

# Pre-CAD-Frication

*Re-establishing Automotive Paradigms to a Manufactured Architecture*

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## *Abstract*

Through the late Twentieth Century, leading vehicle manufacturers increasingly eschewed the drive from mass production and instead focused upon lean production, where output has been determined according to demand. Automotive manufacturers no longer stockpile parts, but vehicles are now made to order, and in doing so the automotive industry has attained flexibility within production; a factor that has historically been unattainable with the simplistic rationalities of mass-production. Automotive manufacturers are now guided with digital design tools, and have further addressed the complexities of flexible production and the modular composition of the 21st Century automobile. Through the utilisation of digital design tools, digital collaboration, organisational capabilities and product technologies the 21st century automobile has successfully shown the world that highly complex products can be produced both efficiently and effectively, with versatility and high craft.

The building industry has not been so swift to exploit the opportunities offered by digital lean production; often still constructing in the same laborious manner it has done so for hundreds of years. Digital lean production offers strategies for exerting efficient, sustainable design within contemporary architecture. Through the design of a flexible dwelling, this thesis establishes how the principles of digital, lean production can be utilised within Building Information Modeling to address the issues of speed and precision within the design and manufacture of contemporary architecture.



## *Acknowledgements*

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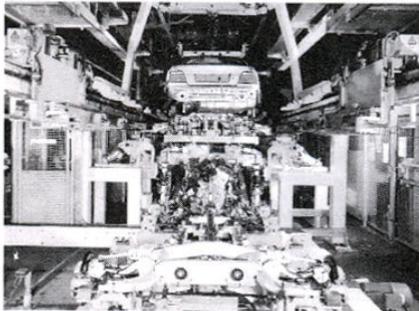
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**SINGULAR CRAFT 1900**

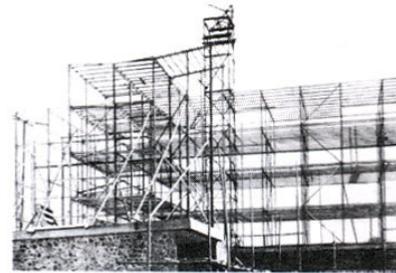


**ASSEMBLY LINE 1920**



**MODULARIZED 2003**

**VS.**



**SINGULAR CRAFT 1900-2003**

# 1.0 Introduction

This thesis focuses on the application of automation efficiency in how it can improve speed and precision in contemporary architecture.

In the past decade, architectural construction costs have risen, whilst the quality of construction has dropped due to the limited resources of high-skilled labour. The 'professions apparent indifference to innovation in other fields along with the decentralised nature of the design and construction industries still remains to hinder architects creatively and has kept builders lagging decades behind other industries' (Hart, 2002, para. 3). This phenomenon has been identified in recent years within architectural literature, yet practical approaches are still seldom.

Today, much of the material world is created using a process in which design, analysis, representation, fabrication and assembly comprise a seamless collaborative process dependant on digital technologies (Kolarevic, 2005, p. 7). Mass customisation is rapidly replacing mass-production. For the sake of economic scale, mass-production must design products, as well as appeal to markets that have large numbers of customers with similar needs. Mass customisation, however, satisfies the needs and desires of individual customers. Moreover, it does this at prices below those of mass produced products and services (Fern, 2002).

In comparison to the architectural field, the automotive industry has successfully 'exploited developments in information technology, computer-aided-design (CAD), and fabrication techniques to provide more scope or higher quality in less time and for less money' (Hart, 2002, para. 16). As a result, digital lean production has evolved into the paradigms that now rule industrial design thinking and manufacturing processes. The car manufacturing industry has successfully shown the world that highly complex products can be produced effectively and efficiently. As digital lean-production principles have evolved, automotive manufacture has developed into a product composition that can now be designed individually. The purchaser of a new car is now entitled to selection of finishes, seats, mouldings and electronics that are made to order within short return times. The automobile is now designed for specific clients with, and for, specific needs; the manufacture of the automobile is now a collaborative joining of assemblies produced with both versatility and high craft.

Historically there have been many attempts to imbue industrial production within architecture; however, they have all proven to be difficult (Davies, 2005; Kieran, 2004). Architects have imbued building production with the logics of standardisation, prefabrication and on-site installation (Gartman, 2009, p. 1), and have been

*Figure 1.0 (opposite):* A Craft of Affairs - The automotive industry has seen tremendous shifts in paradigms throughout its history compared to the singular based craft of the construction industry remaining the same over the past century.

Source: S. Kieran & J. Timberlake (2004), *Refabricating Architecture*, New York, McGraw-Hill: p. 84

restricted by geometric simplicity over complexity through the repetitive use of low-cost-mass-produced components. The standardisation of mass-production, however, no longer needs to be the solution to infiltrate quality without additional costs in architecture (Kolarevic, 2005, p. 52). Architecture can now be produced as a product, for specific clients, with specific needs, both efficiently and successfully through the efficiencies of digital technologies.

Unfortunately, the benefits of computer-aided-design (CAD) and computer-aided-manufacturing (CAM) are only 'being explored to make our most important buildings less expensive' (Willis & Woodward, 2005, p. 75) and the vast majority of built form still remains neglected by such technology. 'Technology should be seen as a primary component to improving quality rather than reducing costs' (Kronenburg, 2001, p.14); and the automobiles success could become a precedent for application. The fact is, through the evolution of digital lean manufacture, the automobile has successfully shown the world how to attain flexibility and higher quality both quickly and economically (Hart, 2002), factors that surely can benefit the design and construction of contemporary architecture. This establishes the aim of this thesis: to determine how we can adapt the paradigms of 21st Century automobile design thinking to reinterpret the processes of design and construction in contemporary architecture.

### *1.1 Research Approach*

To achieve this aim, this thesis examines the historical processes within architecture and the automotive industry to establish similarities and differences. This will provide significant background for allowing the application of the automotive industries manufacturing processes and modular architecture to current trends of digital design and manufacturing within the architecture.

Although the historical background information and 21st Century industrial manufacturing processes are applied to the design of a flexible housing system, the findings of the research do not relate to the system alone. The historical application of automotive production has predominantly been focused on housing, so provides relevant background for the application of this thesis to do so. This thesis, however, aims to show the automotive industrial processes of design and production versus the production of 'object types'; a notable factor that has lead to the failure of mass-produced architectural design.

Chapter Two illustrates the evolvement from the automotive means of mass-production and architectural production throughout the 20th Century. It establishes the motives and methodologies established by 20th century

architects through theoretical and applicable background of applying industrial means of production to architecture; defining criteria which somewhat led to the failure of fabricated architectural design. These criteria will establish grounds for determining factors that need to be addressed if architecture is to successfully infiltrate the methodologies of industrialised production with contemporary architectural design and production.

Chapter Three defines the 'post-Fordism' motives of design and manufacture within the 21st Century automotive industry. It illustrates the production processes of today's car industry, witnessing differences and advancements from the mass-production methods of the 20th Century. It demonstrates the high reliance on collaborative computer-aided methods of design and manufacturing, and continues to focus on the current modular architecture of the automobile that has been directly driven by its efficiency of manufacturing processes.

Chapter Four continues to explore and compare the current role of modulation in the architectural industry. With the effects of modulation and digital production outlined in the previous chapter, it will give a comparison and understanding to the differences and similarities that currently lie between the two interpretations. The chapter continues to outline the hypothesis of incorporating modularity and mirroring the computer-aided aspects of pre-fabrication through the process of design within architecture.

Chapter Five will focus on research discovered by reinterpreting the processes of design and production, established in Chapter three. It will not only establish a parametrically driven system that can compose a site-parameterised flexible house, but will more outline factors that establish the design processes in doing so. The system has been used as a tool to present and discover findings through integrating production and architecture. It produces findings that contribute to the way in which we interpret architectural design, concluding by developing a situation for discussion.

Chapter Six will discuss and conclude the findings. It will not only discuss the assembly of the houses, but how we can collaborate construction and architecture as a whole. It discusses comparative relations with current production techniques and relationships with the precedent of the 'mass-produced' houses of the 20th Century. It establishes theories in how we can reinterpret design and constructional relationships to produce speed and precision in contemporary architectural design, concluding with ways in which we can 're-fabricate' architecture for the 21st Century.

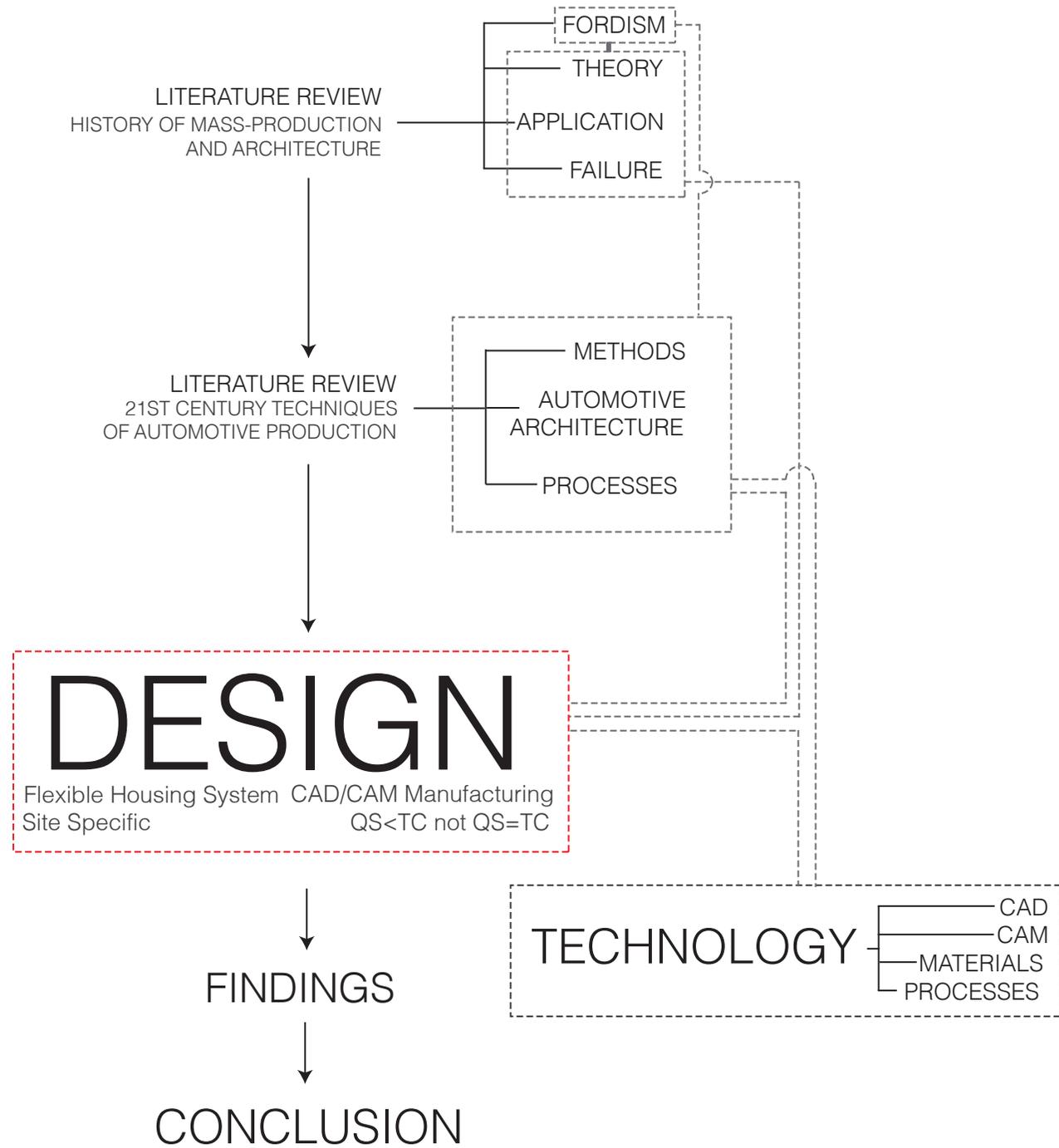


Figure 1.1: Research Methodology Diagram.

Source: Author, 2010

## 1.2 References

Davies, C. (2005). *The Prefabricated Home*. London: Reaktion.

Fern, E. J. (2002). *Six Steps To The Future: How Mass Customisation Is Changing our World*.

Gartman, D. (2009). *From Autos to Architecture: Fordism and Architectural Aesthetics in the Twentieth Century*. New York: Princeton Architectural Press.

Hart, S. (2002). *New Ways to Build Better, Faster, Cheaper*. *Architectural Record*, 190, 131-134.

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Kronenburg, R. (2001). *Spirit of the Machine : technology as an inspiration in architectural design*: Academy Press.

Willis, D., & Woodward, T. (2005). *Diminishing Difficulty: Mass customization and the digital production of architecture*. *Harvard design magazine*, 23(83), [70]-83.



## 2.0 Automobiles to Architecture – A Century of Attempts

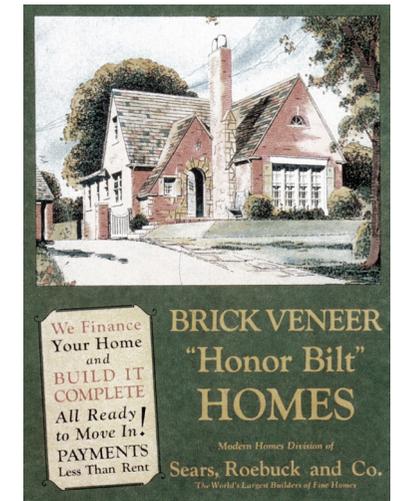
Historically, pre-fabricated kit-houses<sup>1</sup> have answered to affordability solutions in housing. Today, traditional methods of building still dominate the building industry. The definition of prefabrication is 'to manufacture sections of a building, in a factory, so that they can be easily transported to and be rapidly assembled on a building site' (Collins English dictionary, 2000). Prefabrication, however, is still often perceived as the standardisation of the kit-house, which has been architecture's economic rival since the early 1900s (Davies, 2005).

Throughout the 20<sup>th</sup> Century there were many attempts to imbue industrial means of mass-production with off-site fabrication; however, they were all complete failures (Davies, 2005; Kieran, 2004). Architecturally driven, industrially produced housing has been driven by economies and the misinterpretation of the rationales of mass-production; and has been further guided by over-optimistic outputs for housing developments. This chapter, therefore, will explore the differences of the interpretation between the historical precedent of mass-production and the architectural interpretation. It establishes the theories and methodologies for imbuing automotive industrial manufacture and architecture. It defines the differences between mass-production and the architectural interpretations, giving background to the mistakes that can be addressed within 21<sup>st</sup> Century automotive manufacture.

Though this research does not outline every attempt, it focuses on the predominant theories, and gives reference to physical application of imbuing such methodologies within design. It begins by outlining principles of the precedent for application, and then continues to explore the theories and attempts of applying mass-production and architecture. It will conclude by contrasting the different objectives between mass-production and the architectural reinterpretation; illustrating the significant factors that have led to the failure of architectural attempts for mass-produced housing.

### 2.1 The influence of Fordism

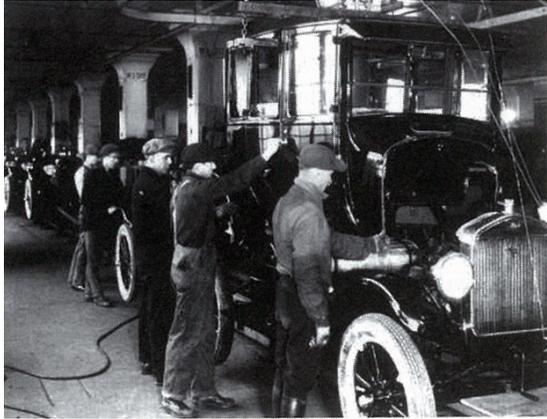
Over one hundred years ago, cars were made piece-by-piece. They were custom-made by highly skilled labourers, produced in limited numbers and were only available to the wealthy (EyeWitness to History, 2005). The laborious, uneconomic development of the automobile would eventually evolve to the paradigm of manufacture that would influence industrial production for the majority of the 20<sup>th</sup> Century; titled *full-scale-mass-production*,



**Figure 2.0:** Sears, Roebuck and Company Sales Catalogue (1910) - Between 1908 and 1940 the company sold over 100,000 homes through their 'Modern Homes' main-order catalogue.

Source: B. Bergdoll & P. Christensen (2008), *Home Delivery*, New York, MoMA: p. 48

1. Entire standardised houses that are prefabricated into components and assembled on site. They are standardised as a complete 'unit', offering little flexibility.



**Figure 2.1:** Henry Ford's Mass-Production Line, Highland Park, 1914.

Source: C. Davies (2005), *The Prefabricated Home*, London, Reaktion Books Ltd: p. 133

introduced by Henry Ford in 1908 (Gartman, 2009).

'Mass-production transformed the visual order and sensibilities of society, the defining principle of which was the subordination to all ends to the efficiency. What was produced was the subordination to how it was produced. Cheap, quick production process required above all, standardisation of products' (Gartman, 2009, p. 1). Whilst this removed the flexibility for consumer demand, it was cheaper than almost any product made by hand (Sterling, 2002) and relied on processes of manufacture. Henry Ford insisted:

Mass production is not merely quantity production... nor is it merely machine production. Mass production is the focusing upon a manufacturing project of the principles of power, accuracy, economy, system, continuity and speed. And the normal result is a productive organisation that delivers, in quantities, a useful commodity of standard material, workmanship and design at minimum cost (Henry Ford:Herbert, 1984, p. 1)

The historical application of hand manufacturing each specific component was removed. Ford insisted that the manufacture of products should be accurate, identical components in which the necessitation for highly skilled labour was not a necessity. Accuracy, therefore, became a crucial factor of mass-production (Davies, 2005, p. 133); it allowed the assembly of the automobile to be composed with precision and speed.

Mass-production was very much a closed system<sup>2</sup>; the specific elements were suited to individual models, and interchange-ability was not an option. As explained later in the chapter, the architectural application to mass-production was a misinterpretation by the 20th Century modernist architects, though their hopes for infiltrating production and architecture would continue to grow, and it was seen what better way than to replicate the success of Ford's Model-T.

## 2.2 Fordism and Architecture

At the beginning of the 20th Century, the two most prominent visions for applying the industrialist means of production belonged to Walter Gropius and Le Corbusier. Architects were faced with imperative housing issues of costs and quality, and the inspiration of mass-production became the precedent for success. The first architectural call for industrialised housing was in the *Establishment of a Company for the provision of Housing on Aesthetically Consistent Principles* by Walter Gropius, 1910 (Arieff, 2002, p. 15; Davies, 2005, p. 132). His theories reduced the idea of geometry and proportion seen in vernacular architecture to proportions of standardisation. What he proposed was the standardisation of elements to compose a modernist architecture, therefore

2. The design and development of products that are to suit only that specific model

allowing adaptability and inter-changeability through the use of mass-produced elements. His proposal was that 'the client can now compose his house according to his personal taste... He even proposes a form of what we would now call supply chain management: contracts with suitable specialist manufacturers ensuring that all parts satisfy the standards laid down by the company and are, if possible, always in stock' (Walter Gropius: Davies, 2005, p. 132)

Gropius' aim was to achieve 'the aesthetic activity of the architect with the economic activity of the entrepreneur', thus establishing 'a happy union... between art and techniques' (Herbert, 1984, p. 34). Gropius was insistent not to impress dull uniformity within his design, and to allow a degree of what we would now call customisation. Gropius, during this time, was working with industrial designer Peter Behrens who was fascinated with infusing industrial production with meaning and spirit through artistic means (Anderson, 2000, p. 108). It is unclear whether he was demonstrating interest in the aesthetics, or the principles of mass-production; though his theories for imbuing industrial production would later evolve with the design of his '*Packaged House*'.

During this period, Le Corbusier was also exhibiting interest in industrialised architecture. In 1923, he published a book called *Towards a New Architecture*, in which the last chapter was titled *Mass-Production Houses*. By this stage, Corbusier, like Gropius, had not physically applied mass-production to housing, but had documented his theories through a range of illustrative sketches (Baukasten, Germany, 1922-1923) and documentation. Corbusier was adamant that the mass-produced house would be the success to housing shortage difficulties and subjected the house 'will no longer be this solidly-built thing which sets out to defy time and decay, and which is an expensive luxury by which wealth can be shown; it will become a tool as in the motor-car' (Corbusier, 1927, p. 237).

Corbusier, through illustrations as early as 1914<sup>3</sup>, explains his visions for standardisation within architectural housing. He states the position of why a house shall be built like the Ford motorcar. He states that standardised elements such as cupboards, doors and windows, which a basic industry can supply and manufacture should all be based upon a basic means of measurement to infill the houses frameworks, with all gaps in between filled with brick, plaster slabs or lathing (Corbusier, 1927, p. 235).

By the 1930s, architects finally found it necessary to deal with the technological imperatives and social ideology of mass housing. Architecture started to see more inspiration from mass-production, yet the affiliation with cheap demands for housing still remained to be the prerequisite for application (Arieff, 2002, p. 15). Factory built housing was deemed to be the preferred option, and it was to be produced the same way as the automobile. Corbusier stated in his *Towards a New Architecture* that the 'right state of mind did not exist for his new epoch to begin', and he was right. 'It did come to pass, but the spirit of living in mass-production houses did not' (Kieran, 2004, p. 113). By this time there had been numerous attempts to architecturally infiltrate the benefits of mass-production with architecture; they were all complete failures (Davies, 2005; Timberlake & Keiran, 2004).

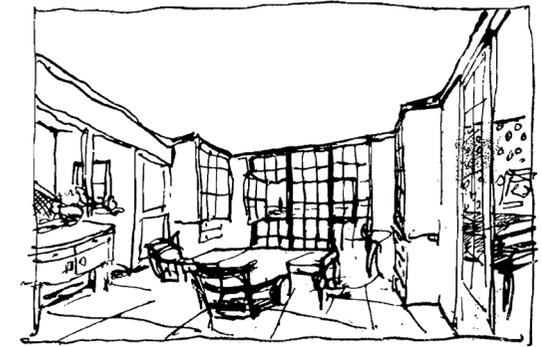


Figure 2.2: *Concrete House* interior, Le Corbusier, 1915.

Le Corbusier insisted, '[m]ass-produced doors, windows, cupboards: windows are built up of one, two, a dozen units: one door with one impost, two doors with two imposts, or two doors with out imposts, etc; cupboards glazed above and with drawers below for books, utensils, etc. All these units, which big industry can supply, are based on a common unit of measurement: they can be adapted to one another exactly. The framework of the house being made, these elements are set up in their proper places in the empty shell and temporarily fixed by laths; the voids are filled by plaster slabs, bricks or lathing; the normal method of building is reversed and months of work are saved. A further gain, of the greatest importance, is architectural unity, and by means of the module, or unit of measurement, good proportion is assured automatically' (Corbusier, 1927, p. 237).

Source: Le Corbusier (1927), *Towards a New Architecture*, New York, Dover Publications: p. 237

3. Particularly the illustration of *Maison Domino*

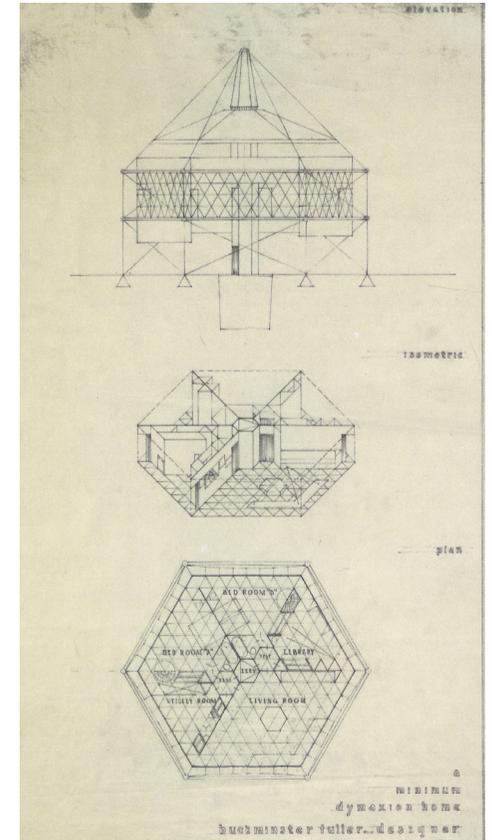
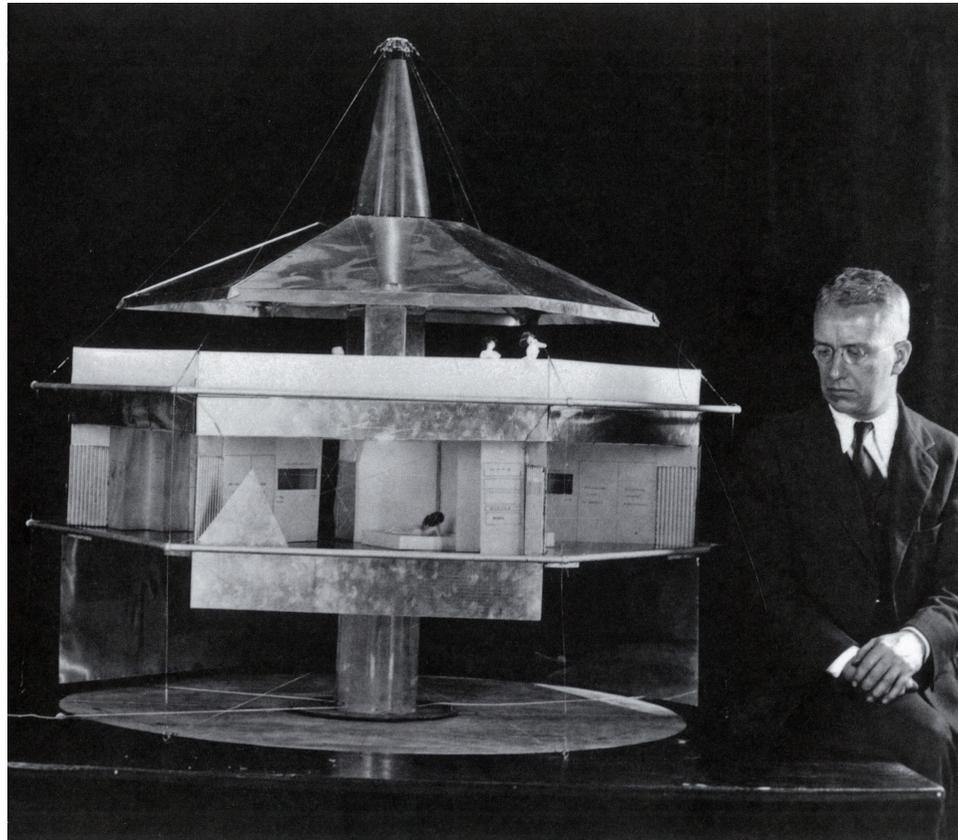
**Dymaxion House:** One of the first realisations of a mass-produced house was Buckminster Fuller's *Dymaxion House*, in 1927. Fuller saw the mass-production of buildings in a variety of pre-determined variations, a process equivalent to the mass production of the motor car (Herbert, 1984, pp. 64-65). It was specifically designed to be un-climatic, un-orientated and facilitated no means of site response, factors, which the previous three architects attempted to initiate. Eventually, the project would fail, and the design was highly rejected.

**Figure 2.3 (left):** Buckminster Fuller with model of his *Dymaxion House*.

Source: B. Bergdol and P. Christensen, *Home Delivery*, 2008: p. 59

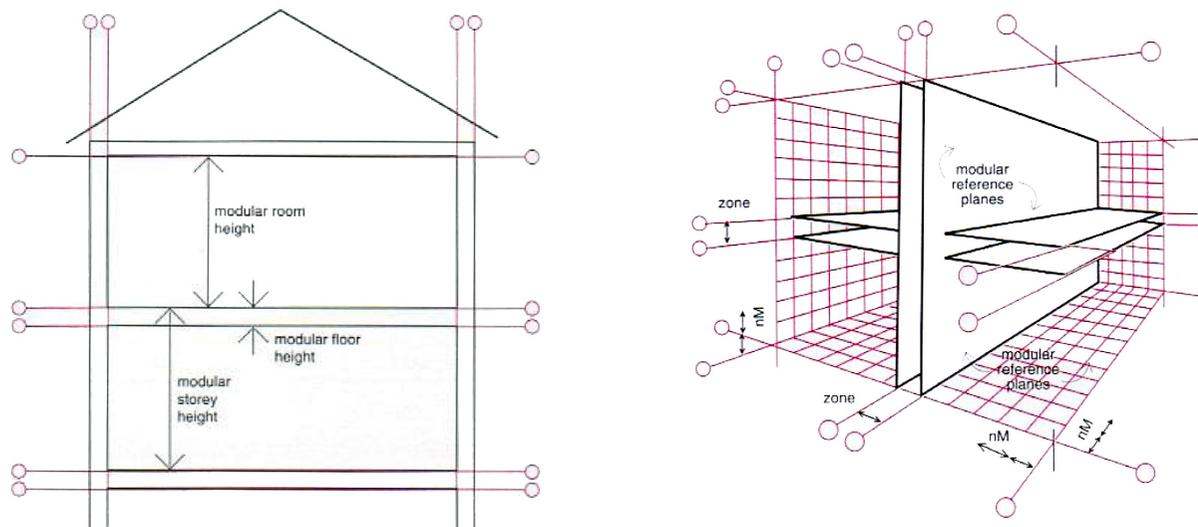
**Figure 2.4 (right):** Elevation, axonometric section and plan composite.

Source: B. Bergdol and P. Christensen (2008), *Home Delivery*, New York, MoMA: p. 60



## 2.3 Modular Coordination

In 1936, American architect, Alfred Farwell introduced a term called modular coordination. His proposal was similar to Gropius, yet it facilitated dimension and structure. Farwell proposed that all building components should be sizes that were multiples of a module<sup>4</sup>, 'that way a perfect fit between components could be guaranteed and manufacturers could mass-produce and stockpile their products in sure knowledge that they would fit the market... A building would be designed as an abstract, three-dimensional matrix into which a range of interchangeable modular components could be inserted' (Davies, 2005, p. 134). Modular coordination was a mathematical variation to the visionaries of Gropius and Corbusier; therefore it was a more practical application to mass-production and architecture. Modular coordination would become the system that inspired architects for mass-produced housing over the next 40 years (Davies, 2005, p. 134).



**Figure 2.5 & 2.6 (left & Right):** Modular Coordination Reference System - the dimensional relationship is achieved by establishing preferred dimensions based of standard increments of size that relates to the international module. All dimensions should be divisible by the greatest possible number of smaller dimensions, all dimensions should be obtained by multiplication or addition of smaller dimensions and, all dimensions should be whole multiples of M.

Source: *Modular Design Guide*, (<http://kedah.jkr.gov.my/ibs/212223.pdf>)

In 1941, Gropius joined with architect Konrad Wachsmann<sup>5</sup> to develop the *Packaged House*, derived from modular co-ordination. It differed from 'kit-houses' as it was to mass-produce the components of the house, not the physical house itself. The system was to produce numerous types of standard components assembled into standard types of dwellings, having ambitions of producing upto 10,000 houses per year (Herbert, 1984, p. xi). Their proposal aimed at two objectives, which in terms of conventional practice appeared incompatible; improved quality of design and construction of greater economy of cost (Herbert, 1984, p. 35). Gropius and

4. Module being based on the utilisation of standard dimension

5. German architect who developed theories and research into the application of mass production and architecture

Wachsmann's vision differed to that of Buckminster Fuller. Where Fuller saw the entire house as a mass-produced product, Gropius saw prefabrication as a vision to the mechanistic world. Gropius' view was to seek and reap advantages of prefabrication through the manufacture of standardized parts rather than the house as a whole (Herbert, 1984, pp. 64-65). Sadly, the financial feasibility for developing a system that could cater for a flexible market could not be attained, and Gropius and Wachsmann would fail to realise their dream in the early 1950s.

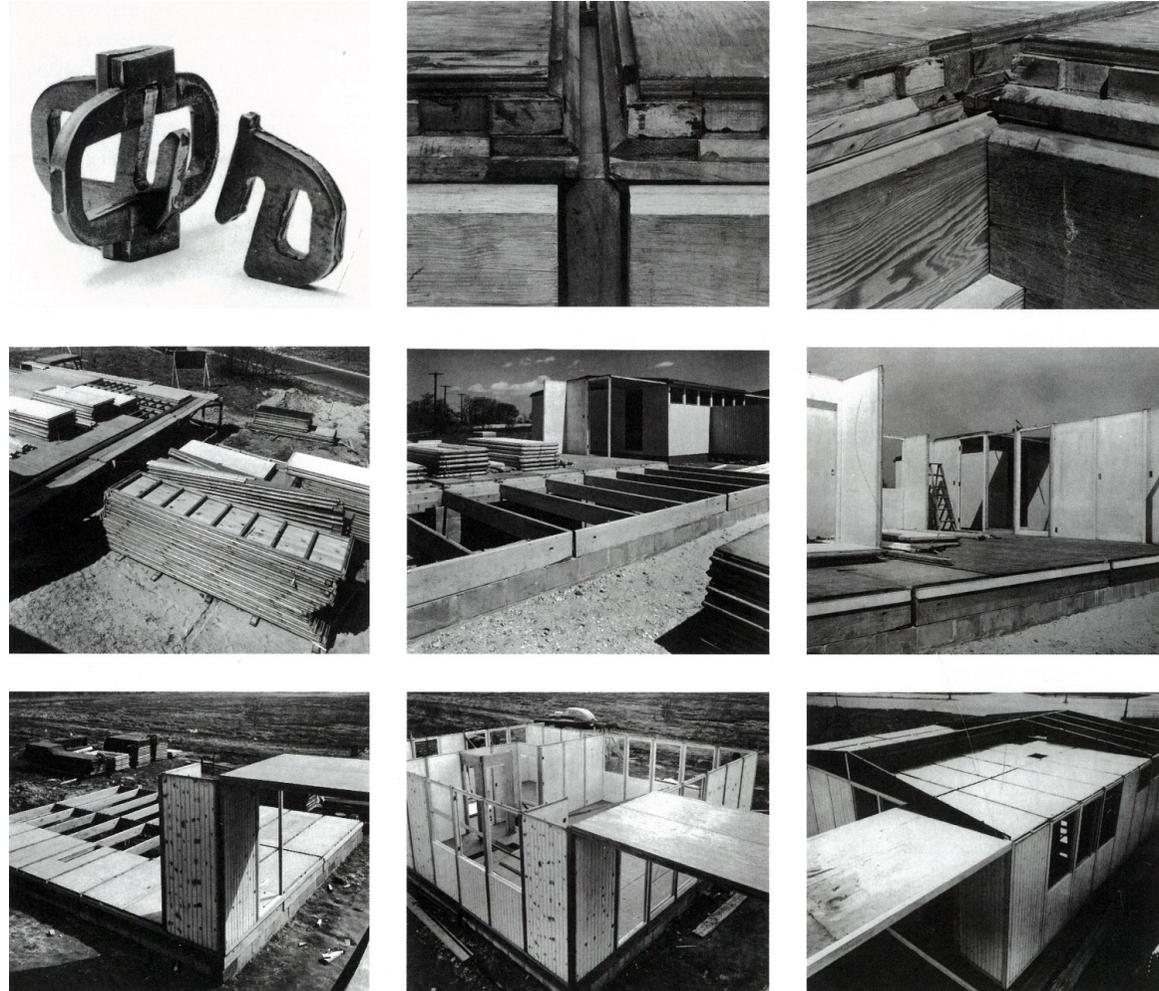
**Figure 2.7:** Gropius and Wachsmann's *Packaged House*.

**Top Row:** Primary Architectural Joint; foundation system; foundation system corner.

**Middle Row:** Panels organised for construction; foundation construction; construction phase one.

**Bottom Row:** Construction phase two; phase three; and phase four.

Source: B. Bergdol and P. Christensen (2008), *Home Delivery*, New York, MoMA: p. 85



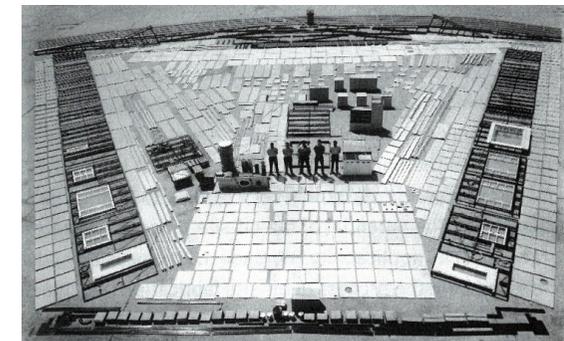
The basic logic of the architectural application to mass-production has always been for factories to establish a standard means of product that can be used for a continuous building programme. To design variances for one-off architectural instances, however, became a geometric coordination puzzle that needed to be solved off site, and it became far too complex in doing so. The idea was to design and construct perfectly coordinated buildings that contained a three-dimensional grid, in which standardised dimensional components could simply be placed within and fixed (Davies, 2005, p. 138). The practice of construction, on the other hand, differs from this. Slots needed to have geometrical certainty and the traditional approach to building construction needed to cater for large tolerances, which were not factored into the component design.

The fundamental theory behind modular co-ordination, however, was a misinterpretation by architects on how automotive mass-production worked. Ford's mass-production-line was based on interchangeability of accurate identical parts (closed architecture), but architects' interpretation was based on the facilitation of tolerable, interchangeable parts (open architecture). Architecture attempted to imply the principles of mass-production through a catalogue of inter-changeable parts that were not building specific but system specific, be it doors, windows, roofing arrangements; 'from an industrial perspective it had nothing to do with the practicalities of mass-production' (Davies, 2005, p. 139).

Adding to the misinterpretation of mass-production was architects hope for the amount of physical application. Architects imagined buildings to be produced by the hundreds of thousands; but the resultant number of houses developed in many building programmes, however, did not necessitate the economic efficiencies of mass-production. Further encouragement was the practical application of such standardisation, even if the economics were there to produce the number panels intended, Colin Davies in his book *The Prefabricated Home* shows that a study carried out by the *Building Economics Research Unit* uncovered that:

Whilst they were standardised, the requirement for adaption in relation to adjoining assembling elements, be it structural columns, panels next to doors, panels with a door on the left and a column on this right, panels with doors on both sides... When all the variants were combined the numbers of identical panels were drastically reduced. In one example cited in the report, the architect 'saw' 229 types of component, the quantity surveyor saw 443, and the manufacturer saw 2204. So much for standardisation. (Davies, 2005, p. 141)

The systems, then, offered very few advantages. From the perception of mass-production, they were complete failures. Standardisation was very rarely applicable and as history would indicate the numerous attempts of applying industrial production to architecture had nothing to do with the rationalities of mass-production.

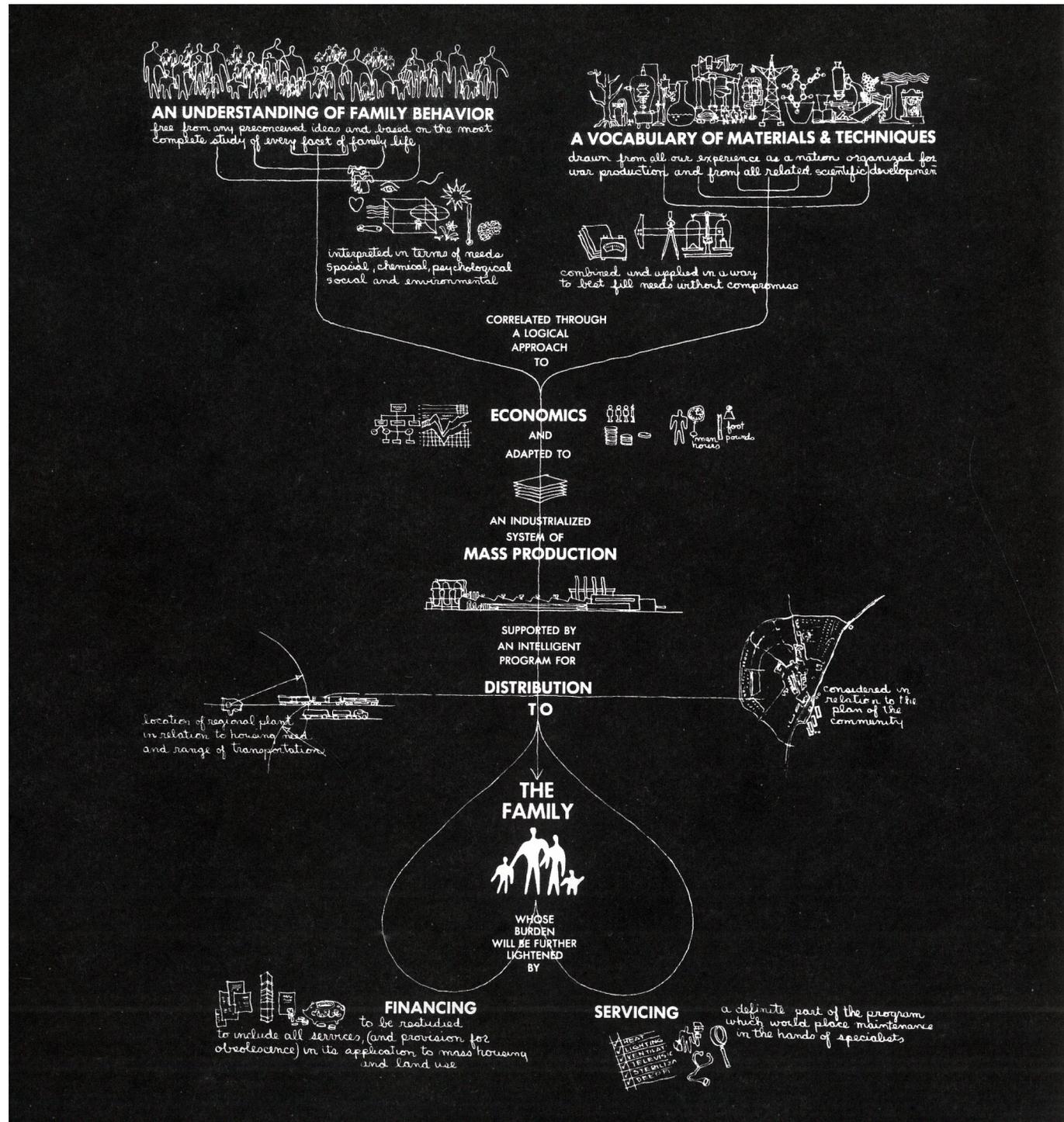


**Figure 2.8:** Gropius and Waschmann's *Packaged House* system - The amount of variable parts in 'kits' became too complex, and did not improve on existing paradigms.

Source: S. Kieran & J. Timberlake (2004), *Refabricating Architecture*, New York, McGraw-Hill: p. 108

**Figure 2.9:** 'What Is a House?' diagram, published by Charles Eames in *Arts & Architecture Magazine*, July 1944.

Source: B. Bergdoll and P. Christensen (2008), *Home Delivery*, New York, MoMA: p. 96



## 2.4 Modernist principles to Residential Architecture

During the Mid 20th Century, though many had attempted and failed to apply the logistics of modular coordination, hope was still evident. Between 1945 and 1966 *Arts and Architecture Magazine*<sup>6</sup> introduced a scheme titled the *Case Study House Programme*, a program that has been well documented since its establishment in 1945 (Fisher, 2008). The program announced that 'each house must be capable of duplication and in no sense be an individual 'performance'...that the best material available be used in the best possible way, in order to arrive at a 'good' solution to each problem, which in the overall program will be general enough to be of practical assistance to the average American in search of a home in which he can afford to live' (Travers, 2010, para. 3).

There would be a total of 36 *Case Study Houses*, both illustrative and built. The most publicised Case Study House (CSH) would be CSH Number Eight (Fisher, 2008), designed by Charles Eames, Ray Eames and Eero Saarinen<sup>6</sup>. The proposals differed from modular co-ordination, as the house was to be built from products that were already established in a mass-produced market.

CSH Number Eight was not initiated until 1949, of which by then Eames had completely reinterpreted the site and redesigned the entire house<sup>7</sup>. 'Whilst both designs were built from the same palette of materials, the two houses were complete opposites upon completion' (Merkel, 2006, para. 6). Charles had an obsession with efficiency, managing to redesign the entire house with only the addition of one structural steel member. According to Ray,

It was like a game to him. How could one enclose the maximum volume with the same steel? It was the idea of using materials in a different way, materials that could be bought from a catalogue. So that there was a continuation of the idea of mass production, so that people would not have to build stick by stick, but with material that comes ready-made — off-the-shelf in that sense (Demetrios, 2002, para. 10).

The design of the Eames House differed from modular coordination. Modular coordination utilised a grid to indicate the placement of components designed within. Eames designed the grid based around existing components and materials that already existed within the market. The definition of these materials and how they joined together were already predetermined. From this perspective, the house was by no means mass-produced but it was the components that composed the house that were. The CSH programme was eventually discontinued as the battle for housing had been won by developers. By 1960, the custom-built small family house was deemed too expensive. 'The Case Study House was a social program; it essentially ended when the house became a luxury' (McCoy, 1977, p. 5) for living in.

6. Eero Saarinen – a furniture designer/architect who researched and designed the application of mass production, manufacturing techniques and manufactured architecture within large scale buildings.

7. Bridge House – the name commonly known for the first design for the Eames House

Since the 1960s, architects have developed a preference for individualised solutions, distancing themselves from the factory. 'Factory produced has become a style, a style that has very limited appeal outside of the architectural industry' (Davies, 2005, p. 182). Through the latter half of the 20<sup>th</sup> Century, there was little attempt to develop mass-production within housing, and the encouragement from government agencies was not as strong as after the effects of the World Wars. Houses are getting far more complicated to design and build with technological advancements. Electrical wires, plumbing, heating, insulation are now all exponentially increasing in necessity. In the 'average' dwelling, building construction times are now longer than ever and comparably, the costs of building architecture has growing exponentially (Kieran, 2004, p. 127).

**Figure 2.10:** Case Study House Number Eight

**Top Left:** Charles and Ray Eames on Eames House' steel frame

**Top Right:** CSH Number 8 exterior view

**Bottom Left:** Interior View of studio

**Bottom Right:** Exterior Detail of entrance

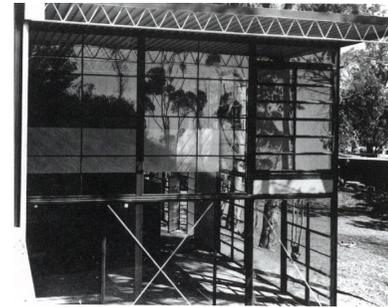
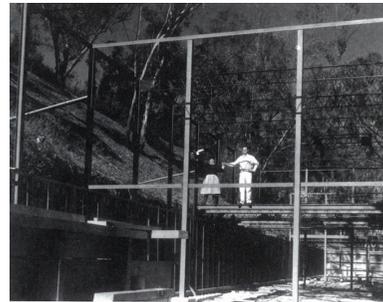


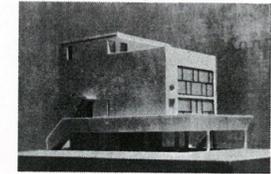
Image source: B. Bergdol and P. Christensen (2008), *Home Delivery*, New York, MoMA: p. 97

## 2.5 Where we are today

Today, the vast majority of houses are built and constructed using traditional methods of building construction, continuing to be built stick-by-stick. 'In the developed world a great majority of buildings, perhaps eighty-per cent by value, are not designed by architects and fall outside of the architecture field... [and] most of the non architectural 80 percent of buildings are houses' (Davies, 2005, p. 8). Design-build firms currently dominate the housing industry; being driven by low-costs and fast schedules, often forgetting to facilitate quality into the equation. 'Their artefacts are buildings, not architecture' (Kieran, 2004, p. 15), yet their existence highlights important factors that need to be addressed within the architectural market; being quick delivery times and firm costs.

The ideologies of applying mass-productions efficiencies to architecture throughout the 20th Century was primarily focused on housing (Timberlake & Keiran, 2004, p127). Architects saw mass-produced housing as a solution to a crisis developed by the economical demands of the World Wars, applying industrial techniques for a product in which they could publicise. Architects were too focused, perhaps with exception of Eames and Saarinen, on the resultant 'product', forgetting to represent the systematic advantages of mass-production. If the logistics of mass-production were applied outside of the residential domain, with few historical exceptions, then the possible interpretations of how mass-production could be applied to architecture may have resulted in an entirely different approach. Colin Davies, author of the book *The Prefabricated Home*, says that the 'one off house for a sympathetic patron is a poor model for popular housing, and the fact is that they should be designed for a market, a customer, not a client' (Davies, 2010). Though this has relevance to kit homes; history has shown that unless prefabrication and architecture can be driven for a specific client, the demand does not exist.

Architects had the right vision to imbue customisation within industrial manufacture (mass-production). However, the technological advancements in achieving such complexity was not apparent. Their visions were far too optimistic for the logistics of mass-production, and the initial set-up costs of factories far outweighed the output for the financial benefits of mass-production. Their artefacts of design were not replicates of one another, and caused complication during the stages of both design and construction. Modular coordination was too complex to apply to a customised design, and physical construction was not accurate enough to maintain the flexibility; and has been a complete misinterpretation between the ideologies of accurate, closed architecture and flexible, open architecture. The truth lies that mass-produced architecture throughout the 20th Century has been a complete failure (Davies, 2005; Timberlake & Keiran, 2004).



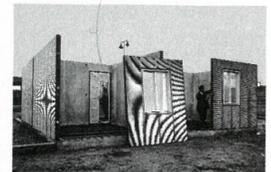
**LE CORBUSIER 1910**



**BUCKMINSTER FULLER 1930**



**FRANK LLOYD WRIGHT 1940**



**WALTER GROPIUS 1960**



**OPERATION BREAKTHROUGH 1970**

**Figure 2.11:** A Century of Attempts - The modernists of the 20th century had many attempts to apply mass-production, prefabrication and modularisation techniques to their designs. None of their endeavours ever achieved success and were soon abandoned.

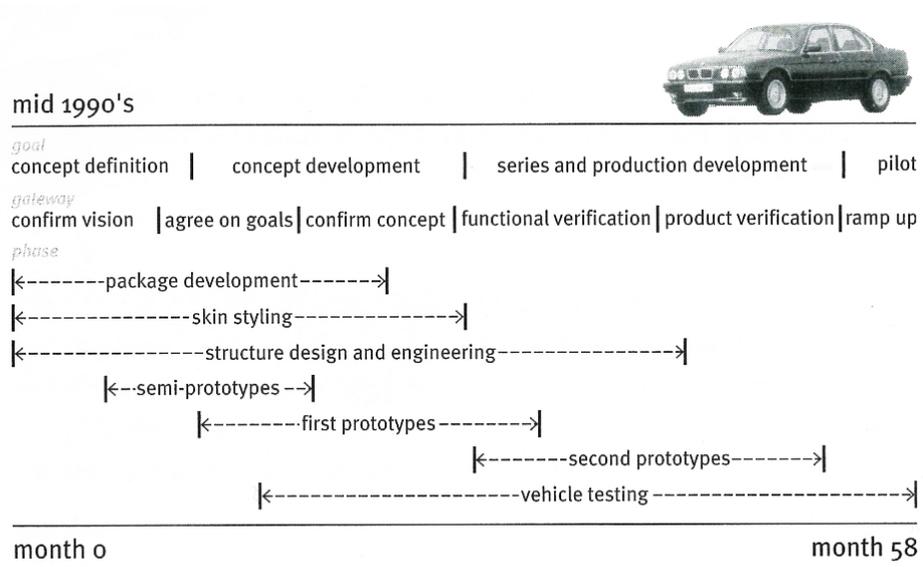
Source: S. Kieran & J. Timberlake (2004), *Refabricating Architecture*, New York, McGraw-Hill: p. 104

The Case Study Houses are potentially the best example of a rationalised process for mass production. The programme focused on processes already in manufacture and, therefore, were utilising economical and efficient benefits already in practice. Their application did not cater for factories, although they were limited by materials available; their designs were customised to the full extent. Their designs were based upon efficiency of predetermined products; products that were already utilising the efficiencies of mass-production.

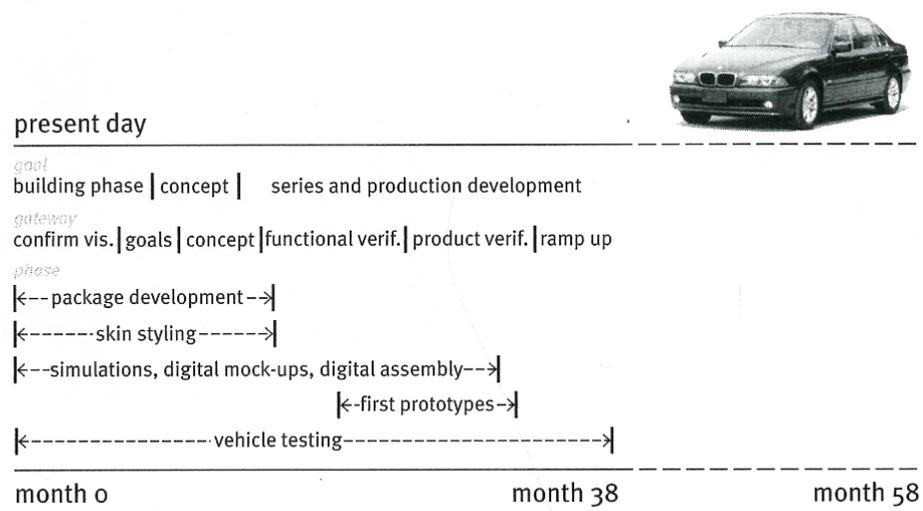
Mass-production, however, was 20th Century. The 21st Century is now overwhelmed with digital lean production and mass-customisation (Davies, 2010, p. 10). Industrial manufacture can now cater with new, flexible architectural models, and digitally driven advancements have guided such complexities, complexities where the technicalities of mass-production and architecture have clashed (Pearman, 2010). If the successful application of 21st Century automotive design and manufacture principles are to fuse with architecture; architecture must learn from the mistakes that have led to the failures of the attempts for applying industrial production with architecture, and confine itself to realistic goals.

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**VS.**



**T = TIME FROM CONCEPTION TO MARKET**

**Figure 3.0:** Automotive Manufacturing Progression  
- The automobile has successfully been able to reduce design and construction time through digital modelling, virtual testing, supply-chain management and process improvements.

Source: S. Kieran & S. Timberlake, *Refabricating Architecture*, New York, McGraw-Hill, 2004: p. 20

## 3.0 *The role of the automobile*

As stated in the previous chapter, mass-production is essentially cost driven. The manufacturing solution to production has been to make and 'develop bigger machines through economies of scale in order to drive down costs, and this became the mentality that ruled the vast majority of the manufacturing world for the majority of the 20th Century' (Liker, 2004, p. 25).

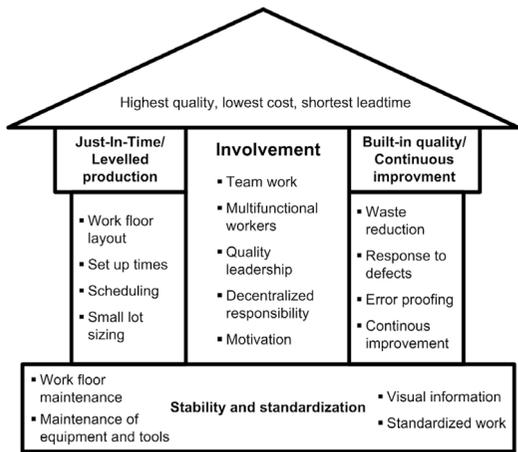
Since the introduction of Massachusetts Institute of Technologies' *Auto Industry Program* and the bestselling book based on its research, *The Machine that Changed the World*, the world's manufacturing industry has discovered the principles of lean production (Womack, Jones, Ross, 1991).

The automotive industry is now aided with digital design tools and simulations that have further addressed the high-complexities of the automobile. Quality, costs and delivery are generally a measure of factory performance, but the auto industry has now added flexibility (Fujimoto, 2007, p. 4); which has historically been unattainable through the rationalities mass-production.

Though many principles of lean-production are not beneficial to a service sector (such as architecture), the organisational capabilities and digital collaboration of manufacture are. This chapter will establish the organisational capabilities of lean-production; defining key principles that have allowed the automotive industry to evolve throughout the beginnings of the 21st Century. It will begin by addressing the organisational principles of lean-production, then further elaborating on predominant factors that have allowed for its efficiency. It will conclude by establishing how the modular-platform architecture of the 21st Century automobile has been derived by its manufacturing processes, and how digital technologies have further guided the efficiencies between lean design and production.

### 3.1 *Lean Production – Organisation Capability*

Firstly, lean Production's success is not just the fixture of one system alone (Fujimoto, 2007; Liker, 2004). It has taken Toyota years of development, both intentional and subliminal, to develop the factors which have led to the success of one of the most consistent, quality and productive companies in the automotive sector. The main goal of lean-production is defined as just-in-time-production; that is encompassing the reduction of non-value added waste. It has been the end result of addressing costs, quality, delivery and foremost flexibility; a notable factor that led to the failure of mass-production within architecture.



**Figure 3.1:** Toyota Production House - (lean production).

Source: M. Höök & L. Stehn, *Lean principles in industrialized housing production: the need for a cultural change*, *Lean Construction Journal*, 2008

As stated earlier, mass production has typically endeavoured to maximise its production efficiencies through producing large quantities of one item at a time. Lean production, by comparison, distributes its costs through the levelling of flexible production<sup>8</sup>. The reduction of lead-time has been lean production's primary goal - that is the reduction in time between when the order was initiated to the time it was fulfilled. As a result it has discovered that when you make lead-times shorter and focus of keeping production lines flexible; you achieve higher quality, better customer response, better quality and better utilisation of equipment and space (Liker, 2004, p. 10). Jeffery Liker in his book, *The Toyota Way*, describes the process of lean production as;

‘a way of thinking that focuses on making the product flow through value added processes without interruption (one-piece-flow), a pull system that cascades back from customer demand by replenishing only what the next operation takes away at short intervals, and a culture in which everyone is striving to continuously improve’ (Liker, 2004, p. 7).

Lean-production's success, therefore, is not directly automated production, but rather the organisational processes which can be used to attain flexibility, reduce waste and attain better quality; through its reduction in lead-time.

To elaborate on principles that have driven the automation efficiencies in production, the differences between lead-times must be established. Not all principles of lean-production are valuable to a service sector, thus lead-time can be categorised into two components: development lead-time and production lead-time. Whilst the automobile industry does require both development and production lead-time, the customer of a new car is rarely affected with development lead-time due to the manufacture of an existing, developed product<sup>9</sup>. This differs, however, from a service sector (such as architecture) where the client has to wait for the design and documentation for an architecturally inspired one-off house. If architecture, however, could be designed through digital processes of utilising existing products and supplier information, it could achieve a reduction in both development and production lead-time; and as history has indicated, this has been the most applicable approach for applying industrial manufacture within architecture.

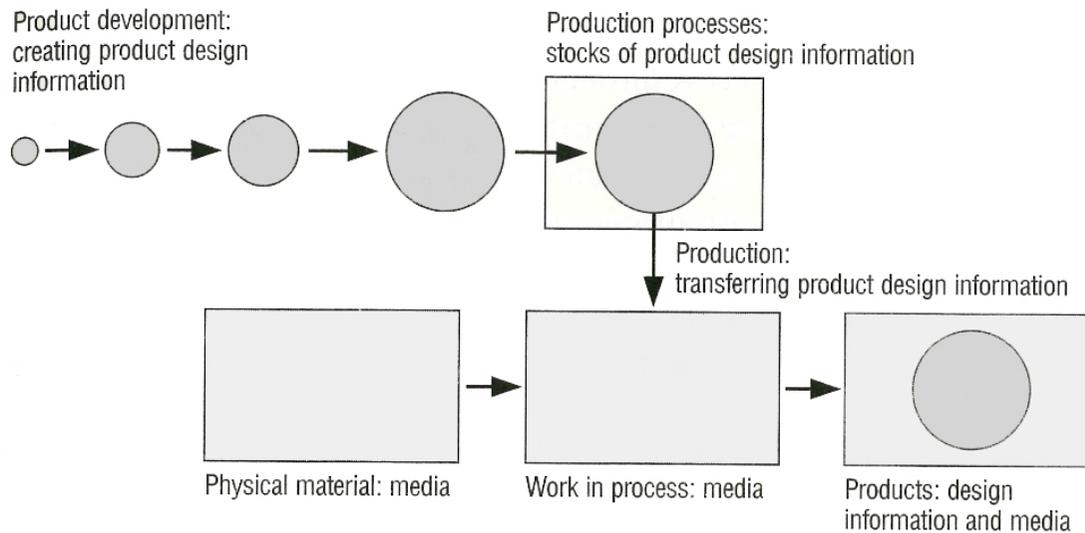
8. The distribution of different models and kinds of parts over different periods of time (Fujimoto, 2007, p. 51)

9. The design and testing of the automobile has already taken place before the vehicle is released

### 3.2 Products as Information Media

From a technological point of view, 'products are merely media infused with information. Product development, therefore, can be seen as the creation of design information, and then production becomes the transfer of that information into physical matter' (Fujimoto, 2007, p. 3). With this understood, it becomes easier to understand how automotive manufacturers are able to successfully implement CAD and CAM<sup>10</sup> with the complex organisational capabilities of lean production; through the digital collaborative storing and transferring of product information between assembler, manufacturer and designer.

#### Production as the Transfer of Design Information



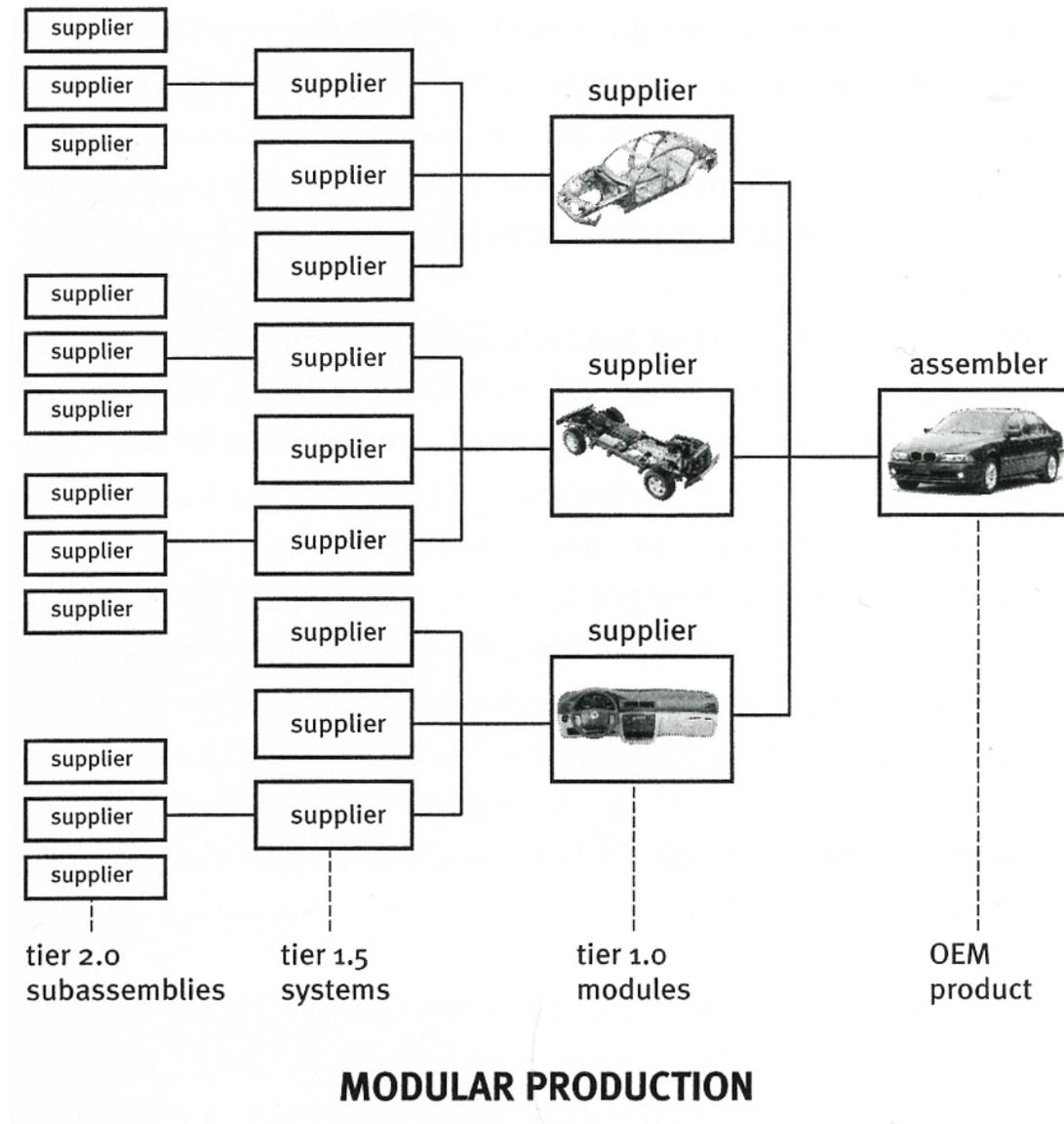
**Figure 3.2:** Production as the transfer of design information - Production is the transfer of design information to physical media. Lean production has been successful in its way to cultivate relationships, and speed the transfer of digital design information to product media (digital production).

Source: T. Fujimoto (2007), *Competing to Be Really, Really Good*, Japan, LTCB International Library Trust: p. 3

<sup>10</sup> Computer-aided-design, and Computer-aided-manufacture

**Figure 3.3:** Modular Production Supply Chain - The automotive supply chain is now broken down into tiers of supplier. It begins by the 'assembler' (manufacturer) who now sub-contract large proportions of the design and manufacture of the components, tiering down to the process and supply of individual components and fixtures.

Source: S. Kieran & S. Timberlake (2004), *Refabricating Architecture*, New York, McGraw-Hill: p. 86



### 3.3 The Reliance on Supply Chains

Historically, the stock piling of parts has necessitated pre-establishing customer demand; leading to the simplistic rationalities of mass-production. Lean-production, however, through digital collaboration with suppliers, now implement digital memorandums of design information with their manufacturers in order to achieve both diversity and complexity (Fujimoto, 2007, p. 6); it is what the automotive industry now call supply chains<sup>11</sup>.

Japanese manufacturers now rely on supply chains to provide large proportions of parts and materials (Fujimoto, 2007, p. 51), of which they expect core suppliers to now undertake responsibility for both design and development of subassemblies within the context of complete vehicle systems. The tiering of suppliers remains in control of the organisational capabilities, and due to the relative complexity of the automobile, assembly manufacturers often limit the number of core suppliers (Fujimoto, 2007, p. 63). First tier suppliers maintain direct collaborative information sharing between themselves and assembly manufacturers, allowing for both flexibility and competitiveness within design. And due to assembly manufacturers' market power, they can maintain a durative change for suppliers to implement to their organisational routines (a notable difference between the building industries market power).

The reliance on supply chains has seen vast improvements in quality, costs and product development (Liker, 2004, p.14). It has allowed the productivity, for both development and production, to become a crucial factor in maintaining company competitiveness. There has been encouragement to ensure that the relationships are maintained between the suppliers and assemblers, and that the successful sharing of information between all parties in the supply chain is always maintained.

### 3.4 Kaizen – Continuous improvement

Continuous improvement (Kaizen) is how car manufacturers have excelled in applying the principles of lean-production. The development of new models often compromises both concurrent and sequential technology transfer; that is the sequential development from previous models in development (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2008, p. 87).

With digital technologies, automotive manufacturers are now able to share and modify platforms (section 3.7) of design components with different models, resulting in reduction of both design and development; with less overall costs through the accessibility to manipulate digital information. The design of sequential transfer relates to the bottom-up<sup>12</sup> process of design, utilising established parts to be placed within complex commodities. This differs from an architectural perspective in which most 'architectural endeavours fall under the new-design



**Figure 3.4:** Tiers of Suppliers - The reduction of joint at the final assembly are reduced through the supply of components in the supply chain.

Source: S. Kieran & S. Timberlake (2004), *Refabricating Architecture*, New York, McGraw-Hill: p. 96

11. the movement of materials as they flow from their source to the end customer

12. Designing the components as individual entities, then modifying them within specific parameters to suit specific design

model; where 'time and resource incentive activities are generally done from scratch on a project-to-project basis' (Schodek, et al., 2008, p. 157). Continuous digital improvement has allowed this to be overcome. Designers now have access to information that can digitally test, adapt and resolve issues in commodity design within virtual simulative models, and the solution is through the front-loading of design.

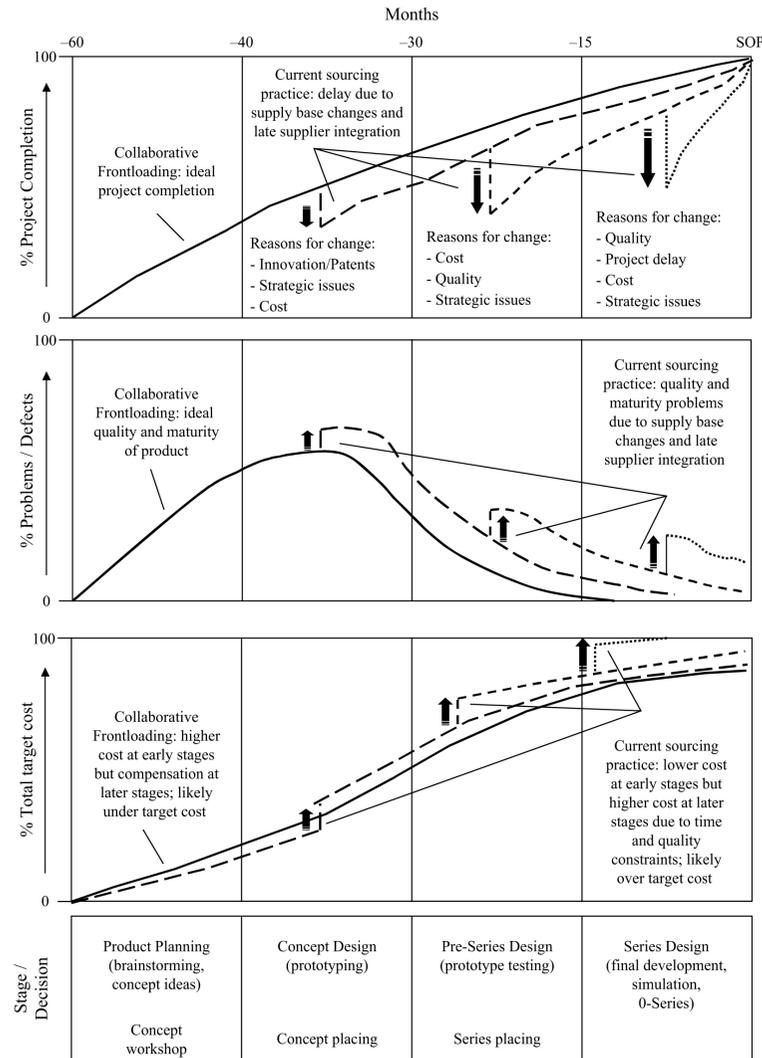
### *3.5 Front Loading – Digital Memorandum*

The front-loading of design refers to 'amassing the skills and resources to solve problems in the early stages of the design', and has been a 'crucial factor for the successful production of the automobile' (Fujimoto, 2007, p. 135). Computer-aided design and component systems have been successful in determining and further amplifying the benefits of flexible, lean production.

Three-dimensional modelling is now implemented at the very beginning of the design stages, and componentised developments allow for the continuous improvement of evolution and adaptation. Adjustments are far easier to make in the design and drawing stages of objects, so front-loading has been seen as the sustainable way in shortening production lead times. Direct information is now embedded within 'information models' that house and contain both design and manufacturable data within digital software (Fujimoto, 2007; Liker, 2004).

Automotive front-loading has been the combination of solving problems across common vehicles, and solving the model at hand. Embedded software has become a large development field in order to allow for the front-loading of design. Although there is freedom within supplier design and technological advancement, the software which interfaces between manufacturer and supplier becomes a crucial link in relating the systems as an entirety. The handling, aerodynamics and complications of sub-assemblies all working together as a uniform product poses huge challenges and issues (Michailidis, Spieth, Ringler, & Hedenets, 2010). Digital information technology has convincingly proved its capability through the speeding up of development in the automotive industry; being a factor of reinforcement for efficiencies, not a negotiation.

The digital continuum of information between supply chains and manufacturers has removed waste. The powers of such companies have managed to enforce lean principles onto its suppliers through continuous improvement in both productivity and relationships. 'Information technology has furnished convincingly, if backhanded, proof of that capability in speeding development' (Fujimoto, 2007, p. 136), and advancements in technology have reinforced, rather than negotiated, the importance of traditional capability building in the auto industry.



**Figure 3.5:** The impact of collaborative front loading on time, cost and quality within the automotive manufacturing industry.

Source: M. Binder, P. Gust & B. Clegg (2008), *The importance of collaborative frontloading in automotive supply networks*, Journal of Manufacturing Technology Management, Volume 19: p. 324

By the 1990s the issue of restoring cost competitiveness needed to be addressed, and the automotive industry turned to product design. Their successful measures came by simplifying product specifications (Fujimoto, 2007, p. 130) and digital collaboration with suppliers through the front-loading of componentisation. It has been the digital, organisational evolution of both its processes and product architecture; and the proceeding principle that ties the two together is modularisation (Fujimoto, 2007, p. 141) (Modularisation with respects to physical sub-assembly components, not 'modular dimension' as prescribed in modular coordination).

### 3.6 *Automotive 'Architecture' - Modularisation*

The physical 'architecture' of the automobile has been developed over time in regards to its process 'architecture'. To establish this process there needs to be a distinction between the two types of product 'architecture'; both integral and modular.

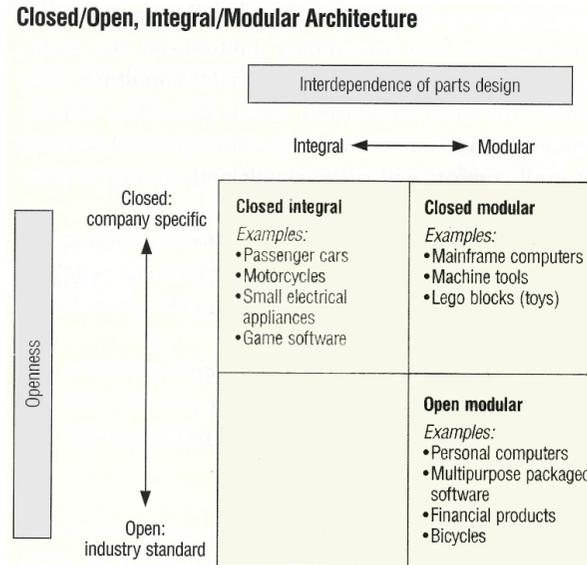
- Though this section defines the 'architecture' of the automobile, it is not referring to the profession of designing buildings, but the arrangement of various components in which they compose a final commodity.

Integral architecture comprises of an entirely closed system, with each individual component developed precisely to interact with that specific artefact. The functionality and performance of that artefact relies specifically on the design and manufacturing of every individual principal component, so manufacturers tend to rely mainly on components designed specifically for their products. Vehicles have historically been a classic example of an integral product architecture; and more than 90% of components in a mass-produced vehicle have been developed to suit that specific model and company (Fujimoto, 2007, p. 17).

Modular architecture, however, is the interaction between components that occurs entirely through clear-cut interfaces; that is the joining conditions between sub-assemblies. Manufacturers of the end product can rely largely on 'off-the-shelf' components as long as the design relates to industry standard interfaces. Modular product designers only require basic understanding of the artefact for which it is produced. As long as the interface and dimensional parameters are clearly defined, the design and production of modules can be entirely integral- they do not require the knowledge of how other modules work, only their specific function. The supply and design of modular architecture is readily available to any manufacturer, but the modular approach to architecture can either be closed or open in regard to determining company relationships (Fujimoto, 2007, p. 35).

In integral architecture, the relationship between functionality and component design are more complex, and often overlap. Epitomising this architecture is the automobile (Fujimoto, 2007, p. 36). Each function of automotive design components have a corresponding factor to cater for in regards to its overall performance. The assembly of such products obstruct how all the systems interact with one-another (Fujimoto, 2007, P. 16). The suspension and handling of a car, for instance, requires factoring in the performance of the tyres, weight distribution, wheel base, steering, transmission and chassis. All these factors rely largely on one another to maintain an individual goal (handling and ride comfort). While each specific component may excel in its individual performance, the composition of the systems working together may not. This is where the organisational capabilities of digital front-loading have taken affect. Digital design environments may appear as striking three-dimensional models, but are not necessarily based on representation alone. Three dimensional models can

contain embedded information of how the numerous systems interact, connect and be produced. The three-dimensional model is an exact simulation of the proposed artefact.



**Figure 3.6:** Relationship between closed/open and integral/modular product 'architecture'.

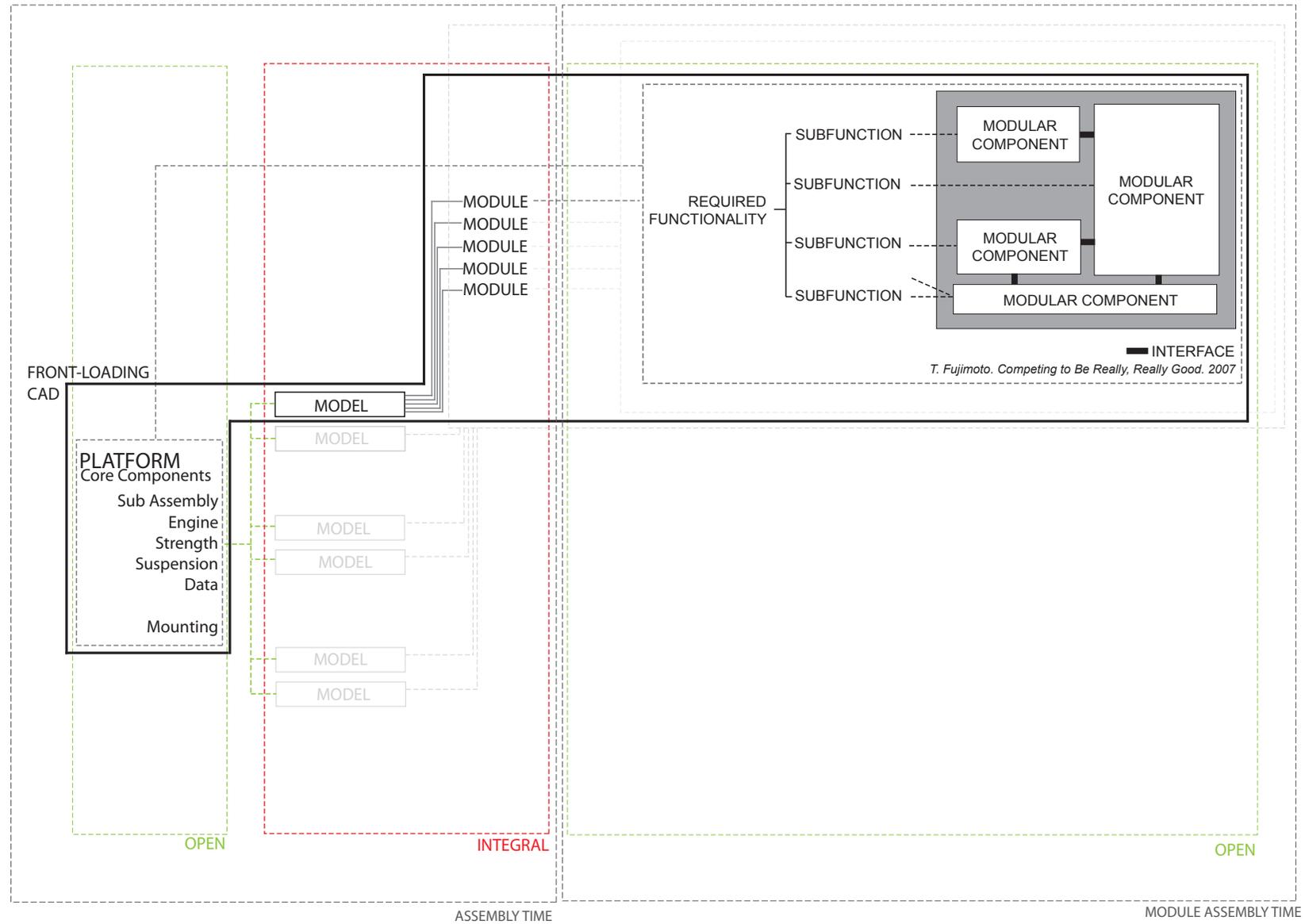
Source: T. Fujimoto (2007), *Competing to Be Really, Really Good*, Japan, LTCB International Library Trust: p. 36

On average, the automobile contains about 109 basic systems. These include power train, body, chassis and interior. It also encompasses dozens of subsystems, which house thousands of functional elements (Fujimoto, 2007, p. 38). It conforms to highly integrated systems and electronics that step outside of the general open modular approach, and relies largely on closed systems that are implemented through modular production efficiencies.

The initial development of the automobile was an open modular design. Mass-production, however, changed the architecture of the automobile into a replicated integral approach. The individual parts were replicated numerous times for efficiency to suit each specific model alone. Cars today, however, are a form of highly integral modular architecture as a result of their development production systems. The system has been able to simplify its manufacture and design processes without simplifying its products complexities. Herbert Simon, a Nobel literature in economics, had already demonstrated the utilisation of such systems, stating that, 'building components in such a manner would maximise both efficiency and quality' (Macduffie & Fujimoto, 2010, para. 3); and the automobile now takes advantage of such processes, and the development of the automotives process architecture has had an adverse effect on its product architecture through its use of modularisation (which supplies components as functionally or structurally stand alone modules).

'BUS' MODULARISATION

Standard structure in which can achieve a number of attached elements to maintain individuality  
Way to reduce costs and allow the maintenance of MORE vehicle models



By the 1990s, more than eighty-percent of car components in a mass-produced vehicle were made for that specific model, or to that specific manufacturer. This number has reduced to around sixty-percent at the beginning of the 21<sup>st</sup> Century (Fujimoto, 2007, p. 130). The architecture of the automobile now comprises of industry standard, company standard, and model specific components. These components are then assembled into company specific products, in which all different models maintain their own design integrity. The facing of these components are then digitally implemented, and the simplification of automobile assembly has now been resolved. It has simply been seen as a way of automating work (Fujimoto, 2007, p. 136). Complex systems are too hard to automate, but the simplifying of assemblies to be later joined into a commodity has become a way of simplifying production without simplification of design integrity.

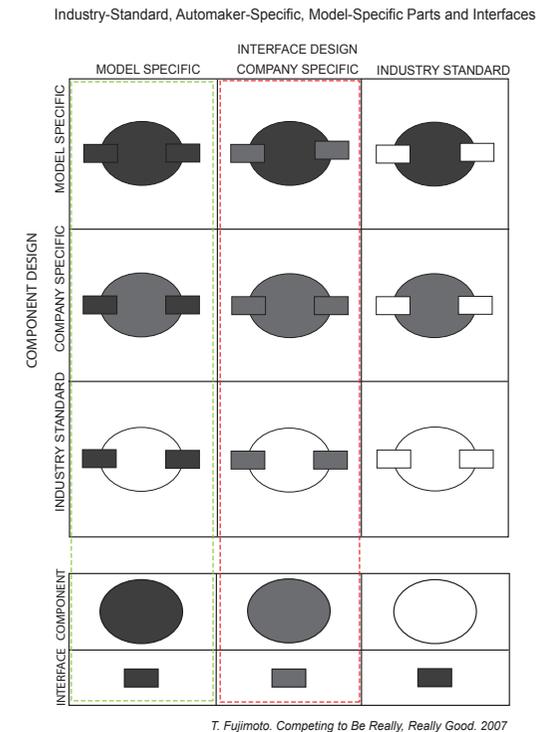
### 3.7 Platform Sharing<sup>13</sup>

The automotive 'platform' has been the 21st Century approach to maintaining model specifics, whilst reducing lead-time and sustaining economics. The sixty-percent which remain similar among models and manufacturers often lie amongst the underlying dynamics and engineering specifics of the automobile, being referred to as the automotive platform.

The platform comprises the vast majority of the mechanical components, that is, the components that take months, even years to develop. If models can maintain similar mechanical and performance criteria, the costs can be distributed across a larger range of models, further levelling production across flexible production lines.

Platform sharing is currently being explored throughout the industry. Nissan for example, which was almost essentially bankrupt a few years back, have become one of the leading automotive companies thanks to the host of new products based on just two platforms. The 'FM' platform lies under all Nissans rear-wheel-drive machines, such as the 350z, the Infiniti G35 (Skyline), the Infiniti FX, and the front-wheel-drive 'FF-L' platform defines the Altima, the Maxima, the Murano, and the Quest (CSERE, 2003). The idea of sharing new mechanical components is not an entirely new concept, American cars of the 70s were using similar ideas through sharing monocoque<sup>14</sup> structures, but the main difference is the amount of external differentiation between models (CSERE, 2003), which has been driven through defining clear cut interfaces of modularity.

The motivation for platform sharing has been costs. The costs of engineering and development can lead to huge expenditure for model development, but through the distribution of costs across common models, development costs can be distributed, benefitting from the efficiencies of mass-production. It must be noted



**Figure 3.8:** Interface Design - Interfaces between industry-specific, manufacturer-specific and model specific parts and interfaces.

Adapted from: T. Fujimoto (2007), *Competing to Be Really, Really Good*, Japan, LTCB International Library Trust: p. 39

**Figure 3.7 (opposite):** Automotive 'BUS' Modularisation - Interfaces between industry-specific, manufacturer-specific and model specific parts and interfaces.

Adapted from: T. Fujimoto (2007), *Competing to Be Really, Really Good*, Japan, LTCB International Library Trust: p. 34

<sup>13</sup>. 'Platform' as being 'architecture', it is the specifics and design not the physical 'platform', or 'chassis' that the automobile sits on.

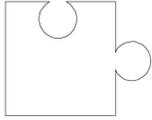
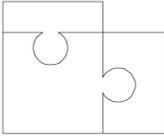
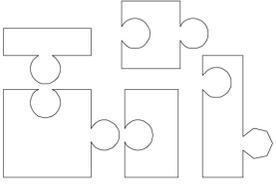
<sup>14</sup>. Construction technique used that supports the majority of structural loads through using an objects exterior

that whilst lean and digital production has catered for personalisation and flexibility within its manufacture, the cost efficiencies of mass-production are still economically greater in a monetary sense. What lean has done is approached a broader range of production costs over a larger range of product (Schodek, et al., 2008).

Though it remains economically efficient to manipulate between flexible manufacturing and lightly adopted mass-production, the adoption of shared components across different models cannot be as precisely optimised as it can be for model specific products. Using the Nissan FX platform, mentioned earlier, for example. The Nissan FX weighs 4497 pounds, and can carry up to 1000 pounds of cargo, whereas the Nissan 350z, which is a two-seated sports car, weighs only 3339 pounds (RSSportscars.com, 2008) would have any structurally sufficient piece over engineered far stronger than it needs to be (CSERE, 2003). For this reason, car manufacturers only share components which are expensive to develop and manufacture, and which will create the least compromise when applied to other applications across the range (CSERE, 2003). This is why many manufactures now respond to the 'platform' as being 'architecture', it is the specifics of design not the physical 'platform' (or 'chassis') that the automobile sits on.

**Figure 3.9:** Modularity as a System - 'The demand for creation of variety by combination and interchangeability goes beyond the individual module. Variety and interchangeability have no meaning unless there are more than one module. Only by seeing the module as part of a system this make sense. From this it follows that modularity is an attribute which relates to the structure of the system - A structuring principle for technical systems.' (Miller & Elgard, 1998)

Image Source: Miller, T. D., & Elgard, P. (1998). *Defining Modules, Modularity and Modularization: Evolution of the Concept in a Historical Perspective*. Paper presented at the Design for integration in manufacturing

<b>From <i>one module</i> point of view (*)</b>	<b>From <i>one product</i> point of view</b>	<b>From a <i>system</i> point of view</b>
		
<ul style="list-style-type: none"> <li>• Self-contained functional unit (testable)</li> </ul> <p>(*) It doesn't make sense to talk about one module isolated according to the previous reasoning. Modularity is a system attribute. A unit is a more correct word. But it does not illustrate the purpose of this comparison as well.</p>	<ul style="list-style-type: none"> <li>• Self-contained functional unit (testable)</li> <li>• <i>Well-defined</i> interface and interaction</li> </ul>	<ul style="list-style-type: none"> <li>• Self-contained functional unit (testable)</li> <li>• <i>Standardized</i> interface and interaction</li> <li>• <i>Combination</i> as a principle for creation of variety</li> </ul>

### 3.8 Digital Lean Production

Automotive complexities still vary across manufacturers, but it is safe to say the adoption of lean-production has developed new hype in industries outside of the automotive. The flexibility that lean production has produced and developed in conjunction with digital technologies and modular architecture now offer new ideas of 'mass-customisation'<sup>15</sup>: that is to utilise the benefits of low-mid volume production efficiencies to produce flexibility amongst specific design.

In a modular structure<sup>16</sup>, a 'module implements only one or few main functions in its entirety, whereas in an integral structure, the functionality is spread over the product' (Miller & Elgard, 1998, para. 17), and this is where the automotive industry has been successful in the juxtaposition between modularity and integral design. Toyota can now produce 60,000 vehicles a month, of which around 25,000 generally consist of individual model variations (Fujimoto, 2007, p. 125). Vehicles now share over forty-percent of common parts; in which they develop a platform of components that can be assembled into both functionally and aesthetically different vehicles.

Vehicle manufactures have shaved nearly eighty-percent of costs through the rationalisation of design (Fujimoto, 2007, p. 129), and advances in computer aided-design and manufacture has guided them to do so. The rationalisation of modulated design and shared supplier competitiveness has maintained the cost competitiveness, quality, and scope within the design of the automobile; all factors that could have positive effect on the way we construct today's buildings. Each of the elements- productivity, lead-times, quality, manufacturing, purchasing- are all the result of a well-established organisational routine, and only when these systems work together do they increase competitiveness. The communication between all these factors is product design information (Fujimoto, 2007, p. 52). The utilisation of CAD and CAM has allowed the automotive manufacturer to further gain advancements of organisational capability through the efficiencies of both lean production and modular manufacture. Digital technologies have had a significant effect on both manufacture and productivity; and front-loading has been the solution through allowing the productive, sequential manufacture of adjoining assemblies. It has shown the world that shorter sub-assembly lines result in fewer workers and fewer parts; of which has resulted in fewer defects within production. The automotive industry has proven that complex systems can work in modular form, and digital production can aid in flexibility. It has successfully shown the world that complex, industrially produced products can be manufactured effectively, cheaply and most importantly with flexibility.

*15. Mass-customisation relates to the automation capabilities to produce flexible customer output, whereas, lean-production is the organisational capability, which allows for efficient, 'lean' manufacture. Mass-customisation should not be seen as a continuous improvement of lean production (Pine, Victor, & Boynton, 1993)*

*16. The composition of an artefact that is composed of numerous modular sub-assemblies*

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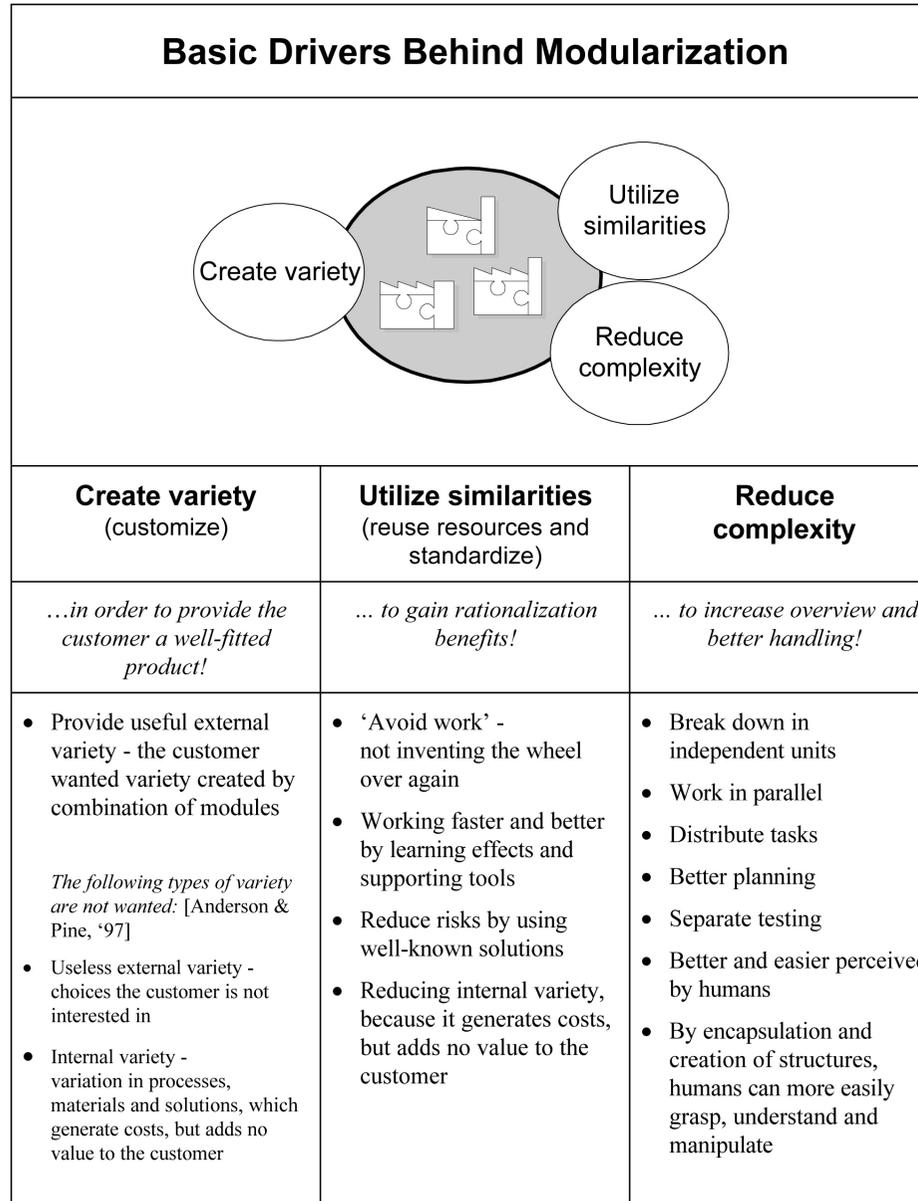


Figure 7: Modularity balances three important basic drivers: Creation of variety, utilization of similarities / reuse of resources and reduction of complexity.

## 4.0 Modularity in Architecture – Current Trends

Modularity in architecture is not an entirely new concept and has become a current trend within current prefabricated design, though many do not attain the flexibility or digital efficiency trying to be attained in this thesis.

The chapter begins by introducing current trends of modularity in architecture; indicating the comparison between the categorical modular architecture<sup>17</sup> of the automobile and the volumetric interpretation<sup>18</sup> within current building prefabrication. The second section then explores the flexibility of manipulating modular dimension and componentisation; further giving background to the concluding hypothesis on how we can apply digital, lean and modular efficiencies to contemporary architecture.

### 4.1 Modularity in Architecture

According to the research text *Defining Modules, Modularity and Modularisation*, based from J.D Millers book *Modular engineering*;

- A module is an essential self-contained functional unit relative to the product of which it is part. The module has, relative to a system definition, standardised interfaces and interactions that allow composition of products by combination
- Modularity is an attribute of a system related to structure and functionality. A modular structure is a structure consisting of self-contained, functional units (modules) with standardised interfaces and interactions in accordance with a system definition. Replacing one module with another creates a new variant of the product
- Modularisation is the activity in which the structural model takes place

'In architecture, modularity is defined as the physical dimension which is given to a geometric classification system'<sup>19</sup> (Staub, Dörrhöfer, & Rosenthal, 2008, p. 44). The physical dimension, which is given to the term module, is dependent on the scale and scope of modularity that is chosen within each design. When companies are searching for customisation, modularisation has been the way to balance between product variety and rational production (Miller & Elgard, 1998). Significant problems with prefabricated buildings, however, are the inability to prototype and refine details prior to final construction; though with manufactured products there is opportu-

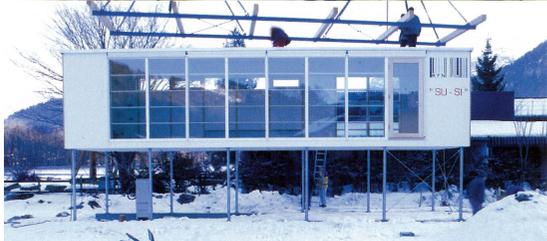
**Figure 4.0 (opposite):** Basic Drivers Behind Modularisation - Three important basic drivers to modularisation; utilisation of similarities, reuse of resources and reduction of complexity.

Image Source: Miller, T. D., & Elgard, P. (2008) *Defining Modules, Modularity and Modularization: Evolution of the Concept in a Historical Perspective*. Paper presented at the Design for integration in manufacturing

17. Module classified by their specific function, not location

18. Volumetric sections of the complete artefact

19. Similar to the modular definition given within modular coordination – a three dimensional grid with reference to a physical dimension



20. They are developed to work as that system, and that system alone

21. The closed systems can be incorporated within a over compositional design

22. For example: Structurally Insulated Panels (SIPs) are generally produced at widths of 1200mm but can often be manufactured up to 2.4m

23. DManufacturing machines that translate digital information into physical material

nity to invest into research and testing prior to production, amortizing these costs over significant production runs (Anderson & Anderson, 2007, p. 14).

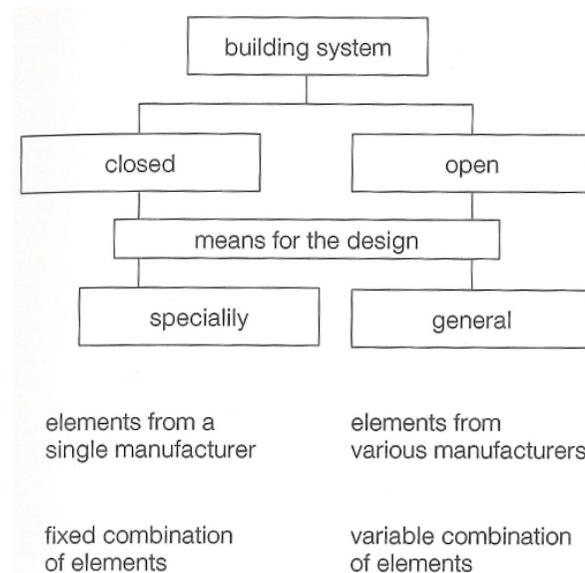
As discussed in Chapter Three, there are two forms of modularity; both open and closed. Modular building systems are often closed, stand alone prefabricated systems that lie independent of specific building specifications (Staib, et al., 2008). They are generally manufactured by individual companies; being manufactured as entire building systems or as elements which construct parts of buildings. They remain closed in a systematic sense<sup>20</sup> versus a schematic sense<sup>21</sup>, and are designed to independently work as unitised systems with no respects to adjoining assemblies. The organisation of components takes respects to both geometric and constructional rules, and the composition of individual elements cannot simply be changed, altered or extended as desired (Staib, et al., 2008).

Open systems, however, offer the possibilities of utilising products from different manufacturers. Compared with closed systems, 'open system are not allotted to an individual building but are based upon the combination of various prefabricated building parts which compose the building as a whole' (Staib, et al., 2008). When designing with open systems, the architect determines the component function and aesthetic, and selects manufacturers accordingly. To minimise assembly difficulties, as modular coordination has perceived, families of components are generally standardised, dimensionally coordinated and constrained to ensure the reduction of problematic interfaces (Staib, et al, 2008). The classification of these elements can exist on different levels. The building industry, by nature, already has industry standard units of measure<sup>22</sup>, though the standardised units of measure are becoming more flexible as the use of digital computer numerical control machines (CNC) grow<sup>23</sup>.

Today, modular application within the construction industry is often referred to as the prefabricated, closed volumetric units that are factory built as complete, plumbed, clad, and standardised units which are assembled on site (Anderson & Anderson, 2007, p. 183). The current generalisation, however, has been that the more standardised the units can be, the more promise they offer through greater certainty of greater production volumes. This, however, is based upon mass-production, and the 'mass-production way of thinking is a way in which the domestic housing industry cannot cater for' (Pearman, 2010, para. 13). The larger the volumetric units become, the more standardised both their appeal and use are; thus the least amount of possible applications can be applied. 'When large, volumetric modules are built in factories in small quantities they achieve only a few of the efficiencies of large scale mass production, and often retain challenges for transportation due to their physical dimensions' (Anderson & Anderson, 2007, p. 183); and as Chapter 2.0 outlined, the initial setup costs far outweigh the production output to gain such financial feasibility.

The volumetric approach works well for modular hotel design- where the rooms are small and easy to prefabricate and transport with identical services, making them easy to slot in place<sup>24</sup>. Permanent housing, however, 'with its variety of room types becomes an entirely different game' (Pearman, 2010, para. 16). The most successful promise for modular design appears to be between the two extremes- semi-finished elements<sup>25</sup> and completed volumetric units- reinforced by Mark and Peter Anderson in their book *Prefab Prototypes*, stating that 'the elements of prefabrication are far more effective than prefabricating the entire thing' (Anderson & Anderson, 2007).

Currently, the chassis and infill<sup>26</sup> approach appears to be the most successful application to componentised modularity within architecture; and is currently being explored by KieranTimberlake Architects and the Massachusetts Institute of Technology's House-N Project. Their research and development focuses on utilising infill components that plug into the 'chassis', which has been defined as the structure; being referred to as 'plug-and-play construction' (Blum, 2007). KieranTimberlake are currently approaching the building sector in a modular fashion; and architect Andrew Matthews recommends that the way forward for domestic architecture may be to learn from office building techniques. Thus, the collaborative approach between the two could be the success of digitally implementing speed and precision to residential architecture.



**Figure 4.1 (top opposite):** Silvercast Western Homes factory - Prefabrication factory that can complete three houses per day.

**Figure 4.2 (middle opposite):** Su-Si House by KFN Systems - Volumetric application being transported to the site.

**Figure 4.3 (bottom opposite):** Su-Si House being craned onto its piles - The houses vary in length from 10 to 14m, and width from 3 to 3.5m.

Source: Arieff, A. (2002). *Prefab*. Layton, Utah :: Gibbs Smith. p. 11 & 101

**Figure 4.4 (left):** Open and Closed building systems.

Source: Staib, G., Dörrhöfer, A., & Rosenthal, M. (2008). *Components and Systems: Modular Construction Design, Structure, New Technologies*. Basel, Switzerland: Birkhäuser Verlag AG: p. 43

24. Bathrooms and Hospital design are also relevant examples for volumetric modular application

25. Lowest Form of Prefabrication- i.e. current trend of building with 2x4 timber lengths

26. Chassis and Infill approach is the idea of separating the structure and partitions within construction. This type of system is often used on commercial buildings to allow for flexible floor plates.

## 4.2 Digital Modularity – Initial Exploration

Though volumetric and componentised effects are currently being used within prefabrication, my initial experiments have been an exploration for the degree of flexibility that can be attained within the dimensional characteristics of modulation. A physical house/system was not needed for this initial experimentation, but it was an exploration of how ‘typical’ building components (structure and infill) can be applied within different scales of modularity. The variance in size and flexibility was used to determine what could be perceived as platform, sub-platform and infill components. The idea was based upon the sharing of platform components through the experimentation for determining the volumetric scale that can be efficiently attained within flexible, modular design.

With reference to the modular dimension’, no numerical figure was given to the components, as this was purely an experiment of modular flexibility. The three categories, platform, sub-platform and infill, were flexed within CAD programme *Revit Architecture* to determine the flexibility and adaptability. The change in scale not only resulted in restraints of compositional flexibility, but the amount of problematic interfaces that remain between components. If an entire closed building system was to be produced, the interfaces could be standardised between all components; though historical application has indicated that utilising existing systems gives more pragmatic application.

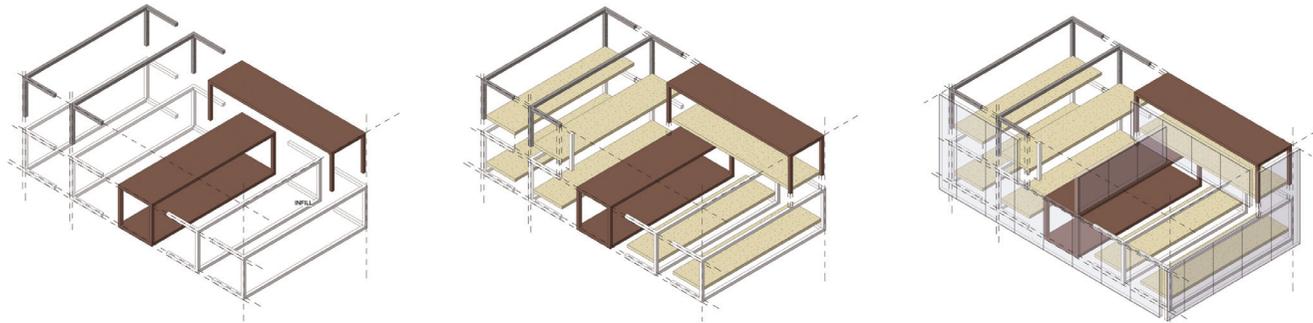
The pre-assembling of structural components was an ideology to between individual members and volumetric application. If the frame is to be structurally efficient and attain the same flexibility of individual members, there needs to be a large number of standardised structural components<sup>27</sup>. The literal interpretation of an automotive chassis was then experimented; applying prefabrication to only the horizontal planes. The only resultant benefit was the flexibility of floor-to-floor height; offering little benefit with respects to prefabrication and/or flexibility.

Using sub-completed modules for the structural design offered very little construction benefit and created large component lists if the doubling of the structure was to be minimised. The most efficient application for modular structure was individual component based platform; this is due to smaller, individual based components being able to maintain the most compositional flexibility without the doubling of structural members. Though more members need to be determined for compositional layout, it was easy to digitally implement the components within the three-dimensional model through the standardisation of interfaces.

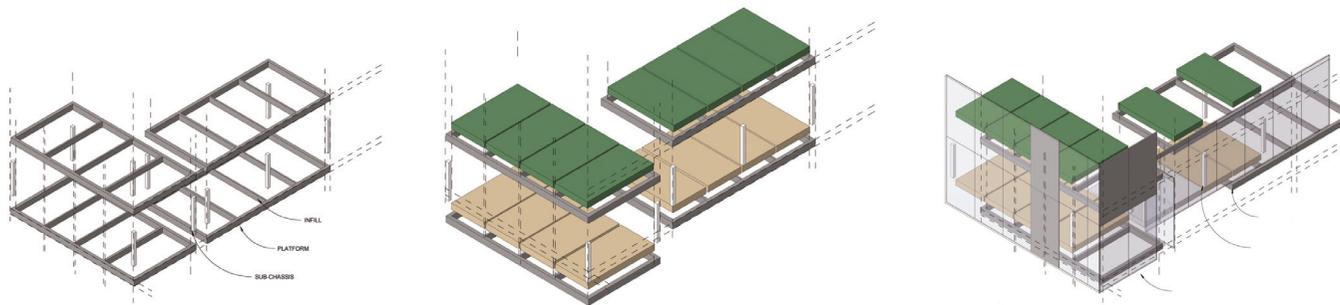
By utilising Building Information Modelling (BIM) the initial exploration of modular dimension and component flexibility was able to be easily flexed within the computer model. Developing and designing components out-

*27. Frames that come as volumetric units double up structural members at their points of connection. Though member sizes can be reduced to cater for this, volumetric units are often over-engineered due to the stresses of transportability.*

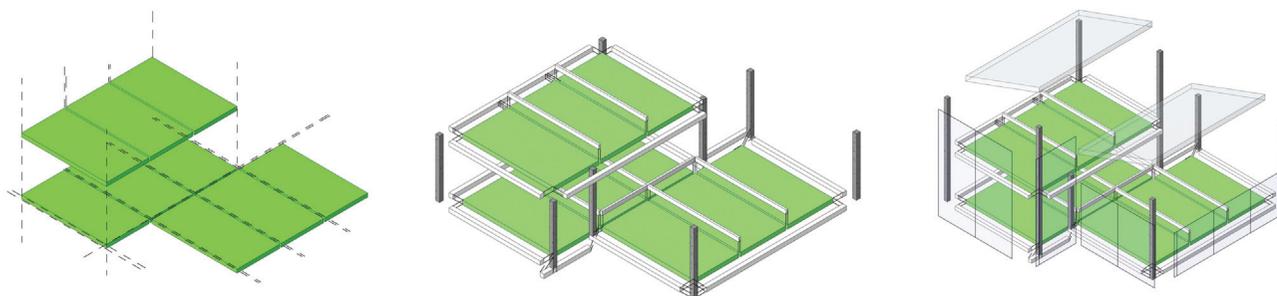
side of the individual compositional model placed great emphasis on both component and commodity design quality. In respects to overcoming the historical complexity of applying modular coordination within componentised design, computer-aided-design (CAD) surpassed all historical challenges of flexing and attaining compositional individuality; both precisely and efficiently.



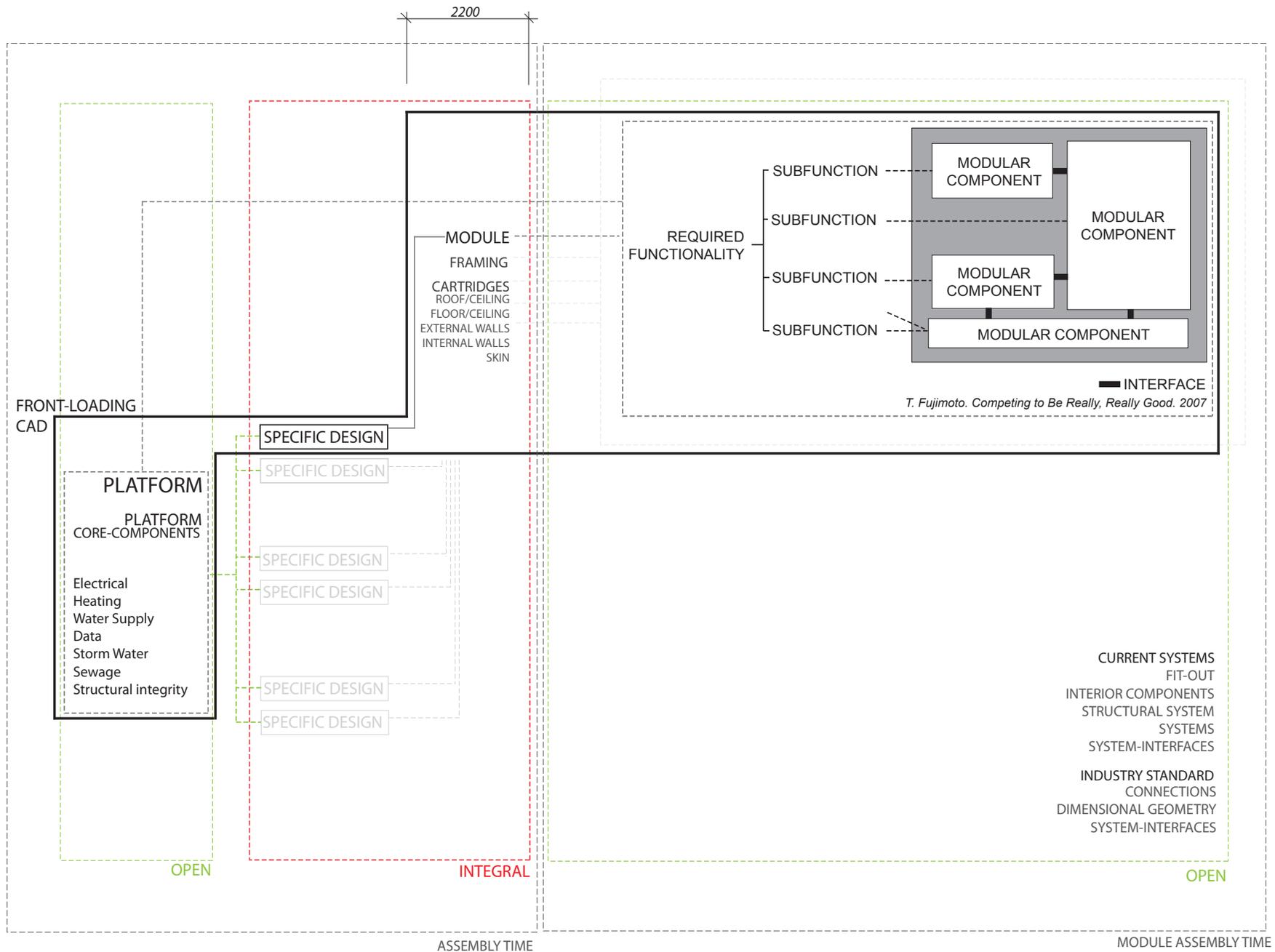
*Figure 4.5:* Structural Prefabrication - Experimentation with larger structural components. Offered little benefits with respects to modular prefabrication, and complexity for flexible composition necessitated numerous components.



*Figure 4.6:* Chassis Prefabrication - Literal translation of 'platform' applied to housing.



*Figure 4.7:* Component Based Prefabrication - Individual structural components, with modular 'infill' achieved the most compositional flexibility through rationalisation of components.



### 4.3 Hypothesis/Design Brief

To achieve the aim of this thesis, applying modular coordination through the utilisation of computer aided design and closed system manufacture appears to be the most pragmatic approach; and that Andrew Matthews' reference: 'we can learn from the commercial building industry' has merit; in that separating structure, skin and services can allow for the precision, modulation and speed of construction. The automobile, here, can become the precedent for success of integral, componentised modulation. And lean production principles of organisation can assist in attaining complex integral design. If the digital encouragement of CAD and CAM can be utilised, architectural design can be done in the same integral manner, yet be manufactured through modular, lean efficiencies.

Though there are current trends of volumetric modular units in prefabrication, they do not parallel the necessity of flexibility with off-site fabrication. Wet areas<sup>28</sup>, however, are the most laborious to construct (due to services installation and finished) and should be determined as volumetric units, which are based around a common platform design<sup>29</sup>. This would replicate the efficiencies seen in current hotels, and the units can be dimensioned for transportability. The remainder of the services should be accessible and based around perimeter installation, allowing for adaptability and easy installation. The remainder of the house should be designed using infill modular components; which are determined by a specified grid. Cars are generally considerably smaller than buildings, so the grid system (explained in section 5.1) is to become a reference point for the location and placement of modular components. The platform of the house will become the dimensional restraint based around existing manufactured sub-assemblies; that can be finished, composed and placed within the integrity of the design.

Component sharing can level production costs across the system. Architects, possibly with few exceptions, do not have the same company power of car manufacturers, so the adaption of pre-existing building systems appear to be most practical approach for application. Currently, there are many systems that are advanced and excel in both efficiency and technological advancements, so should become part of the pre-determined collaboration within the supply chain.

To successfully implement the complexities of integral design and modular efficiencies, front loading is suggested. Currently within the architectural market there are numerous programmes that can be used for the benefits of modular design, and should be used to their full extent; though many are currently only used as tools for two-dimensional representation. Autodesk's *Revit Architecture*, for example, already has scheduling, collaborative and parametric functions embedded within its software features. If such advances can be used to their full

**Figure 4.8 (opposite):** Lean productions approach to architecture - Hypothesis diagram for the application of 21st Century automotive manufacturing and design principles to architecture.

Adapted from: T. Fujimoto, *Competing to Be Really, Really Good*, Japan, LTCB International Library Trust: p. 34

28. Core, Kitchen, Bathrooms

29. As mentioned earlier, similar to that of current hotel design and hospital design

extent, then other aspects of the construction process, such as material ordering and specification can similarly be approached in the same manner of time and cost (Anderson & Anderson, 2007, p. 184). Finally, architects may be able to control the juxtaposition between integrity, standardisation and manufacture. Then the elements of production and adaptability will be able to complement flexibility and standardisation.

## 4.4 References

Anderson, M., & Anderson, P. (2007). *Prefab Prototypes - Site Specific Design for Offsite Construction*: Princeton Architectural Press.

Blum, A. (2007). *Plug+Play Construction*. *Wired magazine*

Miller, T. D., & Elgard, P. (1998). *Defining Modules, Modularity and Modularization: Evolution of the Concept in a Historical Perspective*. Paper presented at the *Design for integration in manufacturing*.

Pearman, H. (2010). *Three Men and a Prefab*. *RIBA Journal*(July/August 2010), 26-30.

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## 5.0 Reinterpretation of Process and Design

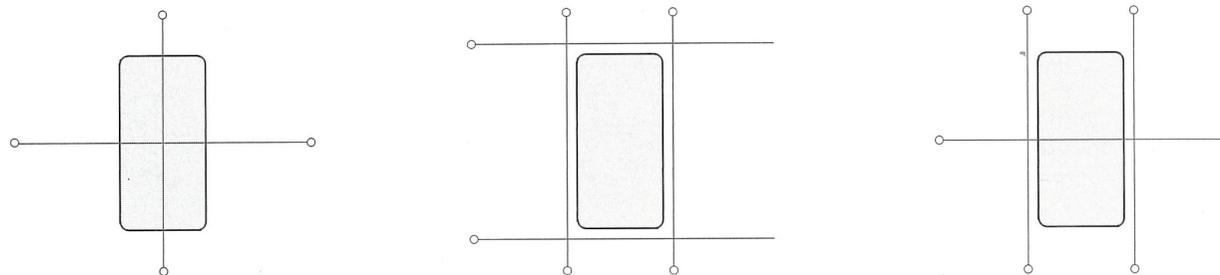
Through the design of a parametrically driven flexible housing system, this chapter explores the use of computer aided design software to establish a response to the hypothesis (section 4.3). The exploration establishes the processes in how we can reinterpret the historical top-down approach of architectural design by designing through digital modulation and lean production principles.

The process and system lie as two different outputs (continually discussed throughout the chapter), and the system has been used as a tool explain and explore the process of how we can apply digital automotive manufacturing principles to the way we design and construct contemporary architecture.

- For the purpose of this thesis Revit Architecture has been used as the CAD software
- For the discussion of this chapter the simplified 'bach' design was chosen

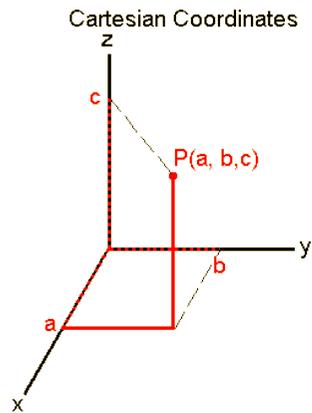
### 5.1 The Grid

The grid is a geometrical system that determines the position and dimension of modular building elements (Staib, Dörrhöfer, & Rosenthal, 2008, p. 46). As determined (section 3.6 and 4.3), to attain the most flexibility within a modular system, components need to be defined as categorical not volumetric. Buildings are generally larger than automobiles, so the grid becomes a coordinative reference to both the location and interface of components. Components are placed within the grid; therefore determining the grid not only affects the positional placement, but the physical constraints that are implied on modular components.



**Figure 5.0:** Different Grid Types - Axial grid, modular grid, and axial and modular grid (from left to right).

Source: Staib, G., Dörrhöfer, A., & Rosenthal, M. (2008). *Components and Systems: Modular Construction Design, Structure, New Technologies*. Basel, Switzerland: Birkhäuser Verlag AG: p. 44



**Figure 5.1:** Cartesian Coordinate System Diagram.

Source: The University of Tennessee, Department of Physics and Astronomy, *3d Coordinate Systems*, <http://electron9.phys.utk.edu/vectors/3dcoordinates.htm>

Through research and experimentation on flexing the grid, four determinant factors were established for determining the grids dimension, being;

- Program
- Transportability
- Available Materials/Resources
- Ratio of off-site to on-site assembly

The four factors, however, do not work as single determining entities. Through the investigation into planning, shipping and flexibility requirements, there are often a number of solutions that can affect the possible outcomes for determining the dimensional constraints of the grid. To reduce complexities within the design process, the grid should be trialed and flexed in the earliest stages of the design; as it becomes a crucial factor that will allow for further variety in system selection (section 5.2).

For the purpose of this thesis, the experimented grid was based on a Cartesian Coordinate System<sup>30</sup>, as the system allows for simplicity of joining conditions between components. To reduce a personal investigation into the pragmatics for flexible housing, Neufert Architects Data<sup>31</sup> was used as a model for the internal requirements of residential housing. Ten sites were then selected and analysed for their 'buildable' constraints with respects to site and council regulations; determining the external limitations that need to be facilitated into the modular dimension.

Transport restrictions, however, necessitated this dimension to change.

<sup>30</sup>. A system in which the location of a point is given by coordinates that represent its distances from perpendicular lines that intersect at a point called the origin. A Cartesian coordinate system in a plane has two perpendicular lines (the x-axis and y-axis); in three-dimensional space, it has three (the x-axis, y-axis, and z-axis) ("The American heritage science dictionary," 2005)

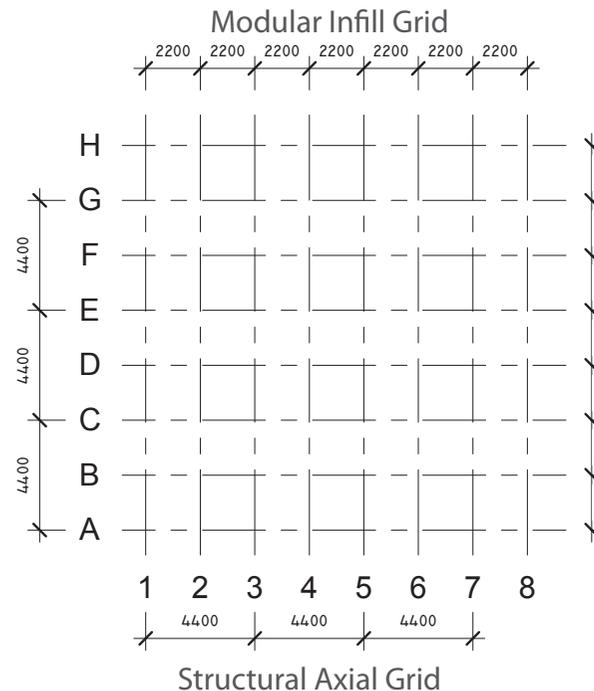
<sup>31</sup>. Neufert, E. (2000). *Architects' data*. Bauentwurfslehre.English, ix, 636 p. .:

## 5.2 Transportability

Cars are comparably smaller than buildings, so the ease of transportability is an essential factor when designing for modular prefabrication. For the purpose of this thesis, a 'standard' shipping container was used as a transportation node<sup>32</sup>.

Due to the internal dimensional restraints (standard sized containers) of a container, a maximum modular dimension of 2.2m must be used, allowing for minor tolerances for lifting both in-to and out-of a container. The dimension then needed to be trialled through the internal and external requirements established in section 5.1. The smaller the modular dimension, the more spacial flexibility available, though consideration for the number of physical components that are to be used needs to be considered. For this system, the dimension of 2.2m was used as not only does it allow for efficient transportability within current container systems, but it allows for adequate dimensioning for standard residential room dimensions (with respects to Neuferts Data)<sup>33</sup>.

Though a container has been selected for a transportation node in this thesis, it is not the only resolution. However, the destination and origin of selected systems need to be factored in for feasible transportability. If local materials and products are to be used, the components can be dimensioned larger than 2.2m, though (section 5.3) finding the manufacturable limitations of suppliers needs to be researched.



**Figure 5.2:** Modular vs Axial Grid - Finalised grid dimensions with respects to transportability, function, structural efficiency and flexibility.

Source: Author, 2010

32. Internal Length 12m, internal height 2.35, Internal Width 2.33m (2.26x2.26m door opening) - (S. Jones Container Services Ltd, 2010)

33. From a materialistic point of view, the grid was further experimented at 1.8m that would allow for a multiple/divisible dimension of the industry standard 1200mm. Though on paper it is materially efficient, for spatial planning it was not. The Neufert's book standard dimensions for rooms, bathrooms and wet areas were defined within 'comfortable' zones, and due to the design of my system prefabricating the wet areas, the 1.8m became an inefficient dimension for in respect to both volumetric and transport sustainability

### 5.3 Finding the Systems

Currently, the most digitally implemented pre-fabricated systems appear to be established in Germany, Scandinavia and Japan. Panelised construction systems appear to be the most advanced with respect to technological efficiency; with many utilising two-axis<sup>34</sup> Computer Numerical Control (CNC) machines. The flexibility of CNC production can allow for suppliers to adhere to custom panel designs as long as they lie within the constraints of their manufacturable capabilities; previously being established within determining the modular dimension (section 5.1).

**Figure 5.3:** *Insulspan* Fabrication Specifications - Many technologically advanced manufacturers are now utilising flexible CNC machines that can allow for flexible manufacturable dimensions within production capabilities.

Source: *Insulspan* Masterformat Specification (2010), Insulspan Inc, <http://www.insulspan.com/downloads/MasterFormat%20Specs%20-%20Insulspan%20SIP%20System.pdf>

#### 2.04 FABRICATION

- A. Panel sizes shall be fabricated in accordance with approved shop drawings. Maximum panel size shall be 2440 mm x 7320 mm (8' X 24'). Fabrication tolerances shall comply with values in manufacturer product specification.
- B. Manufacturing Standards: SIPs shall be manufactured under a third party certification program monitored by an accredited agency and maintain a quality management system in accordance with ISO 9001: 2000.

Though there are many systems currently available within the construction industry, it can be time-consuming when establishing the most feasible system. However, the larger the knowledge base and background researched, the larger the flexibility, freedom and efficiency that was able to be attained for developing specific designs. Though time was spent specifying and determining system feasibilities, a majority of the components were able to be designed from stand-alone systems that are currently available within the construction market<sup>35</sup>.

Due to this research examination not being able to physically build the dwelling, direct collaborative information was unable to be attained between designer and supplier; however, informal collaboration occurred through designing within the capabilities of specified constraints established by manufacturers' data. With respect to this, the direct three-dimensional simulation (Section 5.7) was unable to be a direct translation to manufacture-able machinery, however, accurate two-dimensional representational data was able to be directly outputted from the simulated model, with many systems often further encouraging this with file-format capabilities.

34. Can digitally fabricate along 2 different axis' (x-axis and y-axis)

35. The only exception for custom manufacture remains the aluminium extrusions that were used for the fixture of the SIP's. Though these were custom made, they were based around existing curtain wall fixture systems, and developed through research into component design and manufacture

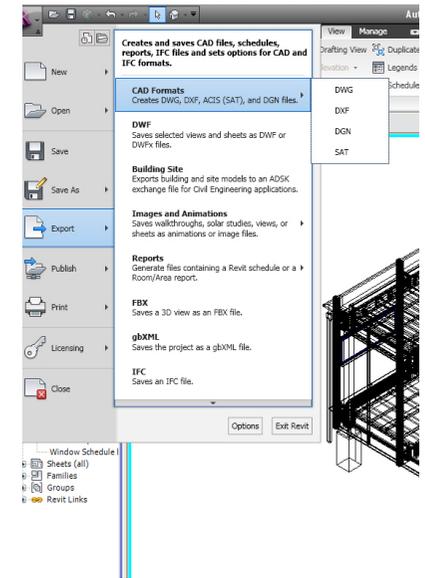
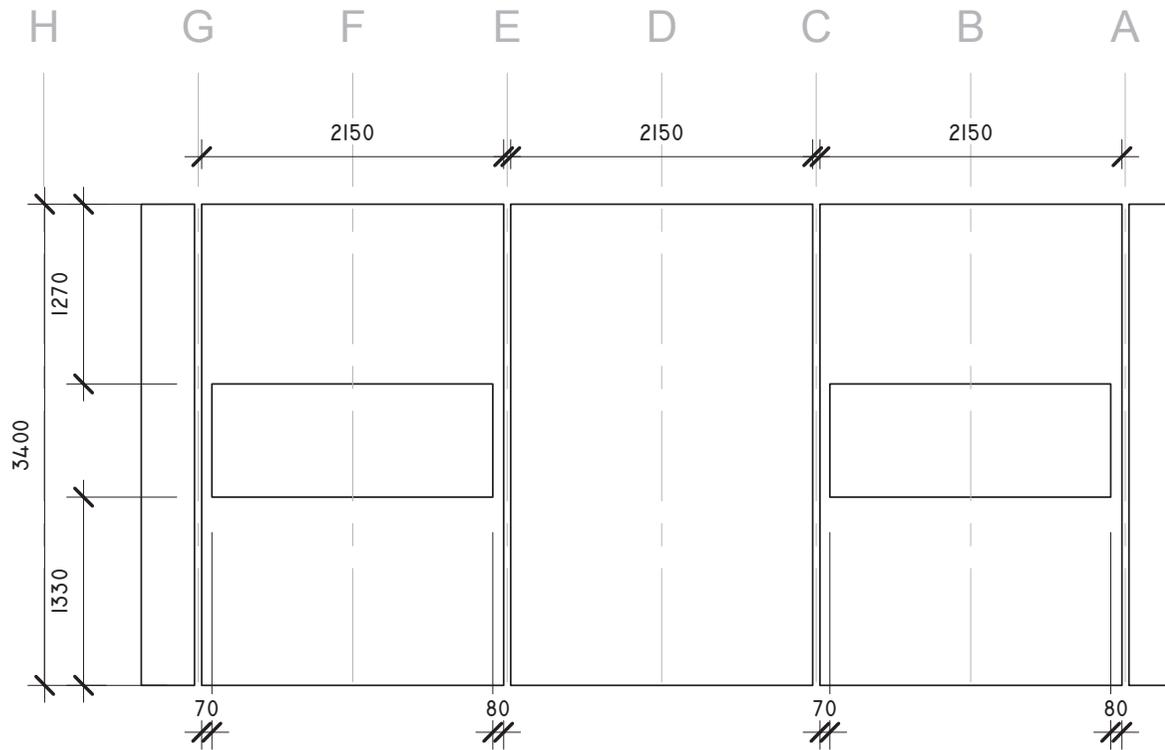


Figure 5.4: CAD Outputs- Two-Dimensional outputs can be accurately translated from the three-dimensional simulation.

Source: Author, 2010

West Wall Schedule							
Location	Length	Height	Width	Manufacturer	Model	Family and Type	Area
E1	2150	3400	114	Insulspan	R16.5	Basic Wall: Insulspan 10MDF_92.2EPS_10MDF	6 m <sup>2</sup>
C1	2150	3400	114	Insulspan	R16.5	Basic Wall: Insulspan 10MDF_92.2EPS_10MDF	7 m <sup>2</sup>
A1	2150	3400	114	Insulspan	R16.5	Basic Wall: Insulspan 10MDF_92.2EPS_10MDF	6 m <sup>2</sup>
G1	379	3400	114	Insulspan	R16.5	Basic Wall: Insulspan 10MDF_92.2EPS_10MDF	1 m <sup>2</sup>
00	379	3400	114	Insulspan	R16.5	Basic Wall: Insulspan 10MDF_92.2EPS_10MDF	1 m <sup>2</sup>

Figure 5.5: Representation from Simulation - Two dimensional output data directly from the three-dimensional simulative model. Schedules and macros can be developed to allow for the filtering of information within the model. Components can also be 'marked' within individual information that can be utilised to specify and their location within the grid.

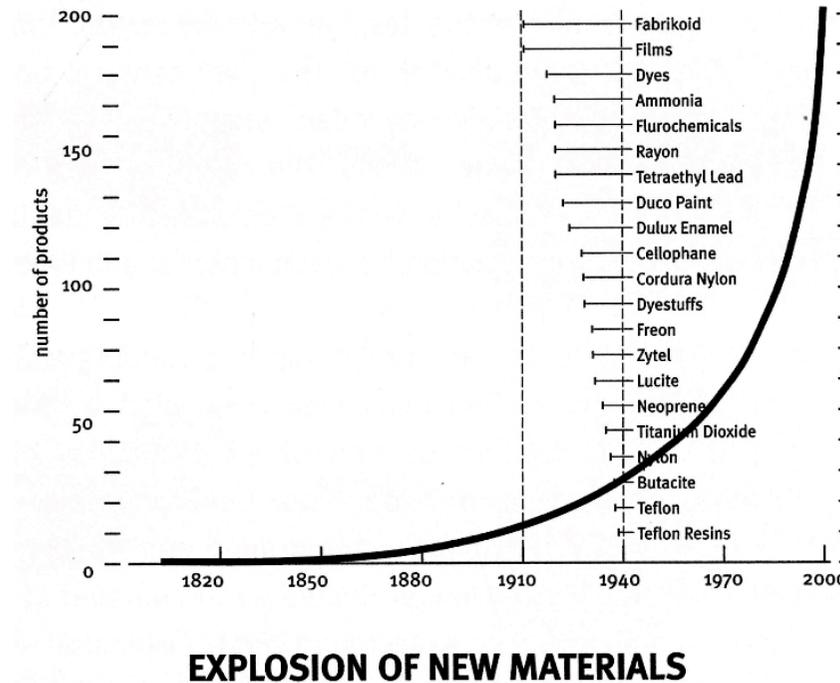
(note: when using modular design within *Revit* wall heights are not directly able to be scheduled, custom based parameters that equate Total wall area - not including window holes - and length need to be established)

Source: Author, 2010

Dimensional restrictions need to be researched for assurance of buildable capabilities that lie within specific designs (section 5.1). Most digital manufacturers list, both standard and custom, dimensions that can be manufactured; and these need to be heavily researched to ensure the accessibility for production of components (or parts of the component). Depending on the level of pre-fabrication required, most systems will not manufacture the modular components in their entirety. Structural Insulated Panels (SIPs), for example, can potentially be supplied complete from the factory, whereas pre-wired floor panels often do not. Whilst both closed and open product systems can be used in coordination with other systems, manufacturers often only supply and manufacture within their specialty. Thus, quality control and supply chains need to be implemented for successful design.

**Figure 5.6:** Exponential Growth of Dupont Products - Throughout the past century the amount of materials available and produced has grown exponentially. Though many of these materials exist, their incorporation into architectural design has been relatively slow.

Source: S. Kieran & J. Timberlake (2004), *Refabricating Architecture*, New York, McGraw-Hill: p. 121



Supplier	Component
Bunnings (Timber Supply, Insulation) Steel and Tube (Fixtures) Electrical Supplier Floor Finish Ceiling Finish Lighting	Floor System
Profab (Modular waterproofing System) Bunnings (Timber Supply, Insulation) Steel & Tube (Steel Bracketry, Fixtures) Electrical Supplier Ceiling Finish	Roofing System
Insulspan (Structural Insulated Panels) Window Supplier	External Wall
Exterior Finish	Skin
Bunnings (Timber Framing) Steel & Tube (Steel Perlins & Fixtures) Electrical Supplier Wall Finish Door Manufacturer	Internal Wall
Bunnings (Timber Framing) Structurlal (Glulam Beams) Unistrut (Quick Assembly Fixtures) Plumbing Supplier Electrical Supplier	Wet Areas (volumetric)
Ullrich (Alluminium Extrusion) Steel & Tube (Fixtures) Engineer (Service hanger) Unistrut (Quick Assembly Fixtures)	Facade Fixture
Kur-tec (Framing System) Structurlam (CNC Glulam Framing) Steel and Tube (Fixtures)	Structural System
	Specific to the integral design

*Figure 5.7:* System Suppliers for a Flexible Housing System - To prefabricate categorical components that are specific to their function often need to implement many different suppliers.

Source: Author, 2010

## 5.4 Supplier Tiers – Quality Control

As automotive manufacturers have noted, the complications of designing and manufacturing through modular design is already complex enough without the further weight of supplier organisation. Further guiding this decision (section 5.3) is that many current construction systems do not manufacture the entirety of the ‘finished’ elements; therefore these finished elements should be located within the second tier of the supply chain<sup>36</sup>.

The first-tier supplier should become the last source of quality control; being a trusted prefabricator. It is here where the pre-fabrication of the volumetric units should take place. Though it would be both financially and sustainably beneficial to source a prefabricated contractor that utilises in-house CNC machines, it is not essential. Further encouraging single source suppliers, is that it allows for the manufacture of ‘finished’ components; providing a single destination for the shipment of products from second tier suppliers.

The architect, thus, oversees this process. He/she controls the collaboration between supplier, manufacturer and assembler. Digital design processes can now be implemented, and architecture can regain its historical role of the ‘master-builder’ through being able to control systems, processes, and construction of both components and their architectural application.

*36. Architects do not have enough market power to force suppliers to manufacture outside of their normal capabilities*

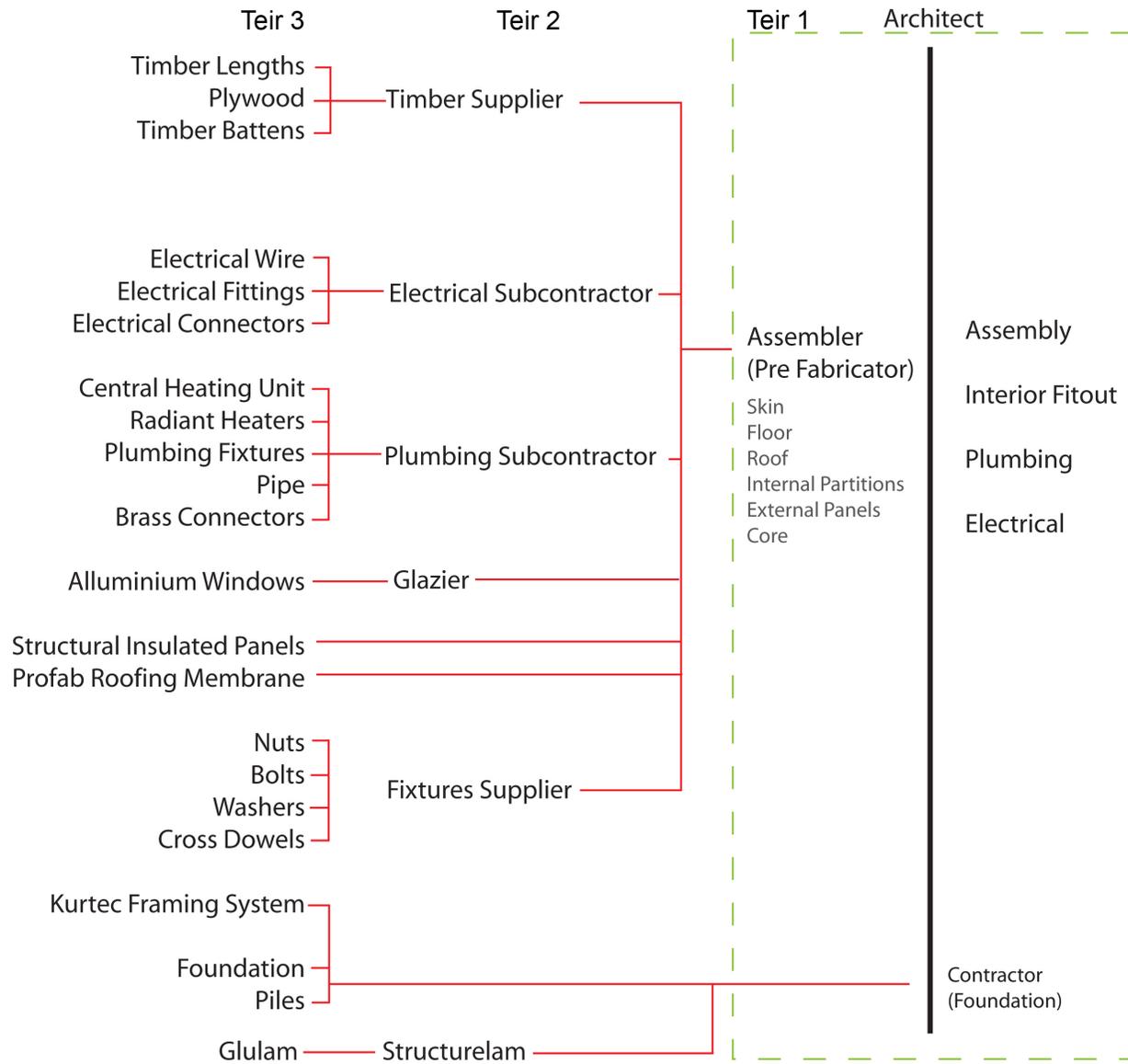


Figure 5.8 Supply Chain Management Diagram.

Adapted From: S. Kieran, J. Timberlake (2008), *Loblolly House: Elements of a New Architecture*, Princeton Architectural Press: p. 42

## 5.5 *Component Design*

Component design is the way in which the system, both individually and compositionally, is designed for both behaviour and aesthetics. As mentioned (section 5.2 and 5.3), there are manufacturing constraints that need to be addressed within component design. Digital design and production, however, has allowed for more freedom which has historically been unattainable through manual coordination and mass-production principles. Parametric and digital manufacturing capabilities can now allow for components to be standardised, yet individually defined within the design of individualistic commodities.

Systems are stand-alone products, designed and developed using closed, in-house technologies. Components need to utilise numerous systems within their categorisation, so component-based software can now be used to precisely document, construct and simulate the composition of both individual components and assembly sequences. Through utilising multiple material systems already in production, the leveling of production and investment has already subliminally occurred through utilising the in-house detailing and system advancements that already lie within such product design.

The way in which these components are designed, dimensioned and positioned, however, still defines the overall aesthetic and function of the design. Though digital production now allows for flexibility within manufacturable coordination, component design can still result in the dictation of the final design aesthetic (discussed later in section 5.8). For component design, the final aesthetic and capabilities of both the individual systems and components working as a system need to be heavily implemented within the selection of such products; due to the adverse effect of aesthetic in the overall integral system.

Componentised design can be done without digital technologies; but the historical application would show that it is far too complex in doing so. Component design is a time-consuming process. Components frequently need to be tweaked, flexed and modified as the specificity of the design evolves; interacting with adjoining systems (continuous improvement). The complexity in component design is the integration of families working together. Applying componentised design to specific models often necessitates the back and forth of updating, adapting and manipulating of the systems; reducing the need for prototyping, which small-scale projects cannot afford to do so (section 3.6). Front loading became the solution to solving such issues (Section 5.7), and was how the digital simulation was able to replicate construction.

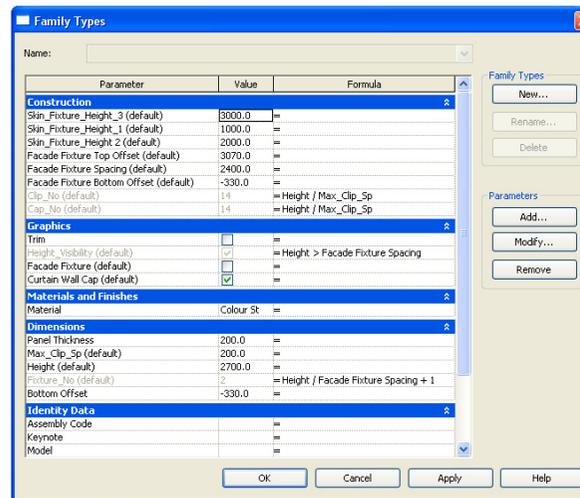
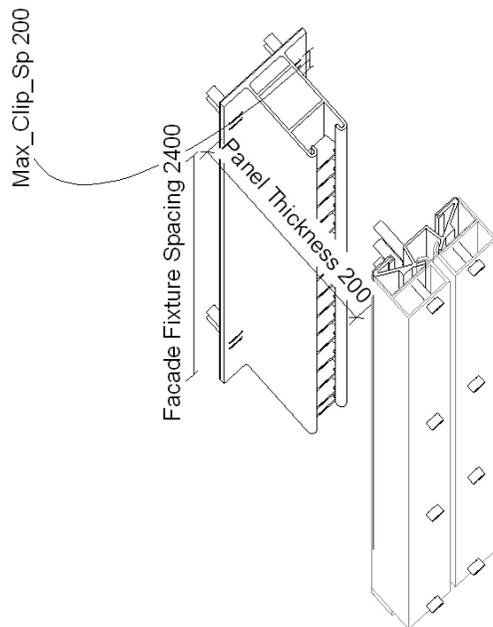
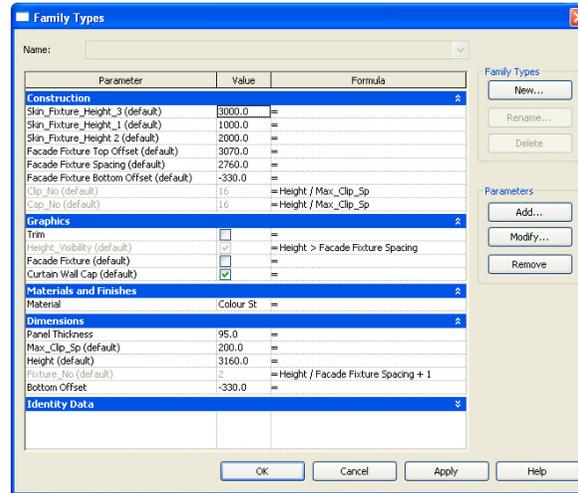
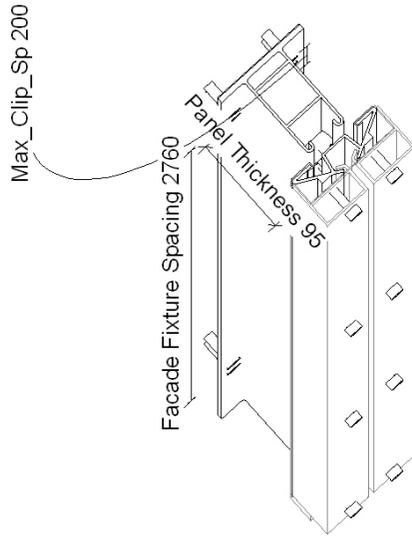


Figure 5.9: Parametrically driven aluminium facade fixture - Through parametric confinements and constraints, individual, yet standardised component data can be easily changed, developed and scheduled within the three-dimensional simulative model. Screen shots in Revit show how changing the constraints of panel thickness and floor-to-floor height, the manufacturable data accurately changes within the model (i.e bolt hole spacing, bolt length).

Source: Author, 2010



**Figure 5.10 (above):** Interior shot of assembled components in 'Bach' House - The system selection and assembly determines the final aesthetic of the integral design.

**Figure 5.11 (opposite):** Floor plan of 'Bach' house - basic reference for following images 5.14-5.36. The finalised plan show the reference for both component categorisation and location.

Source: Author, 2010

## 5.6 Process of Construction

Chassis and infill (section 4.1) does not necessitate the construction process to be an entirely sequential matter; but can allow for simultaneous assembly and manufacture to occur. Though this research didn't eventuate into the construction of a physical dwelling, the process of how we can apply modulation to simultaneous construction was able to be digitally simulated. The power of three-dimensional Building Information Modelling allowed for this simulation to occur; solving the issues of constructability prior to physical application (section 5.7).

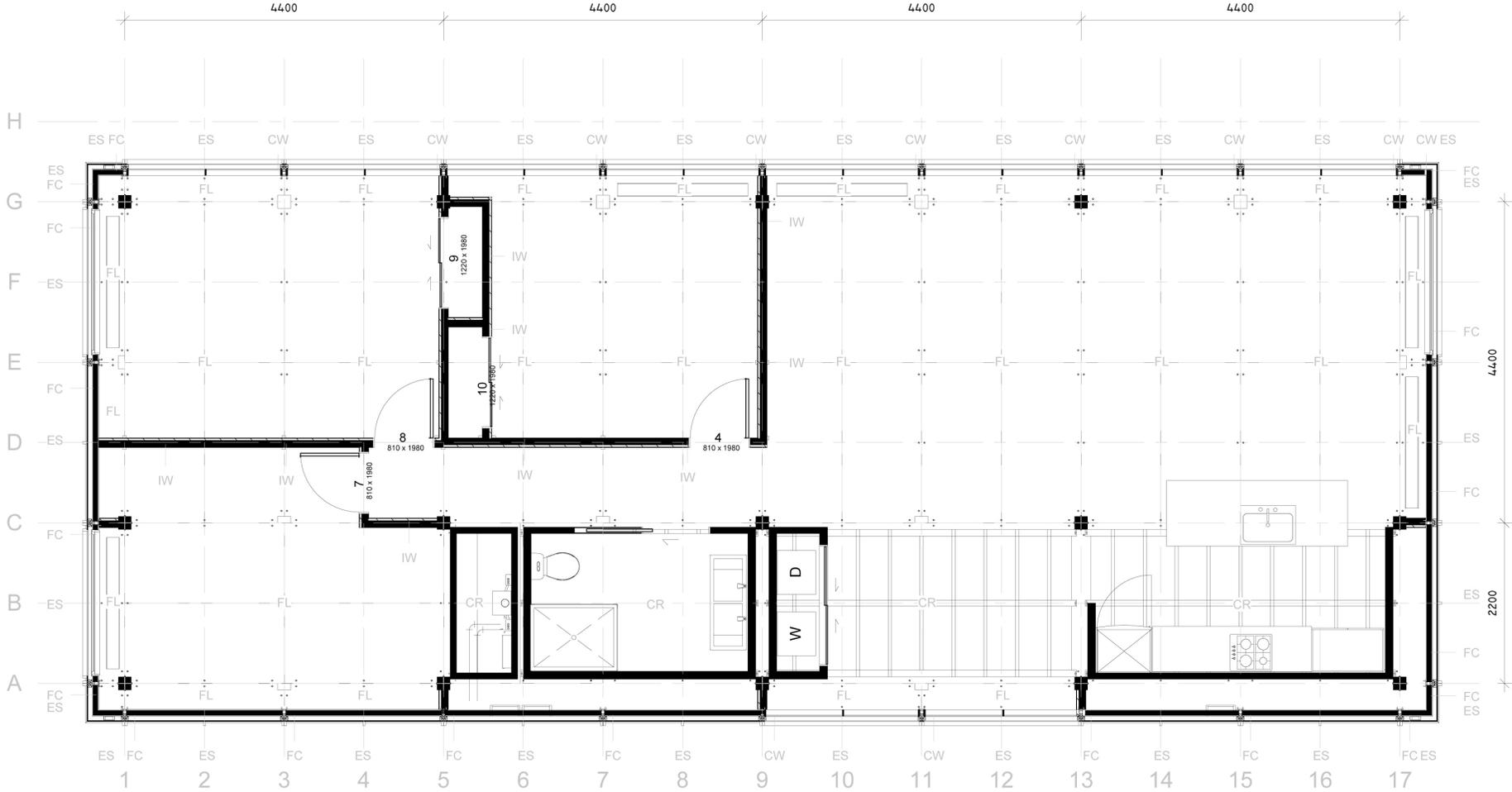
The foundation is the first key aspect to coordinating modular construction. It is the physical reference to the virtual coordination of the grid (section 5.1). Once the foundation has been completed, the remainder of the systems can be simultaneously placed with reference to their simulative grid; 'plug-and-play' construction<sup>37</sup>. The components designed within the system are all individual to their specific location, and can now be individually designed through the flexibility and economics of digital manufacture. For this reason, the physical application of the foundation maintains similar importance to that of the grid; becoming a factor of construction where accuracy and craft must take place.

Through experimenting with different processes of construction, both simultaneous and sequential, (based on commercial construction) separating structure and infill works well; and allows for a sequential construction process to occur once the platform has been established. My research system focused on a fast-track Glulam framing system (Kure-tec, Japan and Structurlam, New Zealand) so the flexibility of CNC manufacture allowed the development of a standardised interface between the platforms whilst adhering to established materials. The interface between all structural, floor, and horizontal connection within the structure remained uniform, so the process of construction, assembly and disassembly can be executed in a simultaneous manner.

Digital 'construction' is more accurate than physical construction. As historically shown, the design for construction tolerance needs to be catered for within the design. Digital manufacture can create direct dimensional replication from product to physical information, but the inaccuracies that occur within placement of these 'accurately' manufactured objects still needs to be factored in. Companies that manufacture components often specify, or can specify, the tolerances needed within their products, though this can become complex when an array of products is being utilised within one component. The keynotes and data embedded in the model becomes crucial to its success; and through designing for tolerable interfaces between precise, accurate, manufactured components, components can be assembled, disassembled and manufactured through the simulative data of building information modelling prior to physical construction; front-loading.

*37. For logical sequence, the wet volumetric areas should be the first to be placed within the structure, as these still having basic connections of amenities, and due to their physical size are the most difficult to situate within the chassis.*

Note: Though virtual construction embodies information about component design and manufacture principles, it does not incorporate the occurring effects of transportability (damage and lifting). To believe that this can be solved through 'careful transport' is not realistic. Practical application needs to subliminally be enforced when designing components; otherwise the damaging effects and 'quality' control of component design cannot be maintained.



*Simulative Construction Process 'Bach House'*

*Figure 5.12 (left):* Foundation Construction.

*Figure 5.13 (right):* Column Assembly.

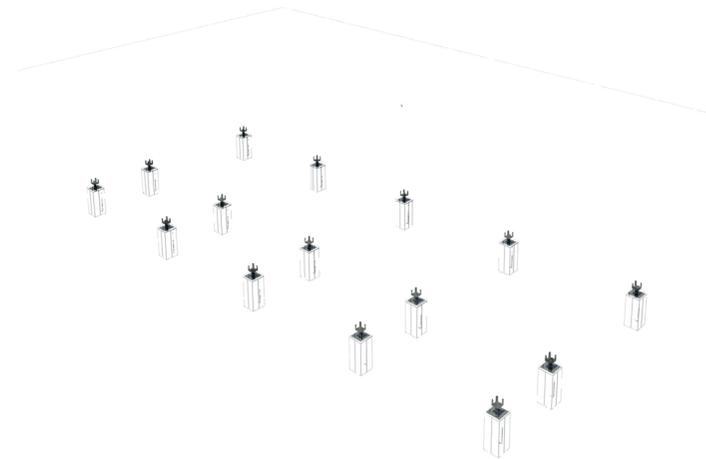
*Figure 5.14 (opposite left):* Detail: Tolerable foundation system, modelled off an adjustable scaffolding system.

*Figure 5.15 (opposite middle):* Detail: Assembly of *Kur-Tec* Japanese framing system. Bolted through pre-drilled holes in *Stratalam* columns.

*Figure 5.16 (opposite right):* Detail: Assembly of *Kur-Tec* Japanese framing system. Bolted in place through pre-drilled holes in *Stratalam* Columns.

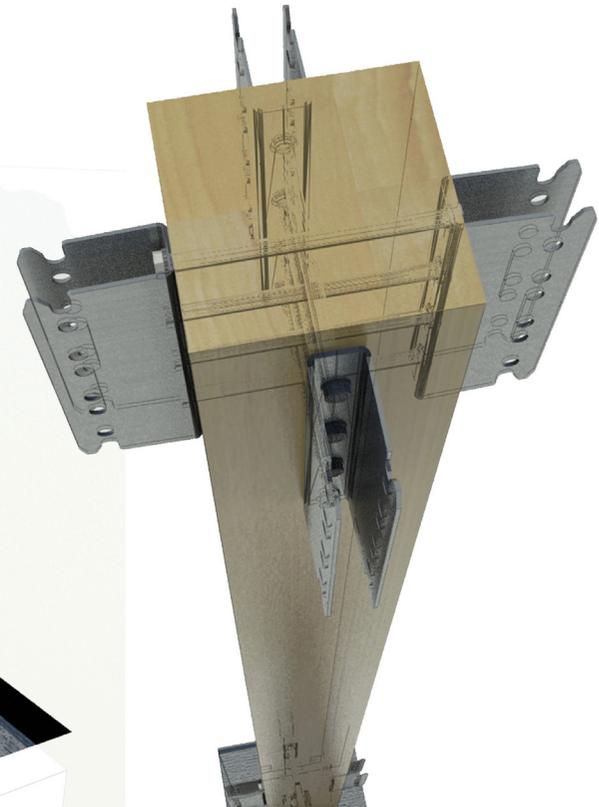
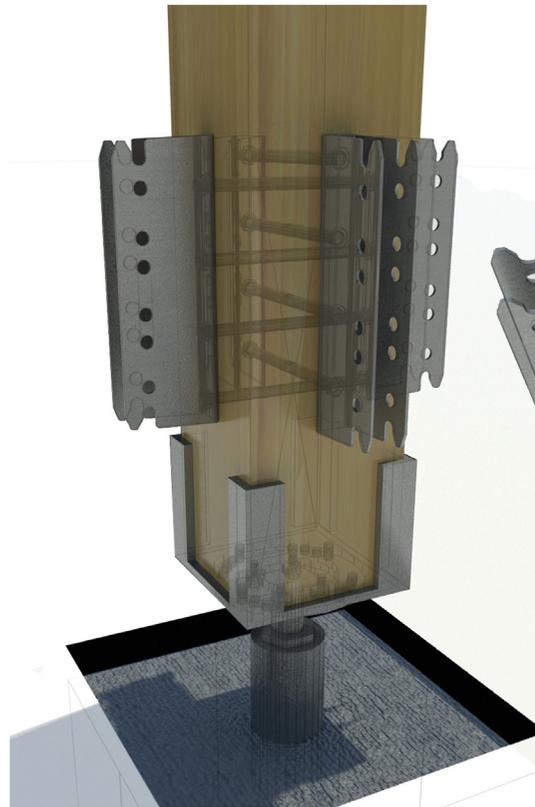
Source: Author, 2010

1. FOUNDATIONS



2. COLUMNS





*Simulative Construction Process - 'Bach House'*

*Figure 5.17 (left): Stratalam glulam beam assembly to Kur-tec framing system.*

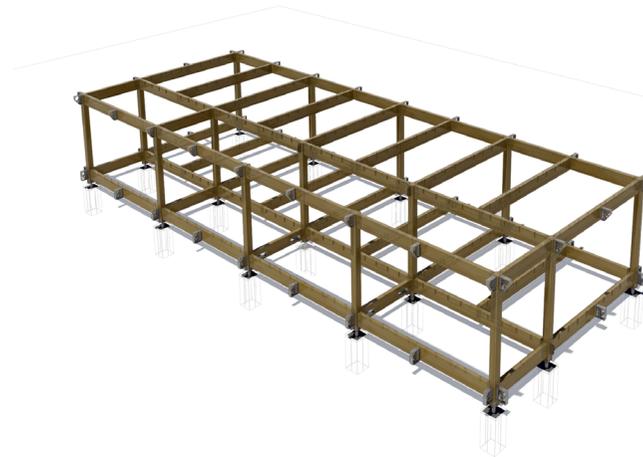
*Figure 5.18 (right): Complete floor modules then assembled in place.*

*Figure 5.19 (opposite left): Detail: Stratalam beam system fixed to Kur-tec framing system. Fixed through wooden 12mm dowels through Kur-tec hander brackets.*

*Figure 5.20 (opposite right): Detail: Floor modules being dropped into place, fixed via Cap Screws into cross-dowels.*

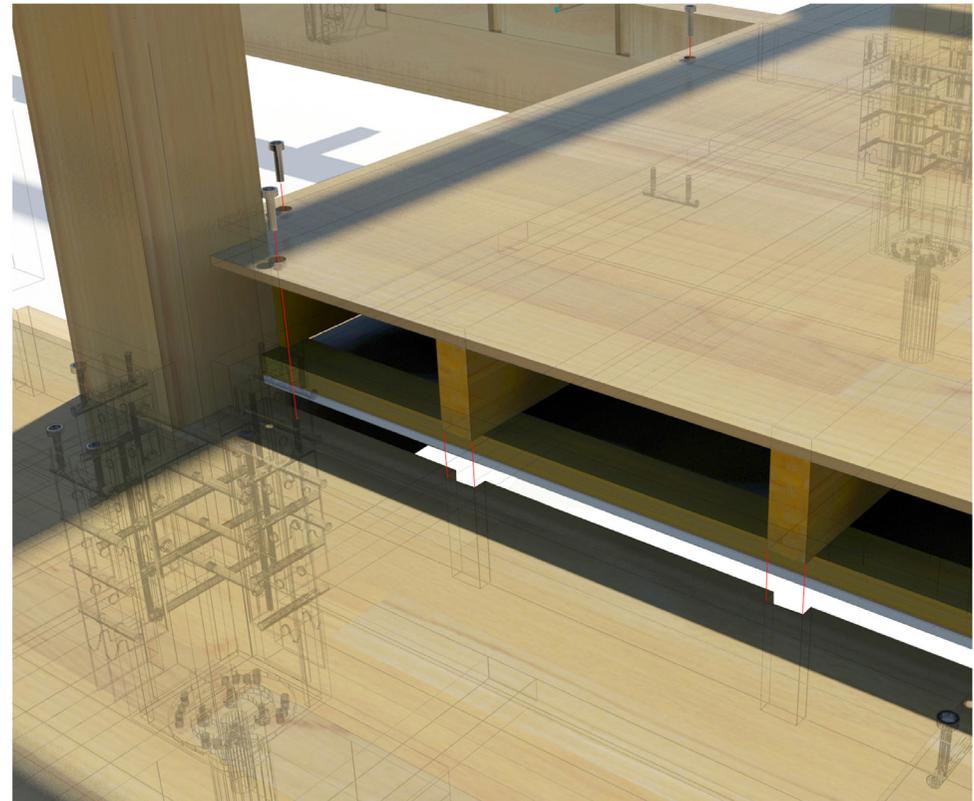
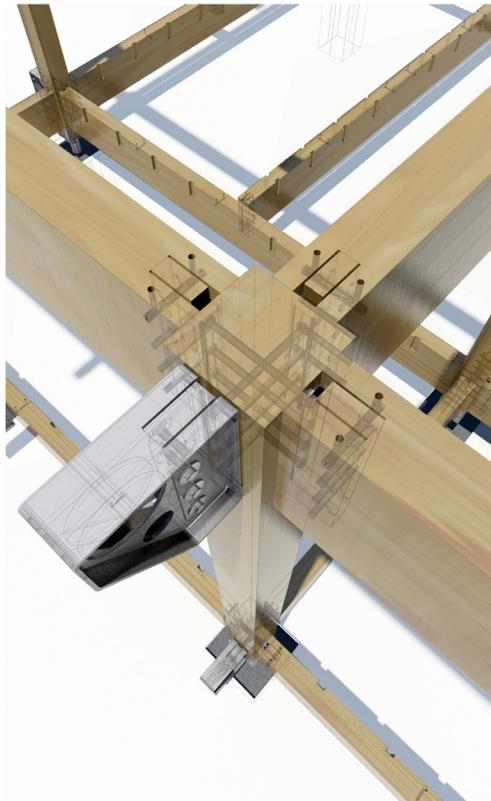
Source: Author, 2010

3. KUR-TEC BEAM SYSTEM



4. FLOOR MODULES





*Simulative Construction Process - 'Bach House'*

*Figure 5.21 (left):* Prefabricated 'wet; areas assembled and plumbed into place.

*Figure 5.22 (right):* Ulrich Aluminium extruded facade fixtured bolted in place.

*Figure 5.23 (opposite left):* Detail: 'Wet' areas being hoisted into place via crane. The volumetric areas house their own structural frame to allow for rigid transportability (note: special connection beams for slip coupling connections).

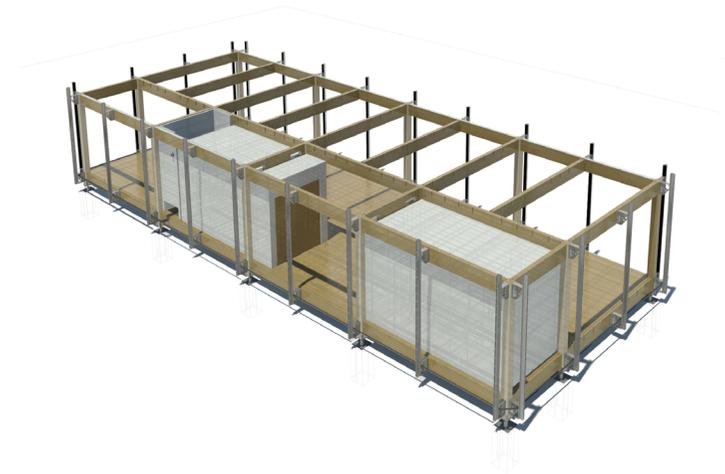
*Figure 5.24 (opposite right):* Detail: Fixture of services that are housed in the perimeter service trace (electrical, plumbing, heating).

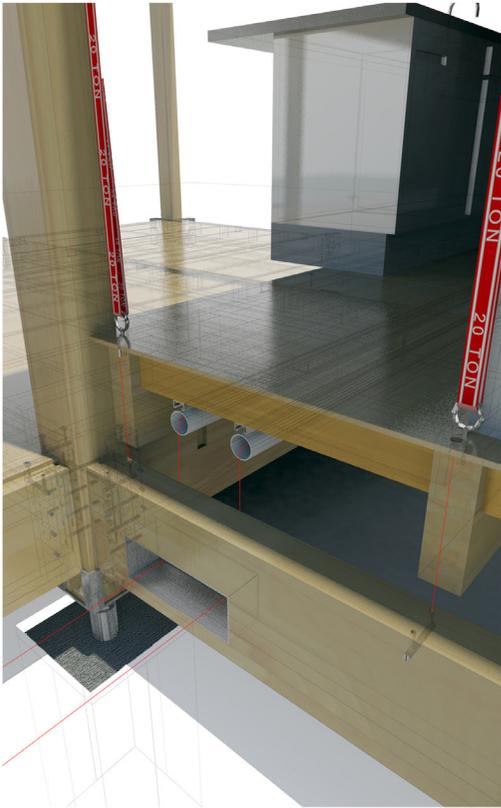
Source: Author, 2010

5. PRE-FABRICATED WET AREAS + SERVICE CORE



6. FACADE EXTRUSIONS + PLUMBING ATTACHMENT





*Simulative Construction Process - 'Bach house'*

*Figure 5.25 (left):* CNC *Insulspan TEK* SIP's, supplier pre-cut, wrapped and finished.

*Figure 5.26 (right):* Curtain wall fixture to standardised interface on facade dixture extrusions.

*Figure 5.27 (opposite left):* Detail: Facade extrusion, modelled of quick-assembly curtain wall system, and pre-manufactured *Unistrut* component fixture system.

*Figure 5.28 (opposite middle):* Detail: CNC *Insulspan* panels fixed.

*Figure 5.29 (opposite right):* Detail: Interior finish of ground components fixed. Note: The cross-dowel fixture of the floor system allows for a flush, unexposed connection whilst allowing for disassembly.

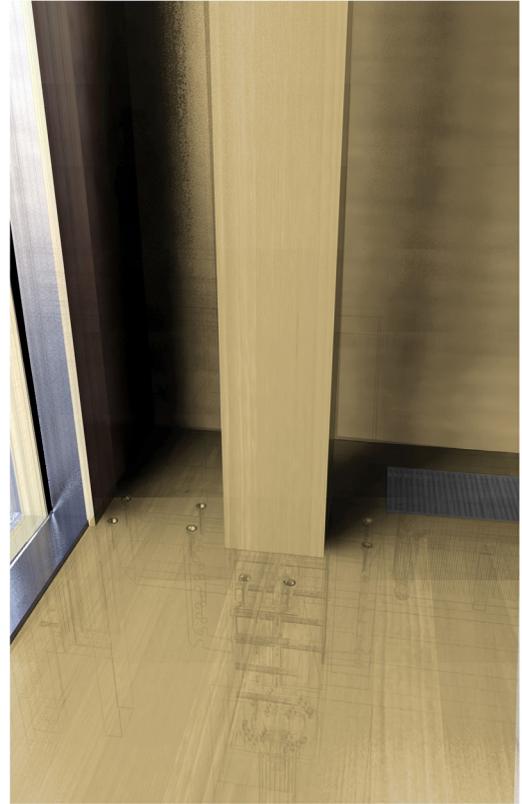
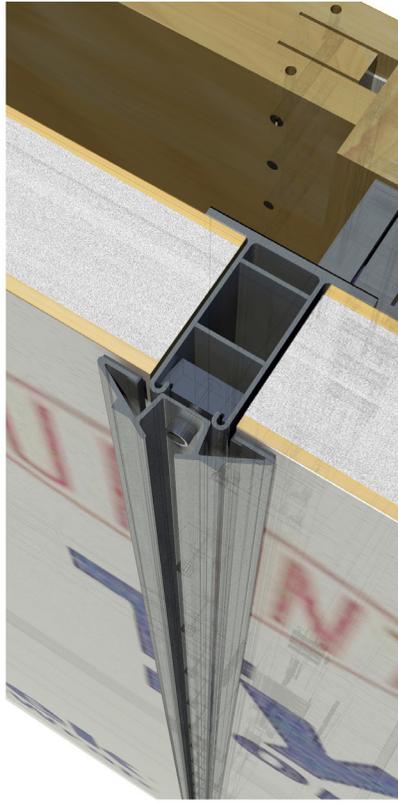
Source: Author, 2010

7. PRE-CNC-CUT TEK SIPS



8. CURTAIN WALL INSTALLATION





*Simulative Construction Process - 'Bach House'*

*Figure 5.30 (left):* Protan Profab waterproofing system attachment, and perimeterised internal guttering.

*Figure 5.31 (right):* 'Skin' fixture.

*Figure 5.32 (opposite left):* Detail: Interior detail of roof connection. Fixed through Steel & Tube bracketry, and weathertight connections are solved through the quick assembly Protan Profab roofing system. Interior ceiling is fixed afterwards. The roof connection has the same interface as floor components to allow for further standardisation.

*Figure 5.33 (opposite middle):* Detail: Roof module and exterior skin connection. Facade skin connection through the same custom extrusion used to hold SIP's in place.

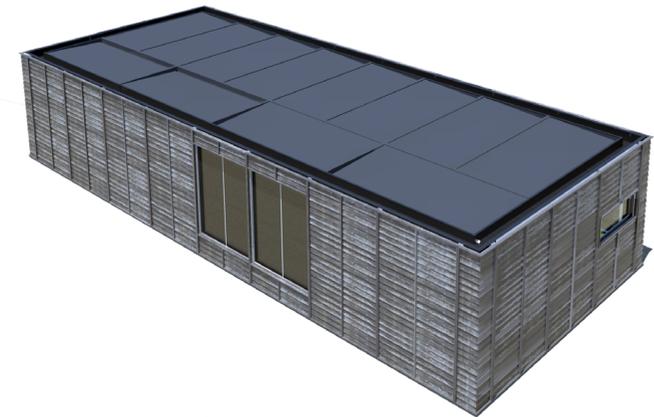
*Figure 5.34 (opposite right):* Detail: Close up of facade and skin connection.

Source: Author, 2010

9. ROOF MODULE



10. EXTERNAL SKIN + INTERIOR FITOUT







## 5.7 Front-loading

Testing of individual components is relatively developed for manufactured items; but the behaviours of the systems working together in large assemblies, or in whole buildings is far more difficult to access. Systems working in conjunction with one another involve numerous variables and have generally had far less industry backing than offered by other industries outside of architecture. The complexities of building construction involve the putting together of all these individual components (Anderson & Anderson, 2007, p. 15); and this can be solved through digital front-loading.

Today, architects spend a lot of invested time and money on construction consultants and design presentations to solve the majority of these issues upfront, but are often still in two-dimensional resolutions (Kieran, 2004). Building Information Modelling offers a solution; though it ensures more time and money is spent up front, it offers more certainty and fewer question during the construction of projects (Anderson & Anderson, 2007, p. 15).

The process of dimensional accuracy within the software plays a large role in its success; and the geometrical definition of the grid becomes crucial for determining such accuracy. Modular components are pre-manufactured, so three-dimensional accuracy is essential within the digital simulation of the design. Nothing in the 'real' world is truly exact, and digital information is developed until it is fully exact, so tolerances need to be catered for in the production and assembly (Willis & Woodward, 2005, p. 73). Though many of the components were all dimensioned and placed within the 2.2m modular grid, inaccuracies become clearly defined when three-dimensionally exploring the model. Bolts, holes, placements and locations all need to be clearly defined when utilising such finely grained componentised systems. It is only once these have all been resolved can you truly utilise the information exerted in the model<sup>38</sup>.

Every component (down to the nut and bolt) was designed, developed and scheduled within the design. The quantifiable data within the software can embed suppliers, manufacturer,s quantities, materiality, lengths and area parameters that can be scheduled as outputs from the model. For complete accuracy, every component needs to be precisely designed, parametrically driven and placed within the model if true manufacturable data is to be obtained. Initially, categorising modular parameters was a time-consuming process, though as the capabilities and efficiencies embedded within the software are realised, so is its output productivity. Once the capabilities and logistics of understanding how the componentised software is realised, output from the model is able to be continuously produced, both as modular outputs and as schedules for collaborative information.

*Figure 5.35:* Exterior image of completed 'bach' - Simulative model can be utilised for representation.

Source: Author, 2010

*38. Dimensionally constraining constructional parameters became a crucial part in establishing a stable model*

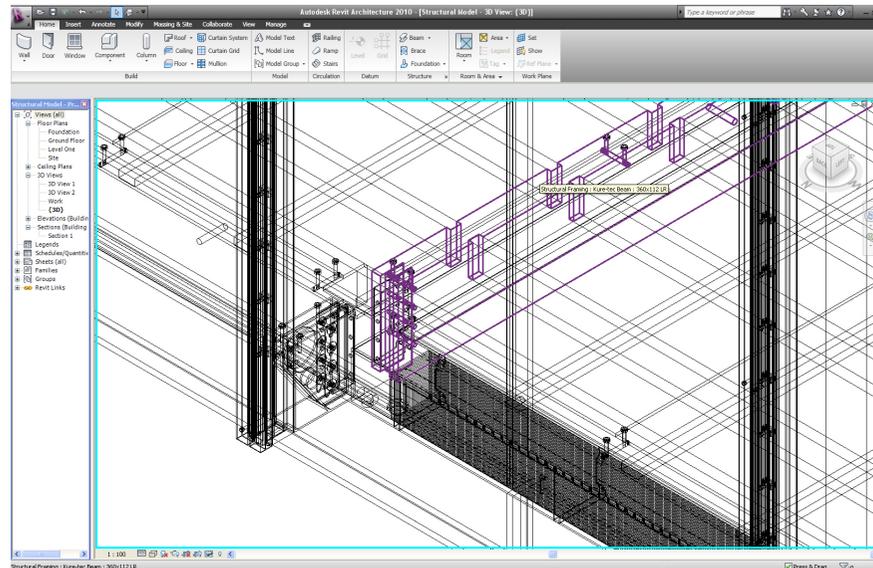
Though the exploration did not apply the direct translation between three-dimensional model and CNC machine, the majority of current architectural CAD applications can export as DXF and DWG<sup>39</sup> formats that can be translated into information for digital two-dimensional manufacturing, though today it is still not as simple as merely clicking 'print'. The relationship of data sharing between architectural programmes and CNC machines still appear to be a current drawback in the industry, though as digital technologies are evolving, file standards are becoming more collaborative (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2008, p. 184) within industry standards.

The front-loading of the design through *Revit Architecture* allowed the successful implementation of scheduling and designing all three houses over a short period of time. Once the barriers of basic mathematics for utilising pragmatic parametrics within *Revit* were understood, the capabilities of the software were able to be further pushed. Utilising parametric design at the beginning of experimentation did not appear to attain the efficiency originally intended, but once the barriers of understanding the programme were overcome, the software becomes incredibly efficient for both the design and manufacture.

The initial costs of front-loading would essentially be addressed by the client. Though the front-loading of manufacturable 'product data' may appear inefficient in the beginnings of design, cost savings through the speed and precision of off-site fabrication would become apparent in the later stages of construction. Through output data embedded within the digital model costs, time and control are now able to be attained; reducing the stereotypical nature of variations and amendments that lie within traditional architectural construction.

**Figure 5.38:** Three Dimensional Accuracy - Three dimensional simulative models needs to be 100% concise to allow for precision within digital manufacture. Although the model is 'entirely exact', and it has historically been stated that the 'real world' is not, tolerances and precise simulation needs to take effects for prefabricated modulation to occur.

Source: Author, 2010



FX - FIXTURES  
ES - EXTERNAL SKIN  
FC - FACADE PANEL  
ST - STRUCTURE  
CW - CURTAIN WALL  
RF - ROOF  
FL - FLOOR  
FN - FOUNDATION  
IW - INTERNAL WALL

RF-01 - COLOUR STEEL LOW CORNER GUTTER  
RF-02 - COLOUR STEEL HIGH CORNER GUTTER  
RF-03 - COLOUR STEEL GUTTER EXTRUSION  
RF-04 - PROFAB ROOFING MEMBRANE  
RF-05 - PLYWOOD SHEETING  
RF-06 - 80mm PVC PIPING  
RF-07 - 140 x 45 PROFILED BEAM  
RF-08 - 260 x 45 PERIMETER BEAM  
RF-09 - 75 x 50 STEEL SECTION FIXTURE  
RF-10 - 50 x 50 PINE BATTEN  
**RF-11 - CEILING FINISH + LIGHTING**  
RF-12 - 260 x 45 SOLID END CAP  
RF-12/2 - 260 x 45 VOID END CAP

FL-01 - FACADE TRIM  
**FINISH**  
FL-02 - FACADE TRIM EXTERNAL CORNER  
**FINISH**  
FL-03 - WOODEN SHEETING  
**FINISH**  
FL-04 - 140 x 45 H3.2 FLOOR BEAM  
FL-05 - 50 x 50mm TIMBER BATTENS  
FL-06 - RIGID INSULATION  
FL-07 HEATED PANEL  
**FL-07/2 - RADIANT HEATER**  
FL-07/3 - FIXTURE BRACKET

CW-01 - 50 x 100 ANODIED MULLION END CAP  
CW-02 - 50 x 100 ANODISED MULLION END CAP  
CW-03 - CURTAIN WALL PANEL  
CW-04 - CURTAIN WALL GLAZED PANEL  
FN-01 - LAYHER BASE COLLAR  
FN-02 - SCREW JACKS  
FN-03 - LOCKING NUT  
FN-04 - ADJUSTABLE BEAM FIXTURE

**ES-01 - CLADDING FINISH**  
ES-02 - 100 x 50 PINE FRAME  
ES-03 - ALLUMINIUM EXTRUSION

FX-01 - M10 x 50mm STAINLESS STEEL CAP SCREW  
FX-02 - P5051 UNISTRUT NUT  
FX-03 - M10 x 1.5 STAINLESS STEEL NYLOCK NUT  
FX-04 - M10 x 40 STAINLESS STEEL WASHER  
FX-05 - M10 x 135mm STAINLESS STEEL BOLT  
FX-06 - M10 x 20 STAINLESS STEEL WASHER

CR - 01 - SERVICE CORE  
VERTICAL PLUMBING  
**HEATING UNIT**  
MAINS CONNECTION

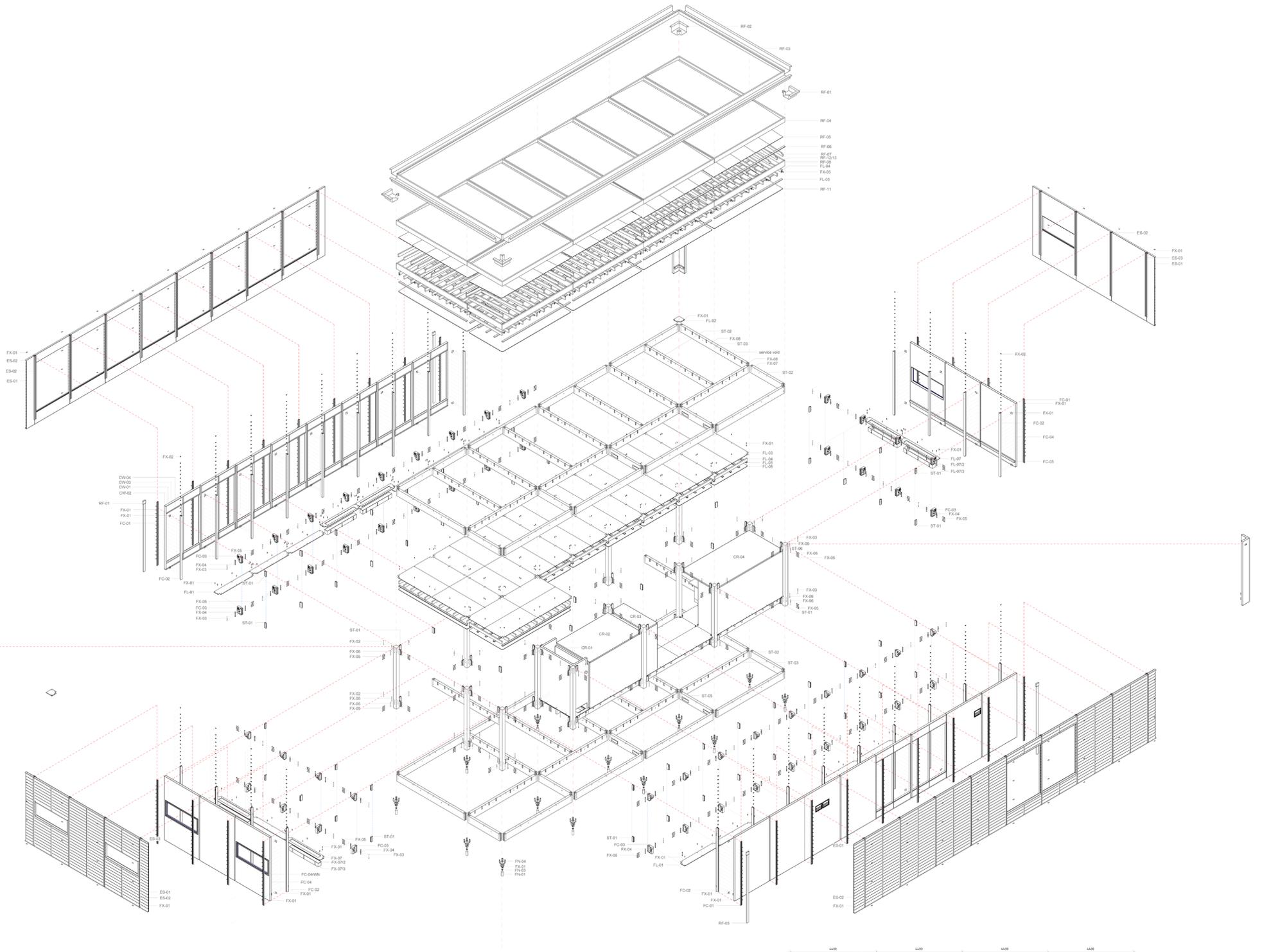
CR-02 - BATHROOM  
**FINISHES**  
CR-03 - LAUNDRY/BATH  
**FINISHES**  
CR-04 - KITCHEN  
**FINIHSES**

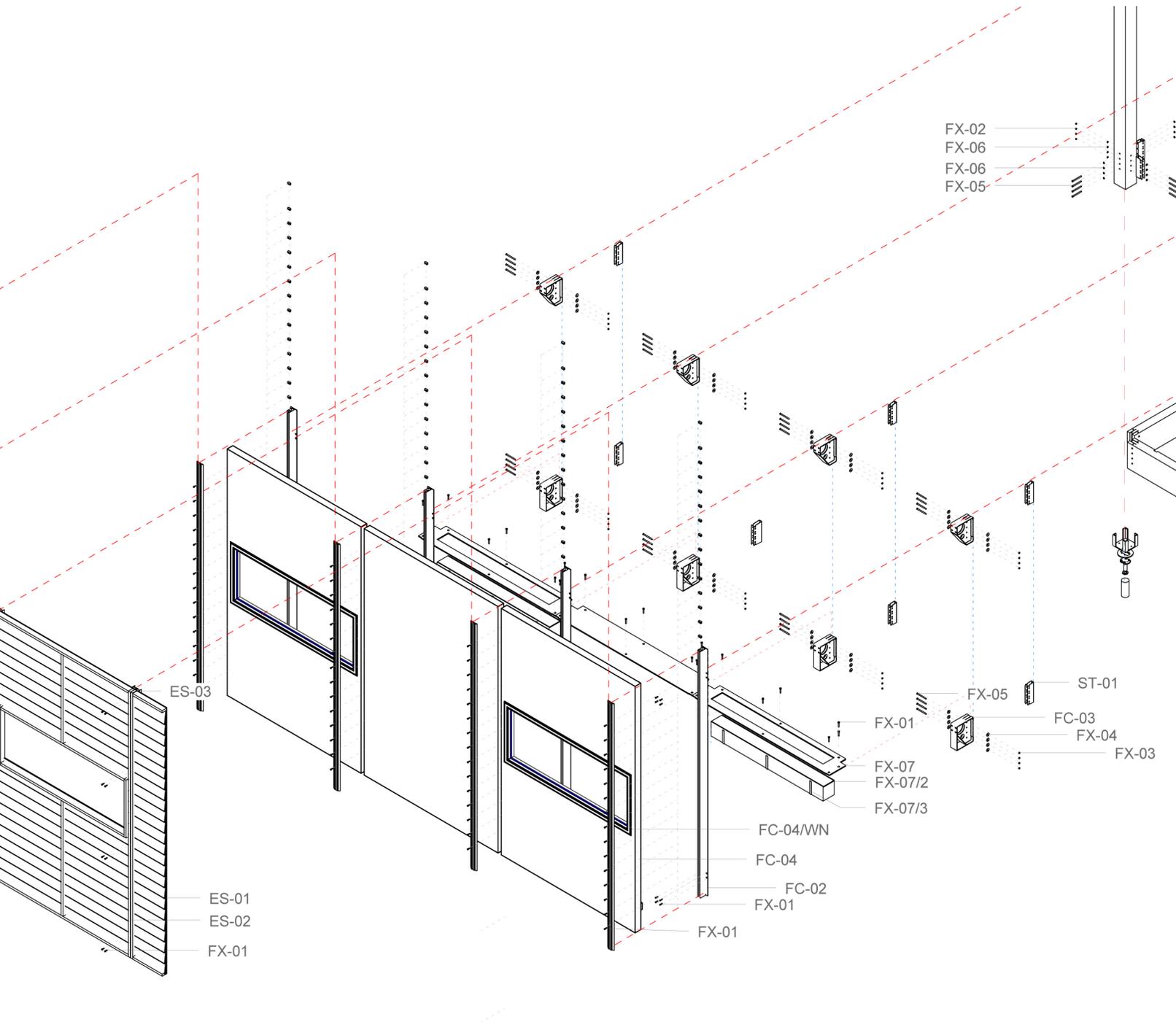
FC-01 - ALLUMINIUM FIXTURE EXTRUSION  
FC-02 - STRUCTURAL ALLUMINIUM EXTRUSION  
FC-03 - SERVICE HANGER  
**FC-04 - SIP PANEL**  
**FC-04/WN - WINDOW**  
FC-05 - 100X50 PINE FRAME

ST-01 - TH33 KURTEC BRACKET  
ST-02 - 360 X 112 PROLAM BEAM  
ST-03 - 360 x 112 PROLAM BEAM SINGLE NOTCH  
ST-04 - 360 x 112 PROLAM BEAM DOUBLE NOTCH  
ST-05 - SERVICE CORE BEAM  
ST-06 - PLP200 STRUCTURLAM POST

**Figure 5.39:** Key to diagram on figures 5.40 & 5.41  
- Individual component list of the proposed flexible  
houing system.

Source: Author, 2010





**Figure 5.40 (opposite):** Exploded Axonometric - Exploded diagram of all the individually designed component working together as a system.

**Figure 5.41:** Exploded Section - Exploded section of figure 5.11; showing components and assemblies working as a unitised system.

Source: Author, 2010

## 5.8 *The System*

The goal of this thesis has been to determine the automation efficiencies seen in the automotive industry and see how they can be utilised within architecture to promote efficient, economic and precise design processes for building. Through the continuous improvement in understanding parametrically determined component based BIM software and lean, modular efficiencies the establishment of a parametrically driven, flexible housing system was able to be attained, in which three site-specific houses were able to be quickly scheduled, developed and tested.

Though people generally still disguise the automobile being a mass-produced product with little attainable flexibility, it has been defined by the market. Digital-Lean manufacturers have discovered the many options that flexible, lean production systems can offer are not wanted (Pine, Victor, & Boynton, 1993). They have found it more beneficial to utilise digital componentisation for the distributing of costs across models versus the array of options for specific models; and my research has focused on just that, using componentised digital libraries to establish a range of site-specific, flexible housing models.

The system is based on standardising structure and a 'platform' of components that can be used to develop a variance of site specific houses. The design (of the system) has been focused upon site-parameters (neighbouring houses, site dimensions, internal design, view), not site specificity but the parameters have been the established factors that have allowed the system to be site-specific. The components, thus, were standardised across the system; and the flexibility was maintained through individual finishes, compositional layout, and parametrically driven through front-loading and simulation.

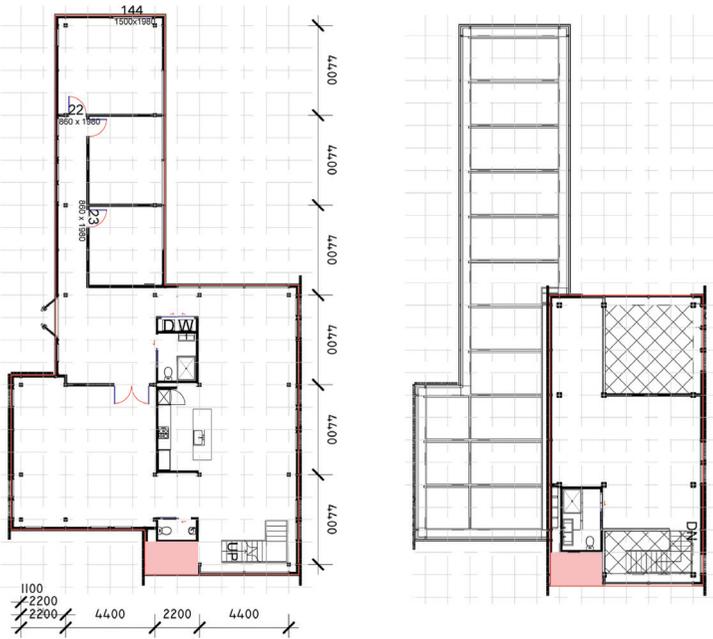
The vast majority of today's conventions rely on two-dimensional constructive data, drawn in two-dimensions after the 'design' has been 'solved'. Many parts, however, in a typical building system are not drawn within these current conventions, and are interpreted by the other industries that construct the representational design. Electrical conduits, plumbing, communications, heating and interfaces between them often never appear in conventional two-dimensional drawings, though, these problems and interfaces can be addressed within the building model. For the complexity of how we design architecture today, however, with services, electrical wires and fittings as an unplanned maze though a conventional model, it appears far too complex to utilise a component based design.

Services are a crucial factor for determining the assembly of the design. To maintain flexibility and simplification, the location of services needs to be established in the early stages of design. Service design (within this

system) is based around a point made earlier in this thesis (section 4.1); in that prefabricated housing can learn from commercial building techniques. The idea of developing a core and perimeter based services allowed for the ease of components to 'plug' into the system, whilst allowing for the 'updating' of housing services to be easily attained through accesibility and cetainty of location (see figure 5.24, 5.43 and 5.44) .



**Figure 5.42 (top):** 'Belmont House' plan - Site specific house design two. Designed for a residential site in Belmont, Lower Hutt using the establised system.



**Figure 5.43 (below):** 'Waitarere bach' Plan - Site specific design three. Designed for a rural coastal site out in Waitarere, Levin.

The services are placed at the periphery of the plan, thus, allowed for the same sharing of systems no matter what the compositional layout. The placement of this necessitated the core to be located amongst to the perimeter, though has beneficial outcomes being that housing services can be installed, disassembled and updated with speed, precision and ease. Electrical services, however, needed to be placed within the grid (lighting etc), though there is technology for preinstalling these in finished components. The installation becomes merely 'plugging' the components around the perimeter trace; and can be installed, disassembled and updated in the same sequential manner.

(construction perspective Figure 5.24)

All three tested designs have wet-areas based off volumetric units (dimensioned and designed to be lifted and transported in open-top containers), and are the only structurally inefficient aspects of the design, dictated by the precedential conclusions for reducing inefficient structure<sup>40</sup>. The design has been based around a 'standard' chassis, which defines the compositional lay-out of the 'wet' amenities. Though this further encourages costs through standardisation, it has been designed to allow for multiple solutions; though it not a necessary factor for attaining successful prefabrication in architecture.

The most simplistic way to attain flexibility is through standardised interfaces. Standardisation of both connection and modular reference allowed freedom within the design of components. As long as components remain restricted to parametric constraints, components can have compete freedom. Though the first exploration was to utilise an industry standard dimension of 1200mm, designing for tolerances and fixture systems still needed to be further implemented if this was to be successful. For example, the wall panels are 2150mm not 2200mm due to fixture width (figure 5.6). Structural components are situated on, not within, the grid so they affect the dimensional restraints for infill components as they are generally attached too, or to an attachment on the structure<sup>41</sup>.

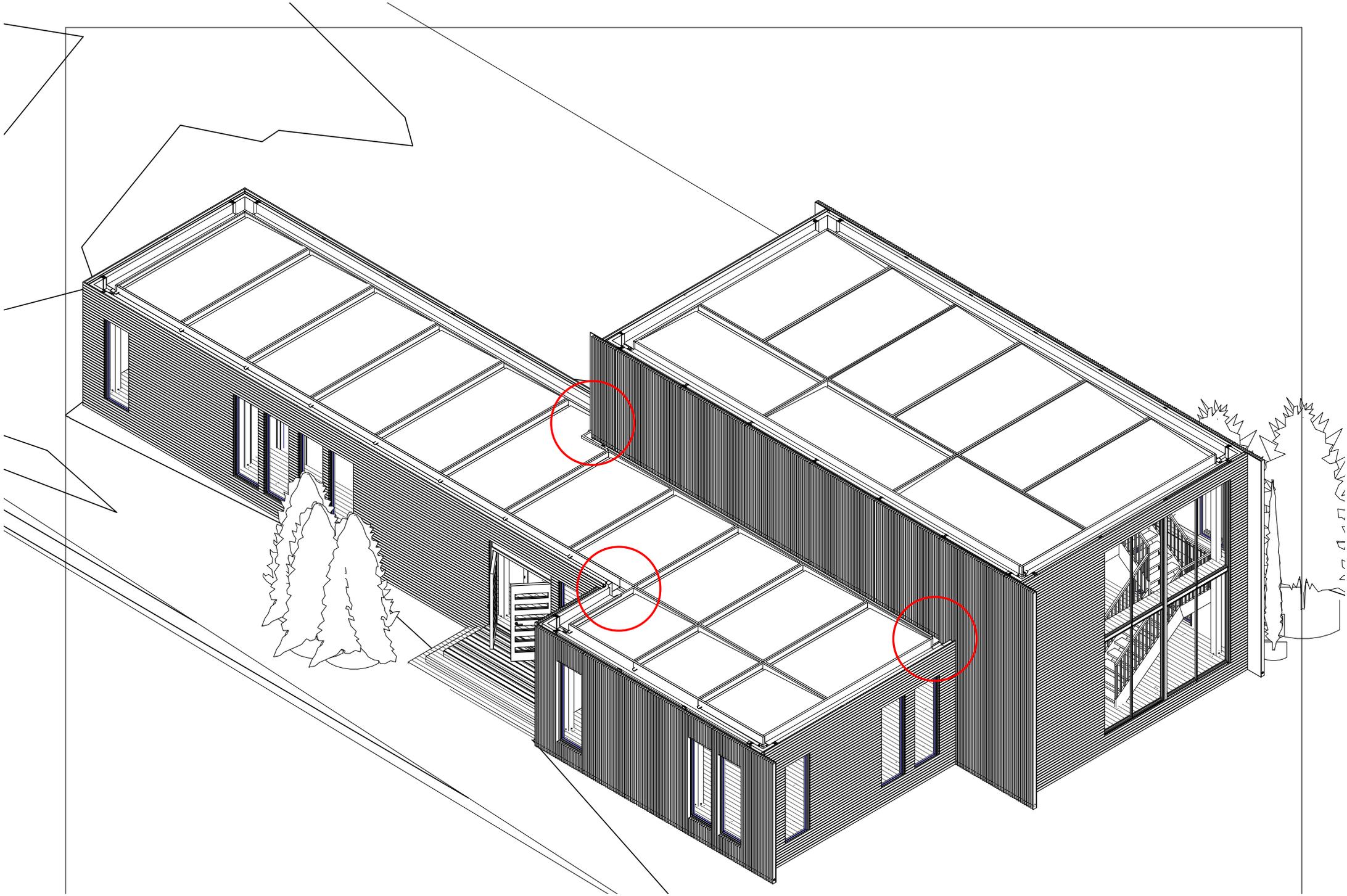
As history has shown, the use of individualising through componentised design is not always straightforward as proposed, and through establishing the three designs, this has again been the case. For example, overlapping floor plates and internal corners create overlap of components, thus step outside of the 'standardised' nature of the modular dimension (figure 5.45). The more the systems are flexed, the more the components, interfaces and systems need to be designed for; though this can be sustainably addressed through the made-to-order nature of lean production and solved through the front-loading of design.

*Figure 5.44 (opposite):* Simulative view of 'Waitare House' - The internal corners and overlapping of modules creates complication with standardised components. These can now be solved through the front-loading of design and flexibility within digital manufacture.

Source: Author, 2010

*40. Extra floor beams needed to be added to allow for the lifting of the 'wet' areas into the structural frame*

*41. Applying structural members 'between' the modular dimension was experimented, though this offered similar complications for selection of different structural system, as it different member sizes created an a flexible, not fixed modular dimension.*



*Figure 5.45 (opposite):* Exterior of 'Waitarere Bach'.

The typical nature of architectural design is a top-down process<sup>42</sup>, and application through digital design has been known to be problematic due to the nature of individual parts reflecting significantly on the whole (Schodek, et al., 2008, p. 200). This experimentation has been a bottom-up process<sup>43</sup>, prioritising assembly, efficiency and construction. Because the explorations of the system were highly driven by efficiency and flexibility, it created more restrictions within the development of site-specific design, though these were often solved through reinterpreting the design, and modular aspects of the individual components, understanding how they work as a unitised system.

Componentised design can work with digital design, but the overall aesthetics in the compositional design and design of components needs to take a large priority. The design focused heavily on the bottom-up process, but for further development of prototype design, more collaboration between top-down and bottom-up process would have allowed for more design integrity within the system; though this thesis has been in determining digital, modular flexibility through flexible, digital production systems, and this has been achieved.

For the application of lean industrial production, as the automotive industry has demonstrated, modular efficiencies must be designed in and as part of the overall commodity; and this is where the effect of bottom-up and top-down processes overlap. Defining the bottom-up closed in-house systems, with digital manufacturable manipulation is how specific integral architectural design can take place within lean production efficiencies. For the design of the system, it has been just that. The system has evolved through digital progression, and as the determinant factors of site were addressed, the compositional layout, and/or specific modules were able to be manipulated accordingly, and specified in doing so.

The flexibility of applying digital lean-manufacture has allowed for top-down processes of individual design to evolve from a bottom-up process, a process that allows costs, specifications and resolutions to be solved prior to construction. Houses can now be assembled, quantified and specified through assembly and adaptability. Architecture can now, finally, be able to digitally address costs, quality and precision through the benefits of flexible digital production.

*42. The process to define the characteristics of the whole and then to create the appropriate sub-components (Schodek, et al., 2008, p. 224).*

*43. The process of designing individual parts and assembling them into a whole (Schodek, et al., 2008, p. 224).*



*Figure 5.47 (below):* Front exterior shot of Belmont House.

*Figure 5.48 (opposite):* Rear exterior shot of Belmont House.

Source: Author, 2010





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## 6.0 Conclusion

The following chapter concludes the research findings that have been explored in the previous five chapters. It discusses findings and current complications associated with how we can redefine modularity and automation within architecture. It will give reference to further utilising computer aided-technologies to assist the design, modulation and collaboration for the application of industrialised production and architecture.

Tolerance, complexity and modular coordination were the three prominent factors that led the 20<sup>th</sup> Century industrially inspired architects to standardising their design. Their precedent of mass-production was a misinterpretation, and their goals were based on the principles of Toyota's lean-production system; through attaining flexibility and cost savings over large ranges of components (the leveling of production). The number of components needed to attain the desired flexibility far outweighed the efficiencies of mass-production; however, they can now be catered for through the flexibility of digital manufacturing systems that can produce numerous outcomes at similar costs. However, by the time digital lean production had been established, hope had already died for an industrialised architecture.

Lean-productions initial goal of just-in-time production has resulted in its modular product composition. Specific manufactured components are now made-to-order, and this is how flexibility is attained without predetermining what the market wants. Digital design, collaboration and manufacture in construction can allow for just that. Building Information Modelling allows outputs, tags, schedules and keynotes that can allow for flexible manufactured systems to be within manufacturable constraints; and the greater the knowledgebase of suppliers and capabilities, the more flexibility that can be attained within the design. To be successful, the integration of the design aesthetic needs to be inherently applied at the early stages of system selection. Architects typically design in this top-down process, but to attain modular automation efficiencies, the negotiation between top-down and bottom-up processes needs to occur.

The initial flexibility first predicted through current trends in automation and robotic manufacture do currently lie within the capabilities of CNC machines, but the costs of developing and translating that three-dimensional information to product information still remain too costly to be realistically attainable by the majority of the architectural market. Large co-operations, such as automotive manufacturers, maintain a large market power. This allows them to ensure that manufactures adhere to the same organisational and digital environment, and this is a comparative drawback that currently exists within the architectural industry; architects are to adhere to cur-

rent manufactures' data, dimensional constraints and file standards.

Adhering to current systems appears to be the most cost, resource and time efficient method to produce modular efficiencies within architecture. For utilisation of these systems, organisational strength needs to take effect, and this is where lean-production manufacturing systems have excelled and can adapt through the control of and organisation of both supplier resources and design/construction processes. Many manufacturers currently utilise digital two-axis CNC machines for precision and efficiency, but how we beneficially use these for quicker, more concise construction still is a large gap that lies within the construction sector, and once the firewalls of file format capability are surpassed, the use of such machines will continue to grow.

If lean modular production is to be applied to the building sector today, the establishment of a trusted prefabricated builder is essential. Manufacturers that exist in the current market are very much closed systems, and without market power their manufacture will remain only to design such specific systems. If components are to become pre-wired, serviced and finished then direct contact with a prefabricated supplier is essential. The first tier-supplier should become the key controller in the supply-chain (second to the architect), determining the last quality control point between the manufacture of prefabricated elements and the assembly of such components to compose the final 'product'.

The establishment of authorship<sup>44</sup> when discussing collaborative design always comes into question, and architects are often believe that authorship of design is lost when utilising prefabricated design (Davies, 2005; Kolarovic, 2005). The digital application of component design and placement remains in control of the designer, and with digital technologies architects can re-establish their historical role of the 'master builder' through the reinterpretation of design, construction and assembly. The digital memorandum of information embedded within building information models now allow architects to implement systems, construction processes, assembly and design; many factors of which currently lie outside architectural design with the current segregation of the building industry. Through the use of modular, digital manipulation (as prescribed by the automotive industry) complex design industries, such as the architectural, can finally maintain the benefits of cost, quality, speed and precision within digital, componentised, contemporary design.

*44. The 'author' of the design. It is often interpreted that 'authorship' is lost when digital, modular manufacture takes place due to the nature of collaborative design.*

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## 8.0 *Appendix*

Real Estate Property New Zealand site surveys - For the establishment of external site parameters for a flexible housing system.



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**10 BOWSPRIT WY, WHITBY**



Photo Date: March, 2007

**Ownership Record**

Whole / NORMAL

Chattels: 0 Others: 0  
 Parties to Sale: Francis/Eichler  
 Area: 630 m<sup>2</sup>  
 Price Value Rel: Bona-fide  
 Sale Tenure: Freehold

**All Other Sales**

Sale Type	Sale Date	Sale Price	Vendor Name
Whole / NORMAL			
Whole / NORMAL			

Displaying 2 of 2 Other Sales Records

**Property Details** 630 m<sup>2</sup>

Category: RV RESIDENTIAL VACANT SITE  
 Region: WELLINGTON REGION  
 Territory Authority: 044 PORIRUA CITY  
 Certificate of Title: 6/43C/449  
 Val Ref: 15445 / 20600  
 Owner Code: Individual  
 Tenure: Not Leased (Owner is Occupier)

Land Use: VACANT RESIDENTIAL  
 Land Value: 250,000  
 Improvement Value: 0  
 Capital Value: 250,000  
 Current Val. Date: 01/09/07  
 Improvement:

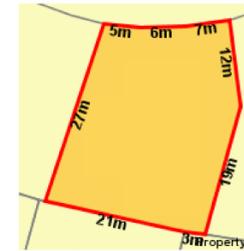
Lotplan: L2458/DP77154  
 Legal Description: LOT 2458 DP 77154

WHITBY 5024

**Mapping**



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\* dimensions are approx. only

**Full Details**

**More Ownership Information**

UNITS OF USE: 1

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### 10 LINKS DR, WAIWHAKAIHO



Photo Date: November, 2007

#### Ownership Record

Whole / NORMAL

**Chattels:** 0    **Others:** 0  
**Parties to Sale:** Links Coastal Development Limited/Vandenberg  
**Area:** 1021 m<sup>2</sup>  
**Price Value Rel:** Bona-fide  
**Sale Tenure:** Freehold

#### All Other Sales

Sale Type	Sale Date	Sale Price	Vendor Name
Whole / NORI			

Displaying 1 of 1 Other Sales Records

#### Property Details

4 1021 m<sup>2</sup>

<b>Category:</b> RD200A RESIDENTIAL DWELLING 2000/2009 SUPERIOR	<b>Certificate of Title:</b> 0/0/272686
<b>Region:</b> TARANAKI REGION <b>Territory Authority:</b> 033 NEW PLYMOUTH DISTRICT	<b>Val Ref:</b> 11661 / 58122 <b>Owner Code:</b> Individual <b>Tenure:</b> Not Leased (Owner is Occupier)

**Land Use:** SINGLE UNIT EXCLUDING BACH  
**Land Value:** 205,000  
**Improvement Value:** 555,000  
**Capital Value:** 760,000  
**Current Val. Date:** 01/09/07  
**Improvement:**

**Lotplan:** L17/DP367214  
**Legal Description:**  
 LOT 17 DP 367214

**Owner:**  
 WAIWHAKAIHO 4312

### Mapping



\* dimensions are approx. only

### Full Details

#### More Ownership Information

<b>UNITS OF USE:</b> 1	<b>BUILDING AGE:</b> 2000-2009
<b>BLD FLOOR AREA:</b> 320.00	<b>ROOF CONSTRUCTION:</b> Steel/G-Iron
<b>WALL CONSTRUCTION:</b> Roughcst,etc	

#### Additional Attributes

4 Bedrooms

#### Telephone

Name	Address	STD	Phone

### 11 CAPRIANA DR, KARAKA

#### Ownership Record

**Sale Price:**  
**Net Sale:**  
**Chattels:** 0      **Others:** 0  
**Parties to Sale:** Karaka harbourside Estate ltd/coker  
**Area:** 627 m<sup>2</sup>  
**Price Value Rel:** Bona-fide  
**Sale Tenure:** Freehold

#### All Other Sales

Sale Type	Sale Date	Sale Price	Vendor Name
Whole / NORM <sup>2</sup>			

Displaying 1 of 1 Other Sales F

#### Property Details 627 m<sup>2</sup>

**Category:** RD200B RESIDENTIAL DWELLING 2000/2009      **Certificate of Title:** 0/0/331205  
**Region:** AUCKLAND REGION      **Val Ref:** 37401 / 481  
**Territory Authority:** 009 PAPAURA DISTRICT      **Owner Code:** Individual  
**Land Use:** SINGLE UNIT EXCLUDING BACH      **Tenure:** Not Leased (Owner is Occupier)

**Land Value:** 300,000  
**Improvement Value:** 360,000  
**Capital Value:** 660,000  
**Current Val. Date:** 01/09/09  
**Improvement:**

**Lotplan:** L81/DP382903  
**Legal Description:**  
 LOT 81 DP 382903

#### Owner:

KARAKA

### Mapping



PropertyIQ



### Full Details

#### More Ownership Information

**UNITS OF USE:** 1      **BUILDING AGE:** 2000-09  
**BLD FLOOR AREA:** 217.00      **ROOF CONSTRUCTION:** Tile Profile  
**WALL CONSTRUCTION:** Brick



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### 136 NAVIGATION DR, WHITBY

#### Ownership Record

**Sale Price:** -----  
**Net Sale:** -----  
**Chattels:** 0                      **Others:** 0  
**Parties to Sale:** Whitby Coastal Estates Ltd/ Singh, Kaur  
**Area:** 638 m<sup>2</sup>  
**Price Value Rel:** Bona-fide  
**Sale Tenure:** Freehold

#### All Other Sales

Sale Type	Sale Date	Sale Price	Vendor Name
Displaying 1 of 1 Other Sales Records			

#### Property Details 638 m<sup>2</sup>

**Category:** RV RESIDENTIAL VACANT SITE  
**Region:** WELLINGTON REGION  
**Territory Authority:** 044 PORIRUA CITY

**Certificate of Title:** 0/0/451571

**Val Ref:** 15443 / 57500

**Owner Code:** Individual

**Tenure:** Not Leased (Owner is Occupier)

**Land Use:** VACANT RESIDENTIAL

**Land Value:** 155,000

**Improvement Value:** 0

**Capital Value:** 155,000

**Current Val. Date:** 01/09/07

**Improvement:**

**Lotplan:** L26/DP413808

**Legal Description:**

LOT 26 DP 413808

**Owner:**

WHITBY

### Mapping



### Full Details

#### More Ownership Information

UNITS OF USE: 1

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### 20 WAKEMAN RD, ACACIA BAY



Photo Date: November, 2006

#### More Photos



<b>Ownership Record</b>	
Sale Price:	0 01/01/30
Net Sale:	0
Chattels:	0 Others: 0
Parties to Sale:	
Area:	1019 m <sup>2</sup>
Price Value Rel:	
Sale Tenure:	
<b>Property Details</b> 1019 m <sup>2</sup>	
Category:	RV RESIDENTIAL VACANT SITE
Certificate of Title:	2/1728/95
Region:	WAIKATO REGION
Val Ref:	7382 / 52500
Territory Authority:	021 TAUPO DISTRICT
Owner Code:	Individual
Tenure:	Not Leased (Owner is Occupier)
Land Use:	VACANT RESIDENTIAL
Land Value:	310,000
Improvement Value:	0
Capital Value:	310,000
Current Val. Date:	01/07/07
Improvement:	
Lotplan:	L76/DPS5898
Legal Description:	LOT 76 DPS 5898 ACACIA BAY WATER SUPPLY AREA
Owner:	TAWA WELLINGTON 6006

### Mapping



### Full Details

<b>More Ownership Information</b>
UNITS OF USE: 1

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**23 LINKS DR, WAIWHAKAIHO**



Photo Date: November, 2007

**Ownership Record**

Sale Price: 0 01/01/30  
 Net Sale: 0  
 Chattels: 0 Others: 0  
 Parties to Sale:  
 Area: 812 m<sup>2</sup>  
 Price Value Rel:  
 Sale Tenure:

**Property Details** 2 812 m<sup>2</sup>

Category: RD200B RESIDENTIAL DWELLING 2000/2009  
 Region: TARANAKI REGION  
 Territory Authority: 033 NEW PLYMOUTH DISTRICT  
 Land Use: SINGLE UNIT EXCLUDING BACH  
 Land Value: 240,000  
 Improvement Value: 140,000  
 Capital Value: 380,000  
 Current Val. Date: 01/09/07  
 Improvement:  
 Certificate of Title: 0/0/272682  
 Val Ref: 11661 / 58118  
 Owner Code: Company (not Crown owned)  
 Tenure: Not Leased (Owner is Occupier)

Lotplan: L13/DP367214  
 Legal Description: LOT 13 DP 367214

Owner:

WAIWHAKAIHO 4312

**Mapping**



\* dimensions are approx. only

**Full Details**

**More Ownership Information**

UNITS OF USE: 1 BUILDING AGE: 2000-2009  
 BLD FLOOR AREA: 70.00 ROOF CONSTRUCTION: Aluminium  
 WALL CONSTRUCTION: Weatherboard

**Additional Attributes**

2 Bedrooms

**On The Market History - For Sale**

Pub. Date	Price / Sale Detail	Agency Details	Agent Contact
10/01/09	Private Treaty \$245000	TSB REALTY	THE OFFICE 069683800

### 280 HARBOURSIDE DR, KARAKA

#### Ownership Record

**Sale Price:**  
**Net Sale:**  
**Chattels:** 0      **Others:** 0  
**Parties to Sale:** Karaka Harbourside Estate Limited/Spence  
**Area:** 554 m<sup>2</sup>  
**Price Value Rel:** Bona-fide  
**Sale Tenure:** Freehold

#### All Other Sales

Sale Type	Sale Date	Sale Price	Vendor Name
Displaying 1 of 1 Other Sales Records			

#### Property Details 554 m<sup>2</sup>

**Category:** RV RESIDENTIAL VACANT SITE      **Certificate of Title:** 0/0/375228  
**Region:** AUCKLAND REGION      **Val Ref:** 37401 / 662  
**Territory Authority:** 009 PAPAURA DISTRICT      **Owner Code:** Individual  
**Land Use:** VACANT RESIDENTIAL      **Tenure:** Not Leased (Owner is Occupier)

**Land Value:** 320,000  
**Improvement Value:** 0  
**Capital Value:** 320,000  
**Current Val. Date:** 01/09/09  
**Improvement:**

**Lotplan:** L194/DP393795  
**Legal Description:**  
 LOT 194 DP 393795

#### Owner:

KARAKA

### Mapping



\* dimensions are approx. only

### Full Details

#### More Ownership Information

UNITS OF USE: 1



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### 45 MEADOWBANK DR, BELMONT



Photo Date: March, 2007

#### Ownership Record

**Sale Price:**  
**Net Sale:**  
**Chattels:** 0 **Others:** 0  
**Parties to Sale:** Fawcett/First Class Builders (2007) Ltd  
**Area:** 1003 m<sup>2</sup>  
**Price Value Rel:** Bona-fide  
**Sale Tenure:** Freehold

#### All Other Sales

Sale Type	Sale Date	Sale Price	Vendor Name
Displaying 1 of 1 Other Sales Records			

#### Property Details

**Category:** RV RESIDENTIAL VACANT SITE  
**Region:** WELLINGTON REGION  
**Territory Authority:** 046 HUTT CITY  
**Land Use:** VACANT RESIDENTIAL  
**Land Value:** 260,000  
**Improvement Value:** 0  
**Capital Value:** 260,000  
**Current Val. Date:** 01/09/07  
**Improvement:**  
**Lotplan:** L46/DP366426  
**Legal Description:** LOT 46 DP 366426

**Certificate of Title:** 0/0/269184  
**Val Ref:** 16151 / 19925  
**Owner Code:** Company (not Crown owned)  
**Tenure:** Not Leased (Owner is Occupier)

#### Owner:

BELMONT 5010

### Mapping



\* dimensions are approx. only

### Full Details

#### More Ownership Information

UNITS OF USE: 1

#### Additional Attributes

4 Bedrooms 2 Bathrooms  
 2 Car Spaces

#### On The Market History - For Sale

Pub. Date	Price / Sale Detail	Agency Details	Agent Contact
1:			

**64 TE WAAKA TCE, KURATAU**



Photo Date: November, 2007

<b>Ownership Record</b>			
Sale Price:			
Net Sale:			
Chattels:	0	Others:	0
Parties to Sale: Te Hiraka/Anderson			
Area: 722 m <sup>2</sup>			
Price Value Rel: Bona-fide			
Sale Tenure: Freehold			
<b>All Other Sales</b>			
Sale Type	Sale Date	Sale Price	Vendor Name
Displaying 2 of 2 Other Sales Records			
<b>Property Details</b> <span style="float: right;">722 m<sup>2</sup></span>			
Category: RV RESIDENTIAL VACANT SITE		Certificate of Title: 2/39D/209	
Region: WAIKATO REGION		Val Ref: 7432 / 30248	
Territory Authority: 021 TAUPO DISTRICT		Owner Code: Individual	
Land Use: VACANT RESIDENTIAL		Tenure: Not Leased (Owner is Occupier)	
Land Value: 295,000			
Improvement Value: 0			
Capital Value: 295,000			
Current Val. Date: 01/07/07			
<b>Improvement:</b>			
Lotplan: L48/DP71018			
<b>Legal Description:</b>			
LOT 48 DP 71018 BLK III PUKETI SD			
<b>Owner:</b>			
64 TE WAAKA TCE KURATAU 3381			

**Mapping**



**Full Details**

<b>More Ownership Information</b>	
UNITS OF USE: 1	
<b>Features of Sale</b>	
BUYER TYPE: Unknown	SALE OWNERSHIP: unknown

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### 8 FAWCET PL, BELMONT

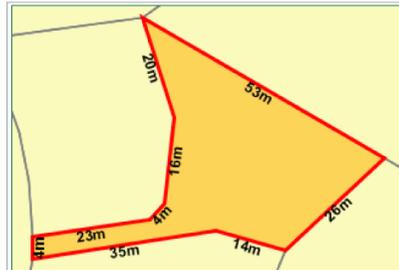


Photo Date: March, 2007

#### Ownership Record

Sale Price: 0 01/01/30  
 Net Sale: 0  
 Chattels: 0 Others: 0  
 Parties to Sale:  
 Area: 1128 m<sup>2</sup>  
 Price Value Rel:  
 Sale Tenure:

#### Property Details

Category: RV RESIDENTIAL VACANT SITE  
 Region: WELLINGTON REGION  
 Territory Authority: 046 HUTT CITY  
 Certificate of Title: 0/0/281327  
 Val Ref: 16151 / 19942  
 Owner Code: Individual  
 Tenure: Not Leased (Owner is Occupier)

Land Use: VACANT RESIDENTIAL  
 Land Value: 255,000  
 Improvement Value: 0  
 Capital Value: 255,000  
 Current Val. Date: 01/09/07  
 Improvement:

Lotplan: L63/DP366426  
 Legal Description: LOT 63 DP 366426

#### Owner:

WOBURN  
 LOWER HUTT

### Mapping



\* dimensions are approx. only

### Full Details

#### More Ownership Information

UNITS OF USE: 1

#### Telephone

Name	Address	STD	Phone

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