porous Concrete 400 Kg/m$^3$ | 3.71 |
| Expanded perlite | 8.00 |
| Fibre Cement (with Asbestos) | 6.00 |
| Fibre Cement (with synthetic and wood fibres) | 6.00 |

**What does it mean to consider embodied energies?**

This table examines the energy consumed by the extraction of the raw materials, manufacture, transportation, installation, maintenance and disposal. This is an important factor to consider when choosing materials for construction as alternative materials with less embodied energy may be available with similar properties. Factors not considered in the embodied energy of the material include energy used in the construction and maintenance of infrastructures, the specific means to build the infrastructures and the human energy of the labor.

| | |
|---|---|
| Wood fibre concrete | 450 |
| Plaster panels | 3.12 |
| Plaster | 3.30 |
| Gypsum board | 3.15 |
| **CERAMICS** | |
| Fired clay, brick and tiles | 4.50 |
| Fired clay, vitrified ceramic materials | 10.00 |
| Expanded clay | 6.00 |
| Porcelain | 27.50 |
| Hollow brick masonry | 2.96 |
| Perforated brick masonry | 2.85 |
| Solid brick masonry | 2.86 |
| **GLASS** | |
| Flat Glass | 19.00 |
| | |

| | |
|---|---|
| **METALS** | |
| Commercial steel (20% recycled) | 35.00 |
| 100% recycled steel (theoretical) | 17.00 |
| Stainless steel | 54.00 |
| Primary aluminium | 215.00 |
| 100% recycled aluminium (theoretical) | 23.00 |
| Commercial aluminium (30% recycled) | 160 |
| Primary copper | 90.00 |
| Commercial copper (20% recycled) | 70.00 |
| Titanium 6% Al, 4% V | 45.00 |
| **ASPHALT** | |
| Asphalt sheet | 10.00 |
| **INSULATION** | |
| Expanded polystyrene (EPS) | 100.00 |
| Expanded polystyrene (XPS) blowing agent HCFC | 100.00 |

# MATERIAL EMBODIED ENERGY

| MATERIAL | EMBODIED ENERGY (MJ/Kg) |
|---|---|
| Extruded polystyrene (XPS) blowing agent $CO_2$ | 100.00 |
| Polyurethane (PUR) blw. ag. HCFC or dichloromethane | 70.00 |
| Polyurethane (PUR) blw. ag. $CO_2$ or similar | 70.00 |
| Phenolic foam | 65.00 |
| Cellular glass | 20.00 |
| Fibre glass | 20.00 |
| Mineral wool | 13.00 |
| **SYNTHETIC MATERIALS** | |
| Acrylic | 105.00 |
| Melamine | 125.00 |
| Methacrylate | 87.00 |
| EPDM | 76.00 |
| Styrene-butadiene | 102.00 |
| Primary Polyethylene (PE) | 77.00 |
| Recycled polyethylene (PE) more than 70% | 0.09 |
| Primary polypropylene (PP) | 80.00 |
| Recycled polypropylene (PP) more than 70% | 24.00 |
| Plastic paint (water based) complies w/ code | 20.00 |
| Plastic paint (water based) | 20.00 |
| Synth. paints & varnishes (enamels) org. solvents CN | 100.00 |
| Synth. paints & varnishes (enamels) org. solvents | 100.00 |
| Polychloroprene (neo-prene) | 120.00 |
| Primary PVC | 80.00 |
| Recycled PVC more than 70% | 2.10 |
| PTFE (teflon) | 295.00 |
| Plastic (ABS) | 74.00 |
| Polycarbonate | 85.00 |

| | |
|---|---|
| Epoxy resin | 137 |
| Polyester resin | 115 |
| Silicone | 91.00 |

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