exploring prefabrication

International study of prefabrication within aerospace, shipbuilding, automotive and construction industries

funded by the Byera Hadley recent graduate travelling scholarship

by James Gardiner

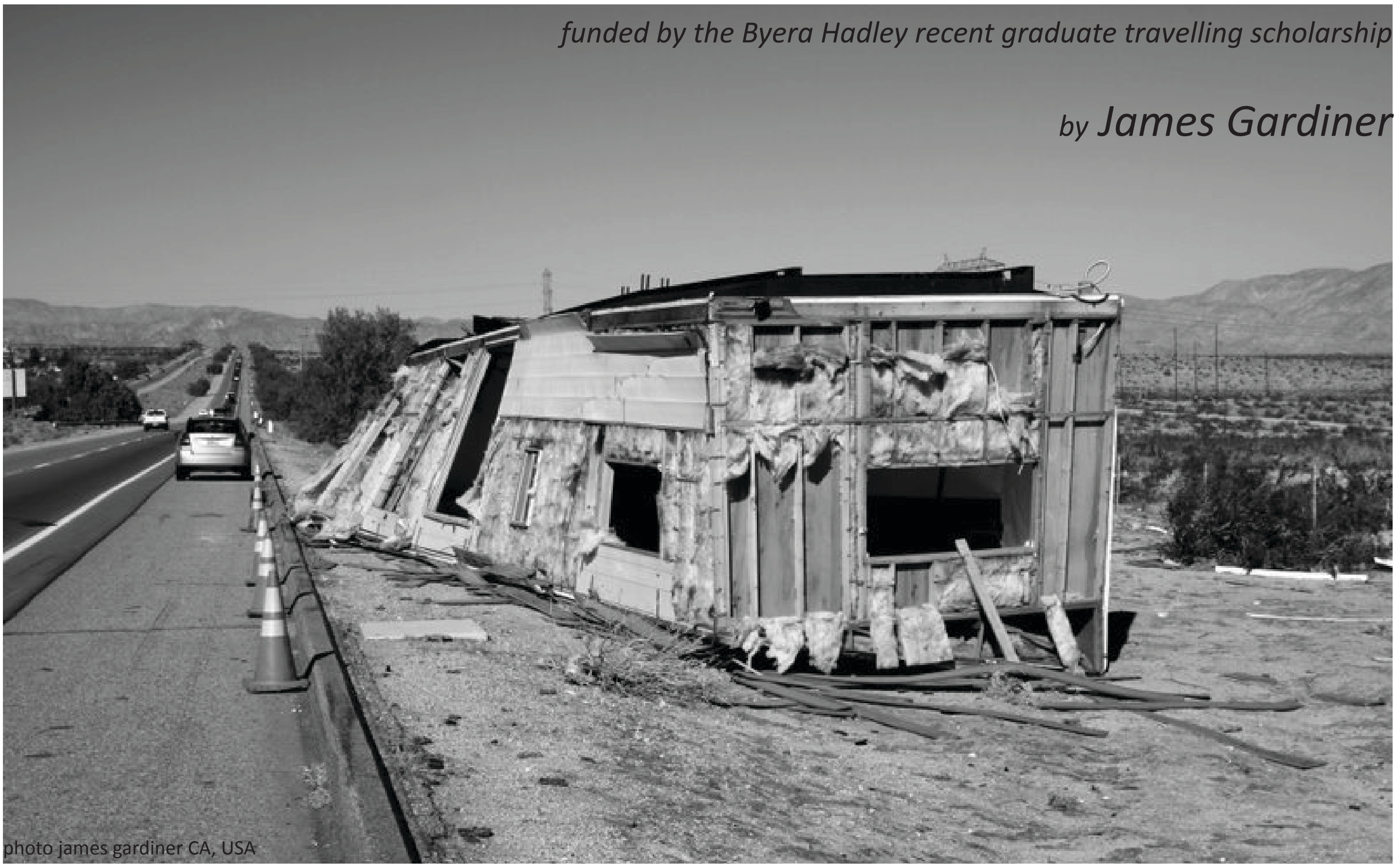


photo james gardiner CA, USA

Contents

All rights reserved, not for sale

Copyright James Gardiner Faan Studio, Sydney Australia

jamesg@faanstudio.com

“more than one-half of China’s urban residential and commercial building stock in 2015 is to be constructed after the year 2000”

(Zhu and Lin, 2004)

the genesis of the research

“The largest savings in energy use (75% or higher) occur for new buildings, through designing and operating buildings as complete systems”. (Mets et al. UN, 2007)

the challenge for construction

The construction industry is moving toward a particularly important milestone in its history, as enabling technologies such as 3D CAD and automated fabrication technologies mature and become increasingly applicable within the construction industry.

The Egan report (Egan, 1998), identifies the construction industry as one in need of urgent improvement. This sector has been identified as the most inefficient of the world's high capital industries (Kieran and Timberlake, 2004), and to compound the problem, the product of this industry (buildings) are also wasteful and inefficient, particularly in terms of energy use.

The construction industry globally is struggling to modernize and keep pace with other industries such as aerospace, automotive and shipbuilding. These industries have made substantial progress in production efficiency and quality in the last 40 years (NAHB, 2001, Egan, 1998).

A pressing need has also been identified by the UN, to shift toward sustainability in construction practice. This has been identified as a key sector to address in order to achieve global sustainability. The way we build needs to fundamentally change; huge improvements are required to move toward a sustainable future.

Misawa homes production line, Japan

The Construction industry consumes much of the world's resources and produces approximately a third of the world's waste.

Boeing fuselage assembly. image Boeing

The construction industry is moving toward a particularly important milestone in its history, as enabling technologies such as 3D CAD and automated fabrication technologies mature and become increasingly applicable within the construction industry.

The Egan report (Egan, 1998), identifies the construction industry as one in need of urgent improvement. This sector has been identified as the most inefficient of the world's high capital industries (Kieran and Timberlake, 2004), and to compound the problem, the product of this industry (buildings) are also wasteful and inefficient, particularly in terms of energy use.

The construction industry globally is struggling to modernize and keep pace with other industries such as aerospace, automotive and shipbuilding. These industries have made substantial progress in production efficiency and quality in the last 40 years (NAHB, 2001, Egan, 1998).

problem

This research project grew from a dissatisfaction with my experience working in construction industry over a 10 year period, prior to commencing the research and a firm belief that architecture and construction had the potential to improve. Prefabrication initially seemed like the obvious answer to many of the issues identified, but the more I investigated this field, I reaslised this industry also had issues that were holding it back.

Many of the issues identified within the construction industrty are also present within the prefabrication sector, although usually to a lesser extent. Such as he following:

Construction industry
inefficiency, high costs, safety, skills shortages, poor competition and poor quality

Construction Sustainability
high embodied energy, high waste production, resource depletion and low energy efficiency

Design
documentation efficiency, design to cost limitations, design compromise due to errors in documentation and on site.

The more I researched prefabrication the more I realised I didn't know, the constant paradox. Although their are hundreds of books on prefabrication and thousands of research papers, many questions remained unanswered. Many mistakes were also being repeated as prefab experienced a resurgence, rather than re-invent the wheel I decided the best thing to do would be to visit the world leaders in prefabrication; not just in the construction industry but also in Aerospace, Automotive, Shipbuilding and manufacturing.

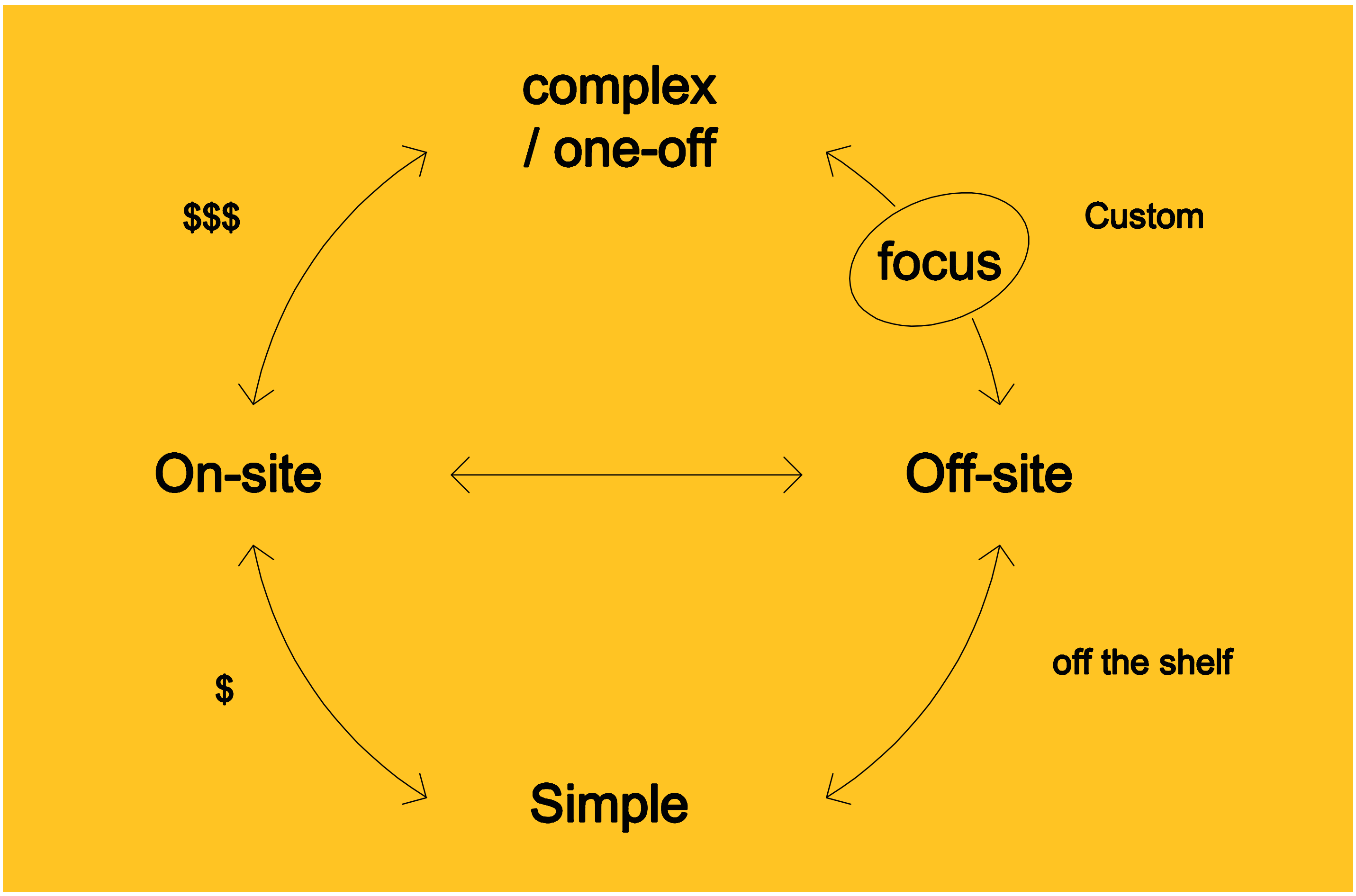
Le Corbusier had extolled the virtues of these industries almost 80 years before, perhaps he was right.

Although the research did have a broad focus it should be stated that my particular focus, as an architect, is on prefabricating customised or one-off buildings rather than on the repetitive mass production of buildings.

This resulted in a focus on companies that were producing to some extent on customised products. A smaller sample of companies were visited that do not focus on customised or one-off designs.

In 'Toward a New Architecture' Le Corbusier stated "the right state of mind for living in mass production houses" was required (Corbusier, 1931). Post war housing, in both the west and the USSR largely mirrored this concept with disasterous results. Mass produced housing has since transformed into mass customization, in response instead to human needs.

The alternative approach is to focus on the system rather than the product. A system, especially when combined with modern manufacturing techniques and intelligent 3D design tools, can provide almost infinite variation and respond to human needs and to local conditions.



world tour companies visited 2006 - 07

Funded by Byera Hadley, Jack Greenland Travelling Scholarships and Faan Studio

Countries visited - South Korea, Japan, China, Singapore, USA, UK, France, Germany, Denmark, Sweden

Companies visited

Aerospace	NASA (US), Boeing (US), Airbus (France)
Shipbuilding	Daewoo heavy (Sth Korea), Hyundai heavy (Sth Korea)
Automotive	Mercedes (Germany), Toyota (Japan)
Manufacturing	Jinli (China)
Prototyping/Tooling	Produktus (Germany)
Prefab	Toyota Homes (Japan), Misawa Homes (Japan), IKEA homes (Sweden), Skanska (Sweden), Pharmadule (Sweden), JM (Denmark), Trivselhus (Sweden), Simplex industries (US), Sun building systems (US), Nipomo homes (US), Kullman (US)
Prefab Architects	Pinchouse (Sweden), Swellhouse (US), Kithaus (US), Living homes (US), Marmol Radziner (US), Taalman Koch (US), Systems Architects (US), Res4 (US), Cartwright Pickard (UK)
Universities	Berkley (US), USC (US), California polytechnic (US), Loughborough (UK)

Australian tour companies visited 2008

Australian Research Council funded project   SIAL RMIT with Industry partner Arup

Australian companies visited / interviewed / surveyed

Aerospace	BAE aerospace, Hawker De Havilland, Boeing
Shipbuilding	Austal, Tenix Marine
Automotive	Toyota, General Motors
Manufacturing	VISY
Prototyping / tooling	Special Patterns, Camplex, Envisage, Concentric
Construction	
Developers / Builders	Bovis Lend Lease, Stockland, Mirvac, Hochtief
Fabricators	Advanced Steel, T& M Engineering, Sebastian Engineering, Timberbuilt, RPC Technologies, Max Mak
Precast	Hanson , Sasso, Fadl
Off-site construction	Weeks Peacock / Supaloc, Modscape, Gateway manufacture
Quantity Surveyors	Ryder Levett Bucknall, Donald Cant Watts, Plancost
Engineers & Consultants	Connell Wagner, Sinclair Knight & Merz, BDS engineering, Irwin Consult , Arup
Architects	Terroir, BKK Architects, Bligh Voller Neild, Tzannes, MacInteractive, Fitt DeFelice, NSW Government Architects office

process

The process that this research took was to identify leading and/or representative companies within each of the industries being researched, contact them and then establish a list of companies and countries to be visited, based on availability.

A series of general questions was developed that could be span the divide and differences between the industries, whilst addressing the questions that I set-out to answer. In many cases questions were answered a completely differently aspect of the question than that intended, which resulted in interesting insights into the differing focus of each of these industries and companies involved.

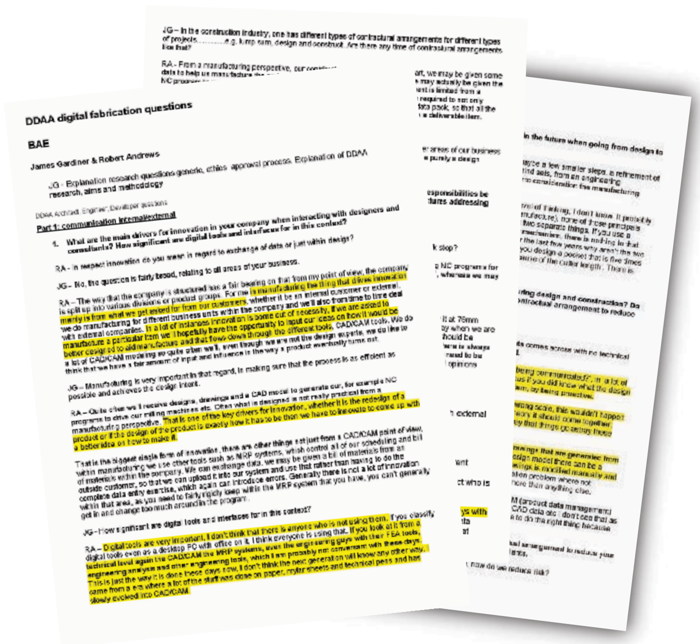
In some cases the same question had to be re-phrased three or four times obtain an answer about the specifc topic in question.

The facility and site visits also resulted in interesting insights, I found that the interview was best under-taken after the tour/visit to ensure the questions were grounded with a clearer understanding of the processes involved in production. The research was all about disolving assumptions.

The photos also proved to be an invaluable asset, with visits often lasting between 30 minutes to a couple of hours it was easy not to notice critical de-tails. The photos could be studied afterwards, often enabling me to glean more information from them than the descriptions given.

Unfortunately automotive and aerospace industries are very strict with their not hotography policies, so photos included here are all sanctioned photos by others taken from the websites or supplied from the companies involved.

Finally the notes and questionaires were collated and analysed to find patterns and trends within the industries and then compared with each other to undertstand similarities and differences between them.


DDAA digital fabrication questions

BAE

James Gardiner & Robert Andrews

Hyundai heavy, South Korea

getting there

Being awarded the Byera Hadley and Jack Greenland travelling scholarships were the easy part in comparison to getting the ok to visit the factories, facilities and houses. Planning the trip, contacting the companies, finding the right person to speak to and finally getting permission for the visit took months of persistant effort and a huge amount of patience.

In some cases I still didn't not have final approval for the visit until the day before I arrived. Every medium was used for contact with these companies, including cold calling, email, fax, letter, referal from contacts and even outlook meeting requests. Each culture responded differently to different combinations of the above contact methods. Trial and error and buckets of patience won out in the end.

The international field visits included 33 companies in 10 countries over a 6 week period. The second trip funded by the ARC delivering digital architecture project included 44 companies over a much less intense 2 month schedule. Many of the lessons learned from the round of contacts were applied the second time, the process of getting approvals for visits wa still just as tough, even within my native country.

Wherever the opportunity arose I managed to organise additional visits on the fly when opportunities arose during the visits.

NASA image NASA

what is prefabrication?

‘Prefabrication is a manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a component part of the final installation’ *(Gibb, 1999)*

what is prefab?

The origins of prefabrication are largely subject to the how you define the term prefabrication. The word can be applied to relate broadly to either fabrication of building parts off-site or the industrialization of the building process.

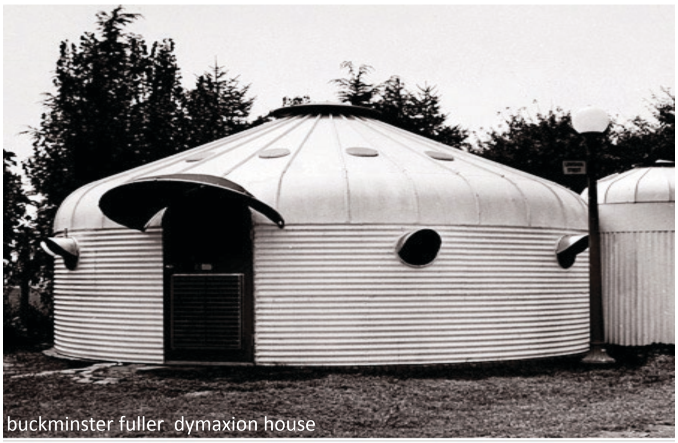
Under the first definition prefabricated buildings date to the Roman empire in the first century AD (Gibb, 1999). Under the second definition the birth of industrialized prefabrication was firmly established in 1851 by Sir Joseph Paxton's Crystal Palace, 'a building process made manifest as a total system' (Frampton, 1997).

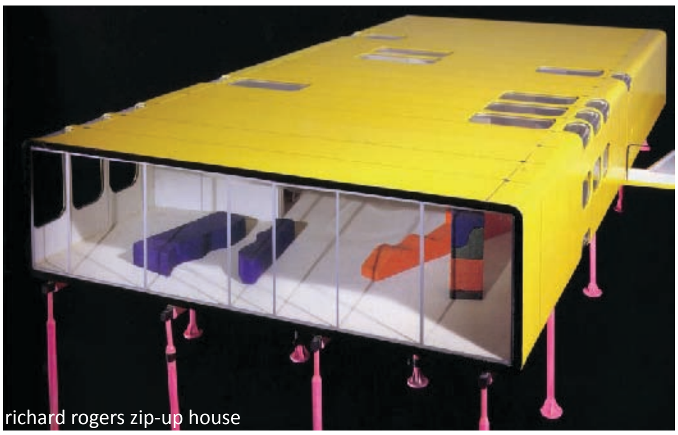
Prefabrication is defined as "1. to fabricate or construct beforehand.2. to manufacture (houses, etc.) in standardized parts or sections ready for rapid assembly and erection." (Prefabricate, 2009).

joseph paxton's crystal palace


Ray & Charles Eames Case Study House

architects


buckminster fuller dymaxion house


richard rogers zip-up house

Most of the prominent architects of the 20th century experimented with prefabrication: including Jean Prouve, Le Corbusier, Buckminster Fuller, Frank Lloyd Wright, Walter Gropius, Ray & Charles Eames and Richard Rogers. None were successful in delivering a cost effective product to a large market (Davies, 2005). In ‘Toward a New Architecture’ Le Corbusier stated “the right state of mind for living in mass production houses” was required (Corbusier, 1931). Mass produced housing has instead transformed into mass customization, in response to a qualitative increase in human needs. However, the technology transfer advocated by Le Corbusier and Fuller is still entirely relevant today and provides significant opportunities for prefabrication in the future.

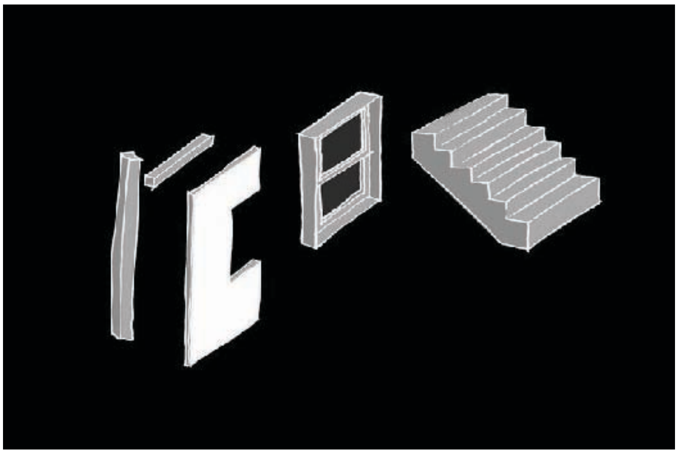
types of prefabrication

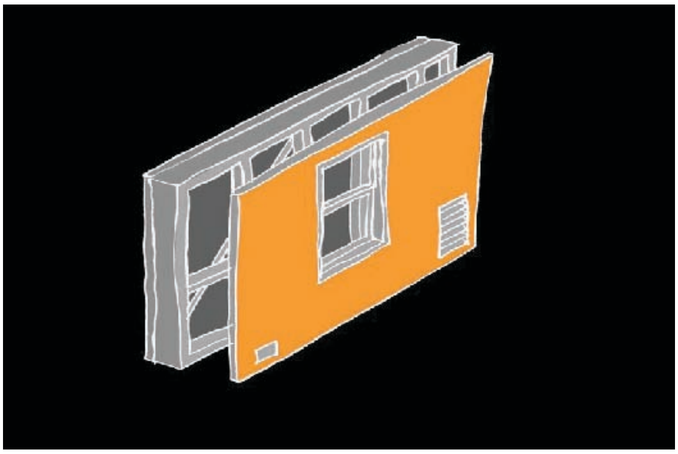
1. **Stick and Panel**; processing of industrial elements to reduce site labour. This definition can be extended to include contemporary building practices, such as standardized window systems.

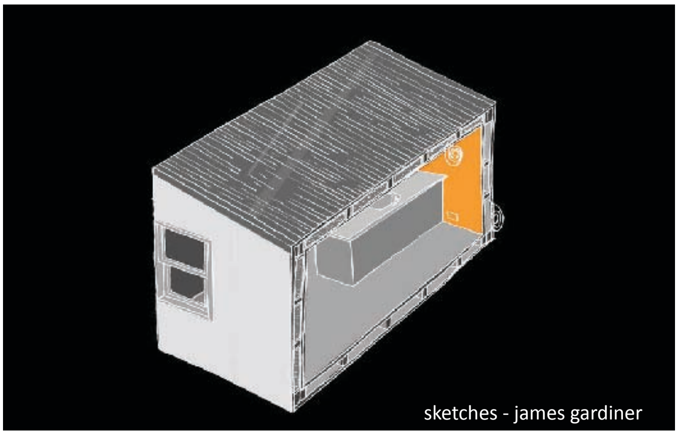
2. **Panelized**; complex assemblies fabricated into panels for ease of transportation, including elements such as services, finishes and insulation, reducing work on site. The definition can include the products of construction sectors such as precast concrete.

3. **Modular** (or volumetric); structurally self supporting or load bearing volumes enclosing whole sections of buildings, typically fitted-out with services, fittings, finishes and joinery. Modular construction is often combined with panalization.
The three terms defined differ slightly in detail, but largely follow categorizations given by (Gibb, 2001) and (Gann, 1996).

These definitions were broadly recognized by global industry participants in the construction and parallel industries interviewed between 2006 to 2008.







sketches - james gardiner

kithaus USA

RES4 - robin hood

cartwright pickard - murray grove project

The projects observed during the research visits included all three of these categories. Although stick and panel construction can be considered a type of prefabrication in the broadest sense, this type of construction is the norm within construction industires of the developed world today. And is essentially a form of industrialised of construction comodities, includes the use of standardised materials (such as bricks, steel and timber sections, window and stair assemblies etc.

Prefabrication today, in order to have any meaning, must be defferentiated from from standard construction practice. Therefore two categories should be present.

1. Significant works off-site (>50%)

2. Preassembly to reduce labour on site

kisho kurokawa nagakin capsule tower tokyo 2007

aerospace

"(the) CAD data, is now being utilized across the whole business. Everything seems to feed off that same data"
Australian Aerospace production manager


image boeing

not one industry

On initial research of the 'Aerospace industry' I was under the impression that this was one single industry with heterogenous practices. After a number of interviews and site visits I realised that this was not the case. Although the leading companies in both industries are often the same (Boeing and Lockheed Martin), there are major differences between the products being produced for each purpose; terrestrial and space flight.

The aeronautical industry and space industries are therefore discussed as two separate industries. The major difference between them is the aeronautical industry produces multiples of a fairly standardised product, whereas the space industry produces highly specific products based on the specific objective being addressed in very small quantities.

Rockets for the launch of space vehicles are often a repeat product, but everything that goes into space, even most satellites are highly specific custom designed objects. In my interview with NASA I was handed a prototype for a new generation of satellite that would use a modular structural chassis. This was apparently new thinking in 2007!

assembling the prefabricated fuselage - image boeing

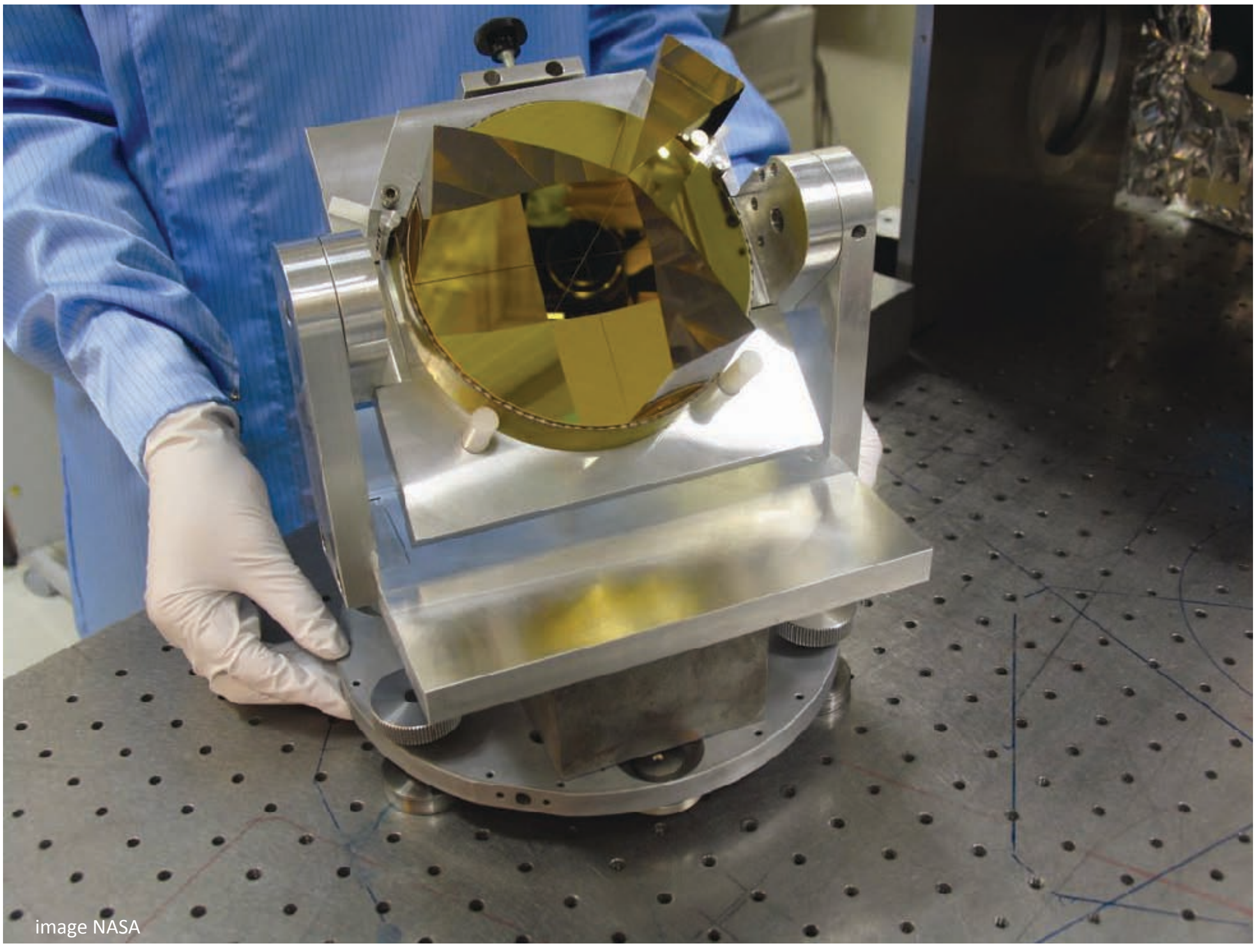


image NASA

On reflection the space industry appears to be the closest industry to construction industry. Buckminster Fuller I believe once stated that each house “is a prototype for a production run of one”. This is also true for the space industry.

As it was explained me at the AMES research centre in California by a satelite development team manager, the costs for sending an object into space were so enormous and the risk of failure so high that every object was precisely engineered to reduce weight and to fulfil it precise functional requirements within an extremely harsh and unforgiving environment.

As a consequence, every object becomes a prototype and thus cost overruns and time delays are common. The major difference between the construction and space industries is, for the space industry there are huge research and development budgets and an unwavering focus on performance and quality. Something that the construction industry could only dream of.

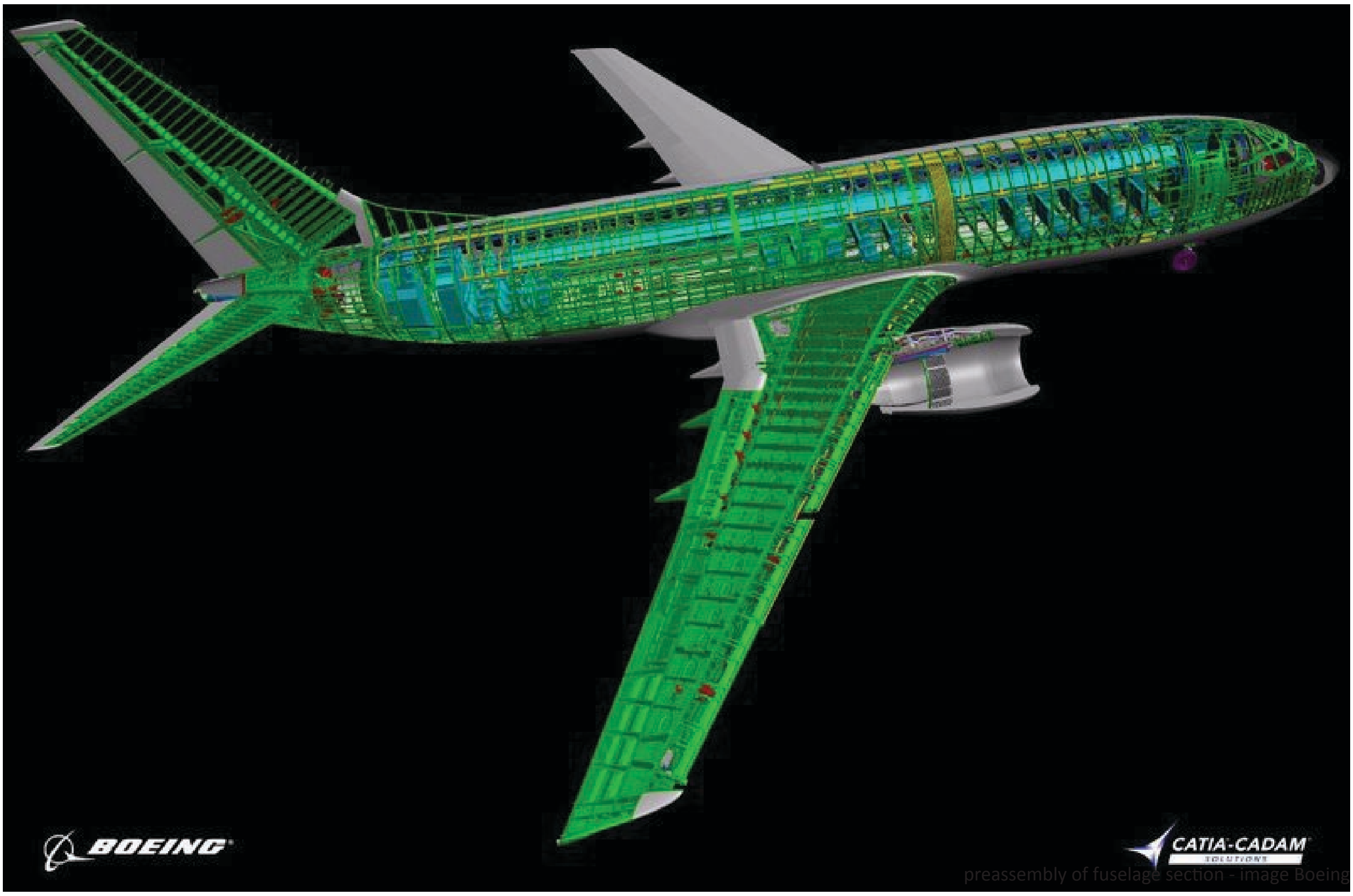
image NASA

aeronautical industry leads the way

The greatest insight into the aeronautical industry came through from a number of extended interviews with engineers and team managers within a number of leading aerospace companies, such as BAE, Boeing and Hawker De Havilland.

Although I knew that many of the substantial advances in Architectural CAD programs had arisen in the Aeronautical industry, such as the development of parametric software such as CATIA®. I did not realise how intrinsic their use of the 3D model had become, the 3D model is now used in every aspect of the companies business from ordering and costing, design collaboration, testing and analysis, certification, automated fabrication through to testing for maintenance accessibility.

The industry is highly regulated and the product is very expensive in comparison to buildings (if comparing cost/weight). The management of risk is extreme in comparison to the construction industry. These companies are required to track each process from decisions made in the design process, sources of materials (including batch numbers), through to fabrication, assembly and maintenance.



preassembly of fuselage section - image Boeing

image Boeing

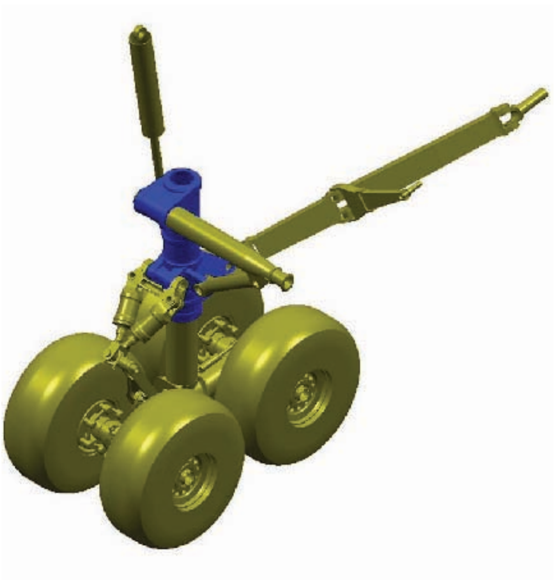
We are a quality controlled company....it doesn't come down to one person standing there and gritting his teeth, it comes down to things being done through a control process with many levels of verifications and checking..... We don't just have a veranda fall off, we have an aeroplane crash.

the benefits of managing risk

One can understand why managing risk is such a priority, if a plane crashes and kills 200 people, there is a lot at stake in finding who or what caused it. Investigations invariably take place and the plane wreckage is forensically examined to decipher the cause of the accident. This is likely to be one of the major reasons for the use of the single model as the central repository for the huge amounts of information stored on a project.

By tagging information to the 3D model, the information remains accessible, if changes are needed to modify the profile of a wing section, the finite element analysis model can be accessed, along with the performance specification and notes recording key decisions made in its design. This is fundamentally different to the way information is stored about buildings.

The benefit here is that this industry has found a way to leverage the 3D model, by clearly identifying the value of this 3D information, there is a case to be made to pay for it.



solid model of landing gear - image Boeing

aeronautical industry characteristics

Small production per annum

Huge R&D resources invested in product

Highly consolidated industry - few players dominate

important practices

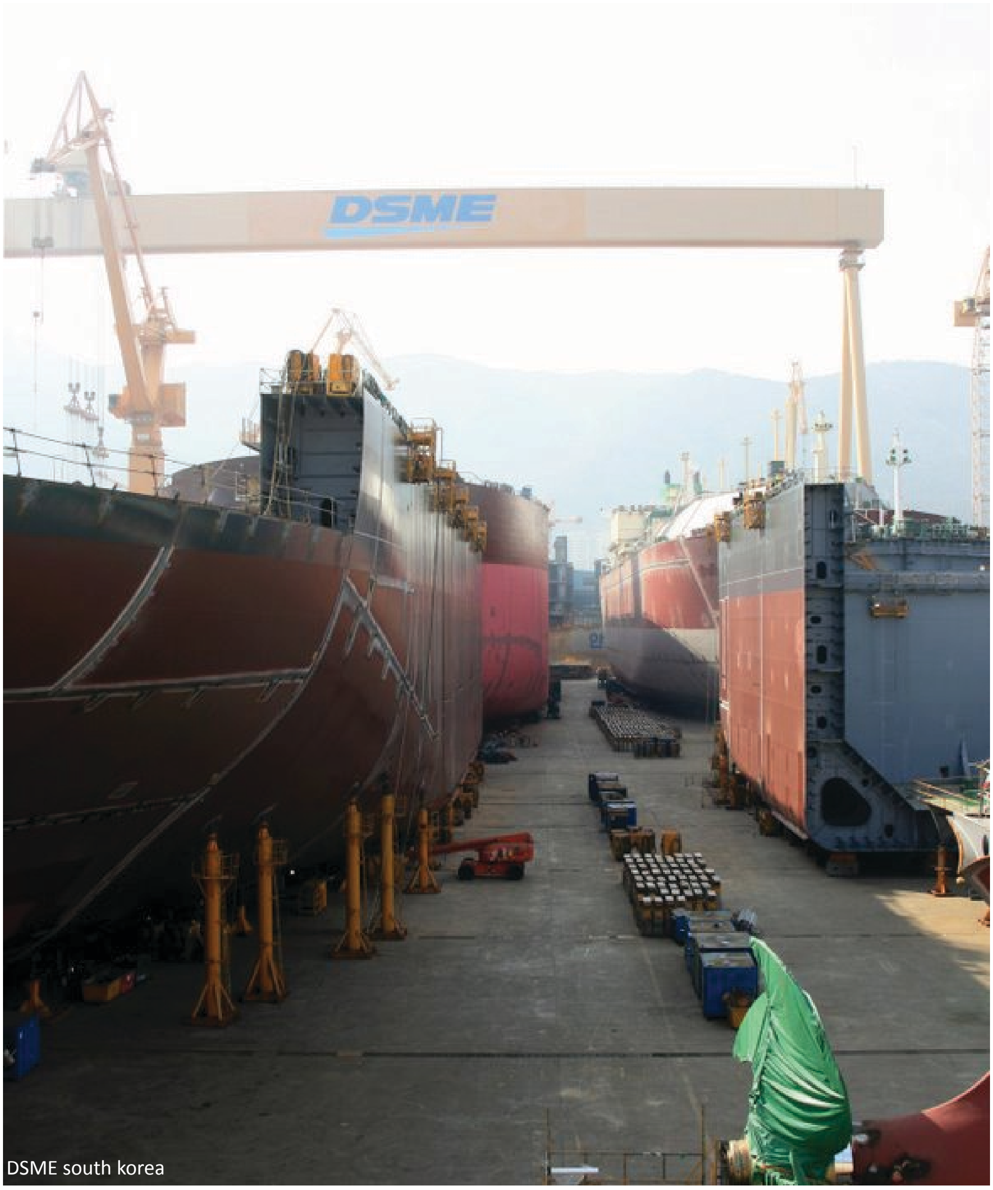
Decentralised production - centres of excellence for production of components

Solid 3D modelling and surface modelling are used to test and evaluate prior to production and then used throughout every aspect of the business, leveraging the same model to its maximum value.

Investment in software development is yielding substantial improvements in quality and efficiency

shipbuilding

"Use of 3D model for documentation to fabrication – reduces rework from 30% to almost nothing." *Australian Shipbuilding Engineer*



DSME south korea

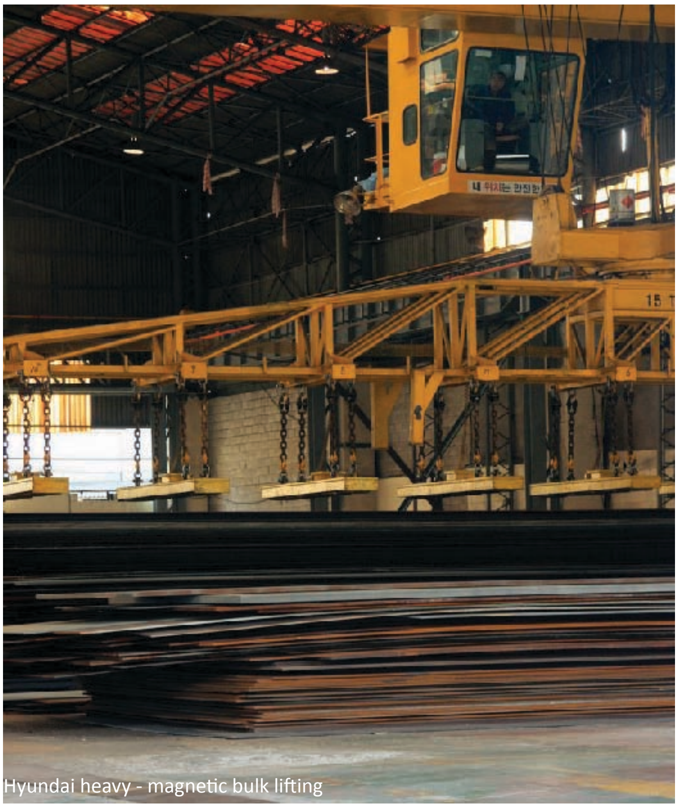
part, block, mega block, ship

The process of constructing a ship in South Korea is a highly organised process, that relies heavily on prefabrication to speed up the fabrication process.

The ship is considered in 4 main stages 'Part, Block, Mega Block, Ship', each of these stages has a series of distinct tasks that are performed and the break down of the ship into sub-assemblies enables many operations to run simultaneously.

Instead of starting in the dry dock and building the ship from the ground up, sub-assemblies are fabricated away from the final assembly site. The process begins with the production of a highly detailed 3D model of the ship. The hull is first modeled in surfaces and tested using finite element analysis (FEA) and other testing software. Once the ship hull design is finalised the model is converted into a solid model and the services and other elements are added to the model. This includes ladders, doors, accessways, hydraulics etc.

The virtual prototype is created, tested and problems identified, prior to fabrication. The model is



Hyundai heavy - magnetic bulk lifting

DSME - plasma cut steel sheet ready for assembly

Hyundai heavy - assembled parts ready for assembly into blocks

Hyundai heavy - assembly of the block

then used to generate the steel profiles to be cut with an automated CNC plasma cutter.

The process of fabrication then proceeds in a similar way to building prefabrication. With subassemblies created (parts), which are then assmbled into modules (blocks), these modules are then assembled into the Mega blocks and these are then used to form the final product (ship).

Although the scale is many times larger than the usual prefabricated building, the principal is largely the same. The dry dock can be considered the site, but only a fraction of the total work occurs within the dry dock, allowing many operations to be done simultaneously, which speeds up the process.

The largest difference is the way that the ship is designed and documented; entirely in 3D. This model is then used generate the files for cutting the steel and other operations. "Use of 3D model for documentation to fabrication – reduces rework from 30% to almost nothing".

Hyundai Heavy - fitout of the block with services

In the last couple of years this practice of documenting buildings from 3D models has increased significantly, with the increased uptake of programs such as Revit™ and Archicad™ by architects. This has been complimented in recent years with the availability of aligned programs, produced by the same companies, for MEP and structural applications that have native interface with these programs.

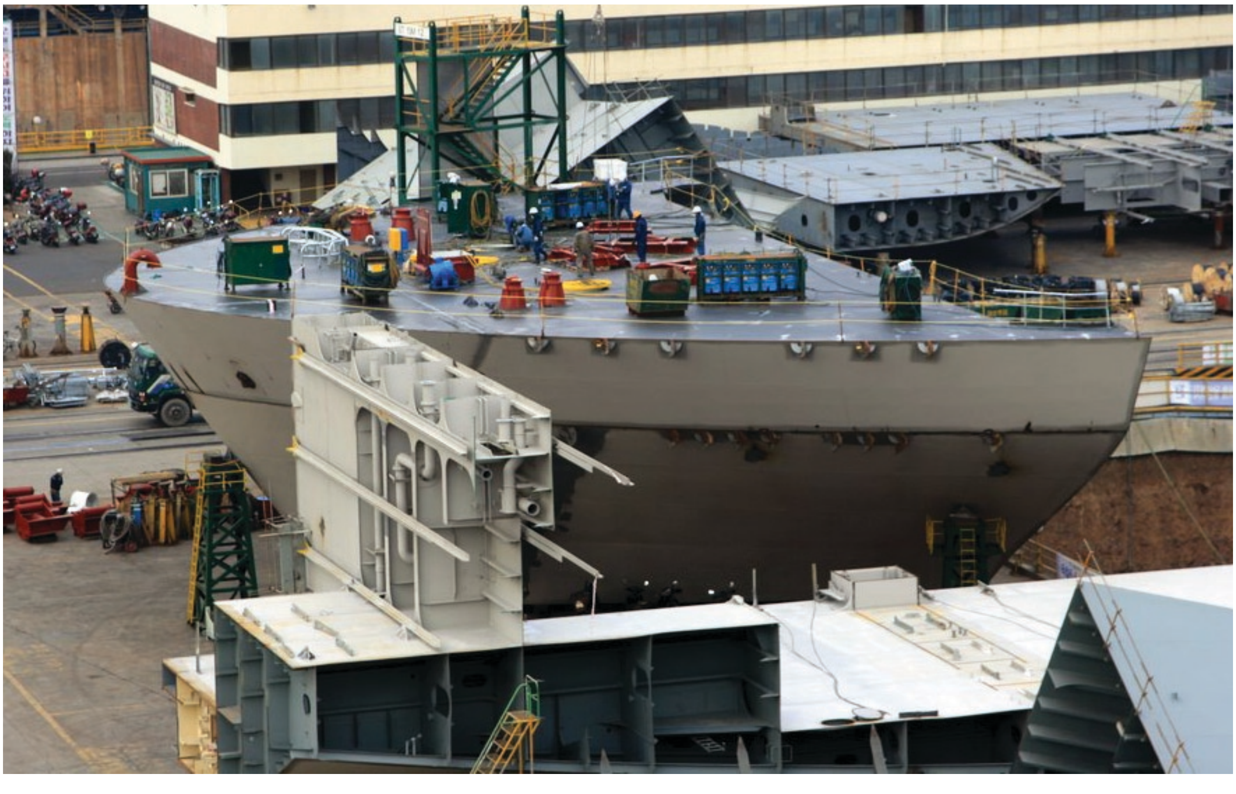
The construction industry has still got a lot of catching up to do in leveraging the value of these 3D models, mainly in the use of this data directly by contractors and fabricators.

Hyundai Heavy - installation of Hydraulics


Hyundai - transportation of the block complete with services


Hyundai - 900 tonne capacity Goliath cranes lift the blocks into position

"For us as an engineering enterprise; controlling (change) is the most important thing" *Australian shipbuilding engineer*



Hyundai - mega blocks are then welded together to form the ship

keep it in-house

One of the unusual charactoristics of the shipbuilding industry is the preference to keep design and production in-house. Hyundai Heavy for example builds its own engines on site, and fabricates as much as possible the other components.

By contrast this would be completely atypical within the construction industry, with a high level of specialisation; door and window suppliers, kitchen specialists and air-conditioning contractors.

This has benefits and draw-backs. In the case of the large shipbuilders, their supply quantities are small, Hyundai heavy at the time of the visit was the largest shipbuilder in the world, producing approx. 90 super tankers a year. In the case of Australian large shipbuilders quantities are much smaller, with the suppliers you get what you are given, in the Australian context this lack of competition and restricted certified market results in limited choice and in some cases a compromised product .

In the case of Hyundai, the company maintains control of almost every aspect of their production, building their engines themselves. In the automotive industry, although they also build their own engines, this is usually done in a seperate specialist facility. Dependence on external suppliers is very high and due to quantities in the 100,000s of thousands bargaining power is used to enforce strict delivery regimes, warranties and constrast improvement.

Hyundai Heavy - cast propellor CNC milled to its final profile

“Most design and engineering is done in house, mainly to manage risk. This is primarily due to the need for (the company) to warrant their product” *Australian Shipbuilding Engineer*

shipbuilding characteristics

Small production quantities

High R & D

Build almost every component at the yard

Important practices

Break down the object into sub assemblies

Fit-out of sub-assemblies complete with services

Solid 3D modelling & finite element analysis for virtual prototyping and testing

automotive

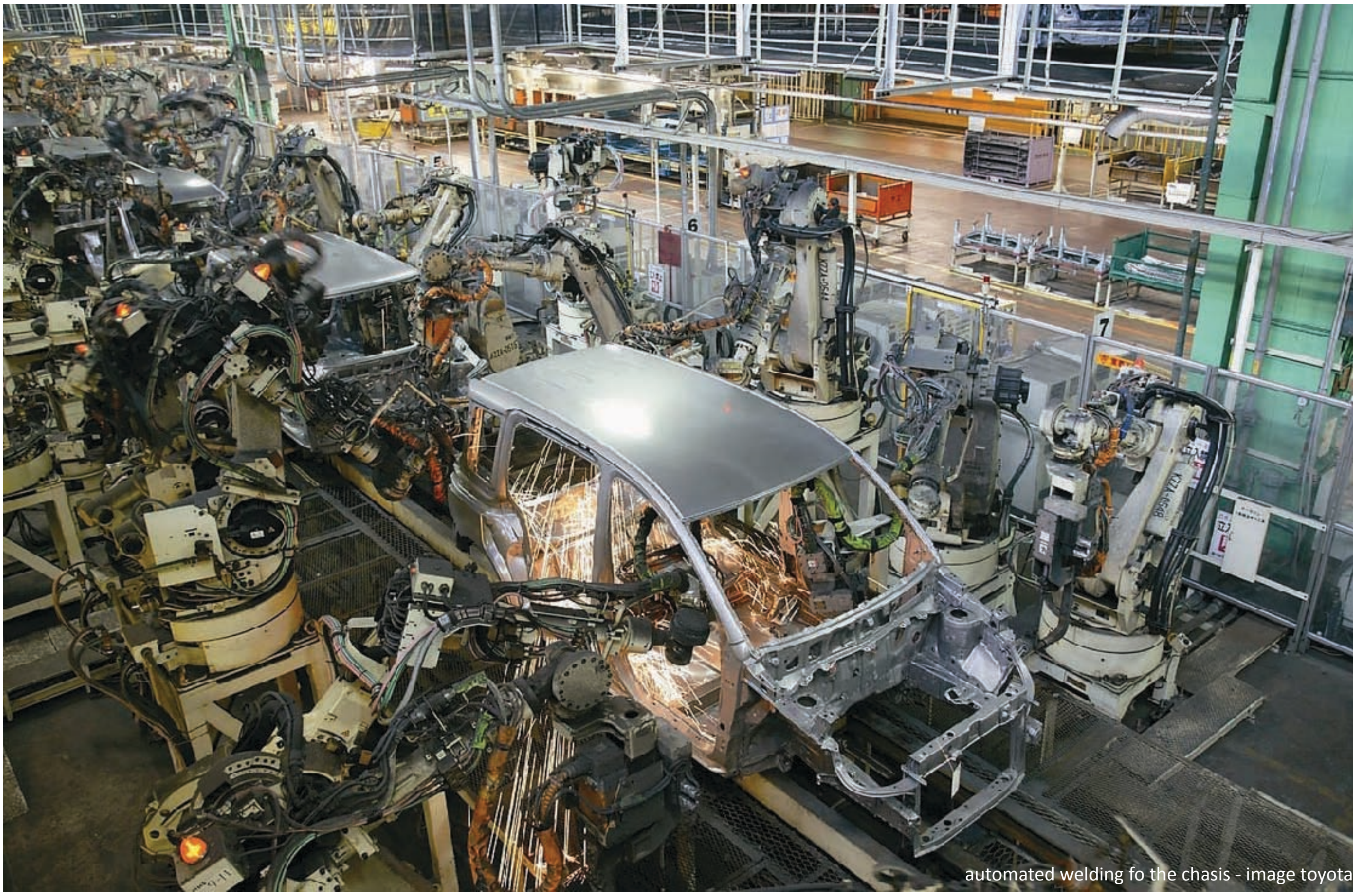
"If you haven't got good quality data management from the word go you are on a very slippery slope to a major disaster….. with 3D data the potential for a huge mistake is immense" *Australian automotive design manager*

automotive automation

The Automotive industry has changed dramatically during the last century to meet the expectation of customers and keep an edge on competitors. Toyota led this shift from the fordist doctrine with the concept 'Lean production', which included the term 'just in time' adopted and championed by the computer assembler Dell. In adapting to consumer taste the industry has reached another dilemma, how to manage consumer expectations.

"The need to meet increasing levels of customer choice for different model options means that a factory has to cope with millions of possible build permutations. Toyota manages this partly by minimising the number of parts in a new model and partly by pushing some of the build complexity out of the plant and down to dealers, who install customer options as bundled dealer installed packages

stamped structural panels - image toyota


automated welding fo the chasis - image toyota

The automotive industry has an incredibly high level of automation, which is possible due to the very large volumes of cars produced. A new production facility and a new automotive line, which may be used for a number of different car models, costs approximately 2 Billion dollars each.

This cost and investment in automation can be amortised through each product produced, resulting in a product that has approx. 100,000s of engineering hours whilst the car ower only pays a tiny fraction for the engineering that has gone into this, as the cost has been spread accross all of the products (Kieran and Timberlake 2004).

sub-assemblies are automatically transported around the plant for attachment to the car chasis - image Toyota

checking operations and complex assembly tasks that are difficult to automate - image Toyota

The construction industry, including prefabrication, is highly fragmented (Egan, 1998) when compared to the highly consolidated parallel industries, principally the automotive and aerospace sectors. This factor reduces the opportunities that larger companies have to concentrate research and development, (funded by very large volumes of products produced) or to spread activity by collaborating with others to share costs and find ways to improve (Egan, 1998).

One of the principal and very significant differences between the automotive and construction/prefabrication industries is the design and engineering time invested in each new product.

Although there is little real variation between these car models, each car that rolls of the production line is potentially unique, given the high level of customisation offered. Although most of this customisation is cosmetic; colour, alloy wheels, trim etc; deeper customisation is also possible, electric seats, bluetooth, LPG conversion.

design and engineering

The cars and all components are designed to fit within a system, that can have interchangeable parts. This system thinking, although potentially limiting in some aspects, can also allow infinite cariation.

Although a car model may change every season, with variations in appearance, inclusions etc the basis of the car is essentially the same for a number of years. This allows for greater resources to be invested in the base product, which has led to predicatable increases in quality over time.

Most houses built today are also a product of this infinite variation although they are not engineered as a system. Although the consenus is often that every house or building is unique there are many elements within buildings which are be repeated constantly. The lesson to be learnt from the automotive industry is not mass-production, not eevn mass-customisation but rather systems thinking.

human intervention is kept to a minimum - image

automotive industry characteristics

Very highly automated production

High production volumes of similar products

most customisation is largely cosmetic

High level of competition

High levels of R&D

Important practices

Mass customisation is the dominant mode, not mass production

Penalties for late delivery act as an incentive for suppliers to deliver on time

High levels of engineering & R&D result in fewer defects and a higher quality product


automated transport of car during assembly- image toyota

prefab companies

"The difference between ours system and many others in our business is that our machines produce finished product for our houses, you pick a wall of a house, a door, a stud........that stud is unique as far as our system is concerned." *who*

why use prefab?

In surveying prefabrication companies the biggest contrast could be attributed to focus. The belief in the old adage ‘of cost, quality and time; you can have only two’ appears to be playing itself out in prefabrication industry.


Show house Nipomo homes, USA

In the USA of most of the prefabrication companies surveyed cost was the major focus, competition is fierce in this realm and quality is the most obvious area of compromise.

In contrast the focus in Japan is on quality, with companies focusing on the mid-to upper cost range of the housing market. Houses come with a 20 year guarantee, in a similar way as warranties are offered on cars.

Although this is a generalisation of the markets in the two countries, it was overwhelmingly the impression for the majority of houses visited in those countries (with the exception of the emerging Architect designed prefab in the US, discussed in the following chapter). The trend is not isolated to these countries, the contrast is just the most apparent in these locations.


Show house Nipomo homes, USA

Show house Misawa Homes, Japan

Show house Misawa Homes, Japan


HUD code home upside down on the side of the freeway

The overwhelming attitude that I am constantly surprised by is that prefabrication is predominantly about reducing costs. The response to the question "why use prefab?" from companies surveyed across the world was that cost was not a primary factor, quality and time were the predominant reasons.

There were a large number of other reasons which also motivated the use of prefabrication. In some countries such as Sweden, weather is strong motivation for the use of prefabrication. Although the types of prefabrication were not always particularly efficient or substantially reducing work on site.


wrecked HUD code home on the road from LA to Joshua Tree, USA

prefab housing stockholm

Sweden has statistically the highest use of prefabrication in the world, with some academic papers stating it is as high as 90%. This compares with approximately 40% in Japan, 20% in the USA and 2-5% in the UK and Australia. Again this is very dependant on the definition of prefabrication.

The reason most often cited for the predominance of prefabrication in Sweden is the long winters which make on-site construction difficult. I visited a number of projects in southern Sweden during winter, including one by the largest builder of prefabricated homes in Sweden Trivselhus. Although this is certainly not the harshest environment in Sweden, it was still very cold and snowing regularly.

I was surprised to find that the houses visited were ‘stick & panel construction’. Although some work, such as creating assembled panels is completed off-site, which may assist with getting the building to a weatherproof state faster, very large amounts of on-site labour are still required to complete the houses and buildings I visited.

Trivselhus house under construction, Stockholm

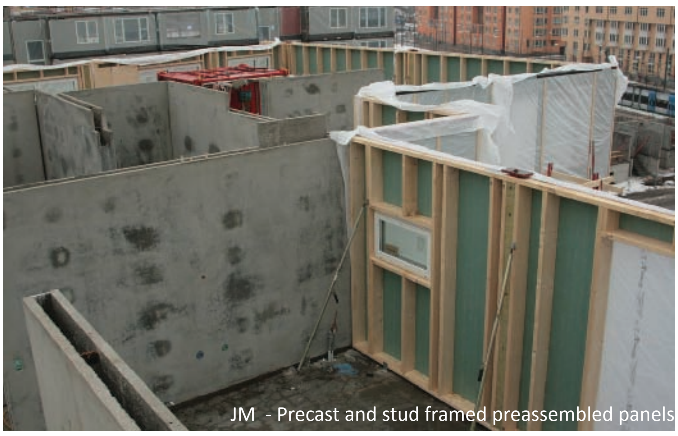
same house interior

By my definition of prefabrication the projects visited would barely be in contention to be called prefab.
Very similar practices were also observed on a much larger multi-storey building that JM was building in Stockholm.

Again fairly basic panel assemblies were used, these also required a large amount of site labour to finish the building. All external finishes are applied after panel installation, as well as internal wall insulation, electrical wiring and finishes.

These two projects are extremely similar, despite the very substantial shift in scale. With both using a minimum of off-site labour overall.


JM Stockholm building site - Panelised construction


JM - Precast and stud framed preassembled panels


JM - adding exterior insulation & cladding

IKEA Boklok prefab bathroom module - Trelleborg

This was not the only method used however; companies such as Skanska the company that builds IKEA's Boklok housing (sold in a number of countries in Northern Europe) prefabricate almost every aspect of the building, including the foundations and tiled bathrooms.

Although the product has little design flair, it is however very interesting to see that virtually every process can be replicated off site. Minor adjustments are made for off-site construction and transportation, such as removing tiles in certain locations that may be prone to breakage during transportation.

This company has a couple of different levels of prefabrication for different markets. For the less expensive low level modular apartments it sells, the building is very substantially fitted out prior to delivery to site. Whereas for the single occupancy homes that sit amongst these apartments on the same sites, these are much less prefabricated. According to Skanska, this was to allow a greater level of customisation.

IKEA Boklok affordable apartments - Trelleborg

Prefab foundations - Skanska precast facility

50

re-engineering old habits

Many of the factories and facilities visited during the research trip revealed that construction tasks were simply being performed the same way in the factory as they were being done on site. With the occasional use of labour saving devices or special machinery.

Due to conservative attitudes of home buyers and the stigma that is still attached to the word prefab, many of the houses produced are emulating traditional forms, while substituting materials and cutting corners and quality.

Where real innovation is apparent and real efficiencies realised is when the whole process is re-engineered, as it has been done in the parallel industries. These industries have experienced major increases in efficiency, quality and profits since adopting this approach.

Sun building systems - modules ready for delivery

Sun building systems - display home Scranton, USA

Simplex Homes, Scranton USA

Industrialising Prefabrication

Giants from other industries are also becoming involved in prefabrication. Companies such as Toyota and Muji are moving into the sector, presumably looking to diversify their product range, as IKEA is building the houses to put their products into.

In Japan Toyota Homes and some of the native prefab companies, such as Misawa and Sekisui are making significant advances toward industrialising the construction process. The Misawa plant, the most impressive of plants visited, runs moving production lines and has heavily automated much of the production.

The approach of Misawa compared with Toyota is different, Misawa does not prefabricate bathrooms and kitchens , for reasons similar to those of IKEA, to allow for a higher level of customisation to occur for their wealthier clients.

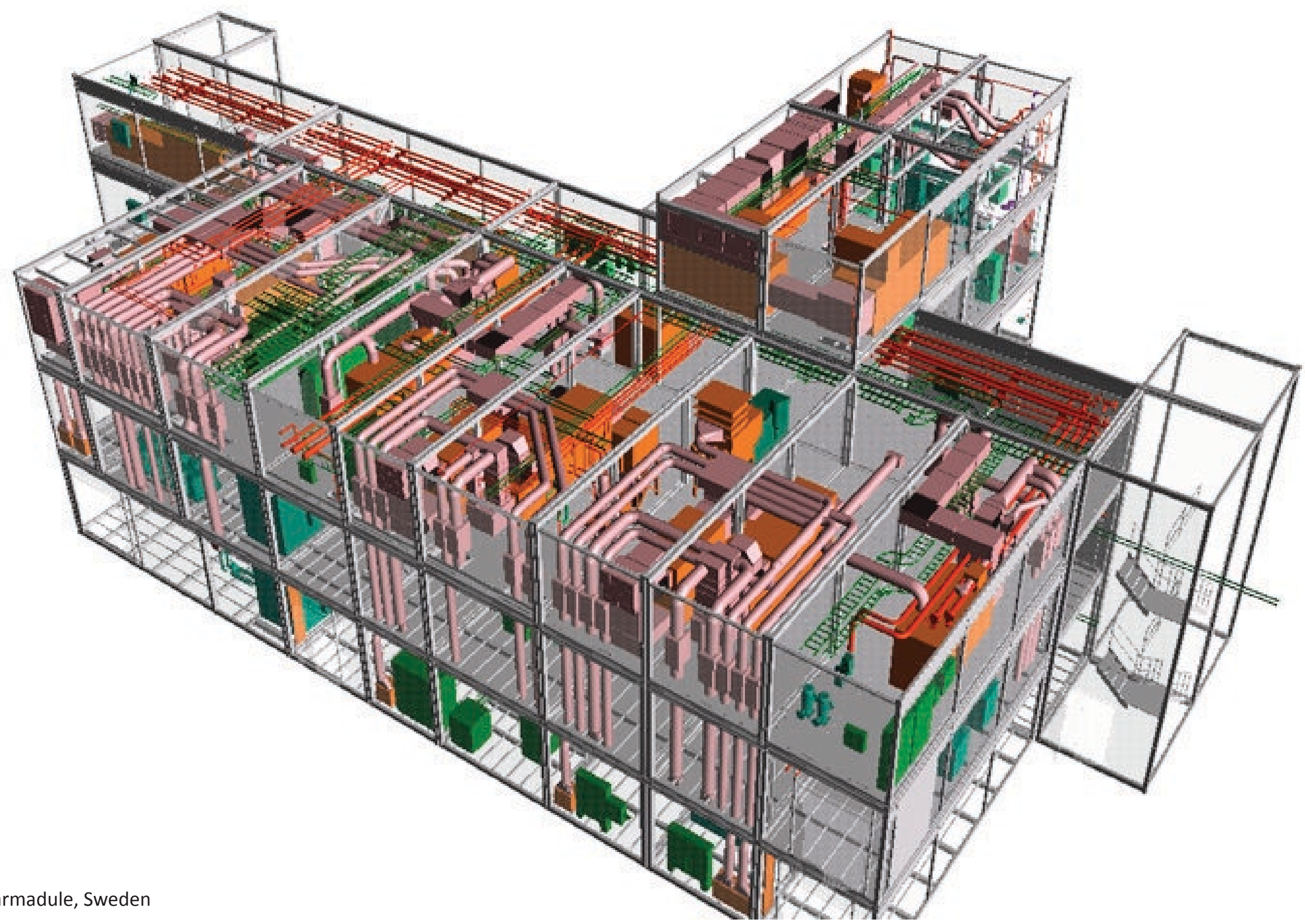
Strangely, despite automation and huge sums spent on plant and R&D (approx. 2 billion invested in both) they are still using timber stud framing rather than structurally insulated panels (SIPs), which would substantially simplify construction.

Misawa Homes, Japan

Misawa - automated steel frame production

Specialist, non-construction companies have also adopted prefabrication techniques to deliver high value, very high quality production facilities. Pharmadule, based in Stockholm Sweden design and produce modular pharmaceutical facilities. These modular buildings are constructed complete with all services in Estonia, then assembled and tested within the factory to ensure the whole facility functions as designed. The building is then dismantled again and shipped around the world, including the Middle East and South America as a ready made pharmaceutical facility.

Every element of the facility is solid modelled and tested using a range of different software tools prior to fabrication. This, as in the parallel industries, helps to substantially reduce mistakes and re-work.



Pharmadule, Sweden

prefabrication industry characteristics

Highly fragmented industry

Low R&D generally

2D design & documentation predominates

important practices

Design for quality, speed and added value not primarily for cost

Don’t reinvent the wheel, there are very innovative systems in use

The public is not **as** focussed on design as architects wish, education is key to changing this

Everything can be prefabricated including foundations

prefab architects

“With 3D, the problem is…..for us it’s just one way traffic”
Prominant Australian Architect 2008


Home Delivery Exhibition NY 2008

for love or money?

My interest in prefab, as stated above, is not in mass production of homogeneous products, but in its potential to deliver a unique product, using a systematic approach. Surprisingly although many of the architects interviewed focus on delivering a unique product, only a small proportion of them had a clear systematic approach. Instead many of them simply focussed on the design of a small number of products, which would then be customised if and as required.


pinc house, Sweden

The page opposite summarises some of the responses to a series of questions that I had regarding their approach, such as; What method was used for the development of design, size of modules used, whether bathrooms and kitchens were prefabricated, were services integrated off-site or on site as well as the percentage of work completed on-site.

All of the sizes and costs have been converted to metric and Australian dollars for ease of comparison.


Taalman Koch - desert house

One thing that became quite apparent from undertaking this process of comparison was that there are companies that are truly passionate about prefab and focus on understanding it and strive to innovate and then others that appear to be using the term prefab simply as a marketing tool. In some cases re-badging construction with only pre-cut structural components and 90% work done on site as Prefab.

As stated earlier prefabrication in its broadest, least meaningful context is the construction industry today, using standardised building products and sub-assemblies. It is misleading however to try to sell standard construction practices as some form of new prefab housing concept.

Company name	OMD	Living Homes	Marmol Radziner	Kithaus	Taalman Koch	Cartwright Pickard
benefit prefab	time, quality, sustainable	time, quality, efficiency, sustainability, cost only with larger volumes	time & quality	time, cost, quality, sustainable	quality not possible by regular construction at remote sites	time, cost
areas prefab does not meet expectations	cost savings not great, economies of scale difficult to achieve	Cost savings not realised with one of projects, fabricators conservative and unwilling to change, quality can be an issue.	cost savings not great, economies of scale difficult to achieve	cost savings do not meet expectations, but is still cheaper	cost savings not realised to date	time & cost, quality so far has not been as high as expected
Type prefab % (stick, panelised, modular)	10% panelised, 90% modular	modular 100% R & D on panelised system	modular 100%	Stick 100%	Stick 100%	load bearing modular 100%
Frame material	Steel	Steel	Steel	Aluminium	Aluminium	Steel
elements done on site	Foundations, exterior stucco	foundations, interior timber lining, plasterboard and tiles finished on site,kitchen joinery onsite	foundations, exterior decking and shading, connection of services	foundations, interior finishes, services	everything except cutting of materials prior to delivery	external cladding, connection of services, stairs & balconies
% work on site	10% average	35% aiming for 20%	10%	20% interior	95%	5-10%
tolerance achieved	25mm	5 - 15mm	+ / - 5mm			+ / - 5mm
size modules (if used)	L 21m W 3.6 - 4.8 H 4.5 m max	L 3.6 - 18 max 21m W 2.4 - 3.6 H 3.6 m max	L 7.3 - 18m W 2.4 - 3.6 H 4.1 m max	Non modular L 3.9 - 5.1 W 2.7 - 5.1	Non Modular	L 8.0 W 3.0 H 3.0 m
Is this dictated by transport	Yes	Yes	Yes	No	No	
relationship with builder	projects tendered	projects tendered, would be interested in ongoing relationships	build in house	build in house	projects tendered	projects tendered
design focus	material honesty, minimal aesthetic, outdoor connection	spatial - height and openings, using materials as efficiently as possible, the 6 zero's	spatial, sustainable,indoor / outdoor connection	aesthetic, sustainable	aesthetic	
client motivation	design, sustainable	time, cost, sustainable	time, cost, remote site, aesthetic, sustainable	time, cost, quality, remote site, aesthetic, sustainable	aesthetic, modern	time, predictability, quality
how many buildings completed (feb 2007)	3 complete 3 under costruction 5 contract	1 complete 1 under costruction 12 contract	2 complete 2 under costruction 12 contract	6 complete 3 contract	4 complete	6 complete 3 under contract 1 tendered
build cost (m2 AUS feb 07)		$3,400	$4,100	min $2730	$4,100	
design unique, customised or off the shelf	custom configurations using standard modules	Standardised floor plans, customised to site within a 12ft module, bathrooms and kitchens standardised	custom configurations using standard modules	off the shelf design with limited customisation	off the shelf	unique
biggest poblem faced in using prefab	authority approvals, perception is that housing should be built on site if the cost is high	authority approvals	labour efficiency, transportation logistics	building codes & local councils	authorities, delivery difficult to organise for remote sites	
Types of buildings	single housing, school	single housing	single housing	single housing	single housing	Multiple housing

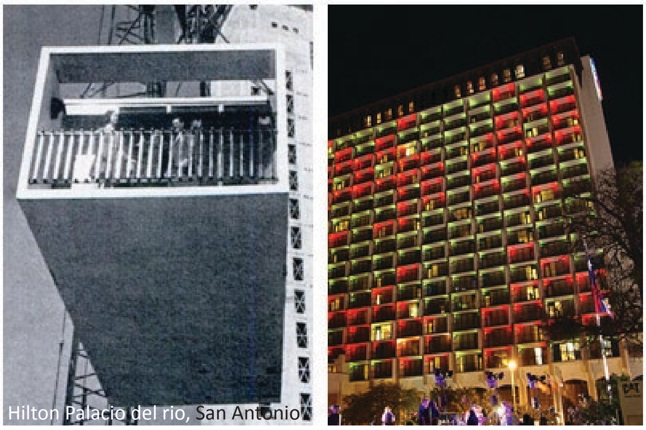
re-inventing the wheel or inventing a new future

Sustainability emerged as an important motivation for the use of prefabrication techniques. Whether sustainability is the primary motivation, is not terribly important, there are a number of benefits of aligning the use of prefabrication techniques with the sustainability issue.

There are benefits such as reduction of construction waste, trade travel to building sites, higher energy efficiency in construction through use of tailored fabrication tools, greater control and testing of subassemblies or modules prior to delivery and tighter control of the use of sustainably sourced materials. The practice can obviously also deliver quantitative benefits such as energy efficiency, this can be further enhanced by ensuring that the delivered product actually meets its stated sustainability targets.

image RES4


RES4 peconic Bay House - Southhampton

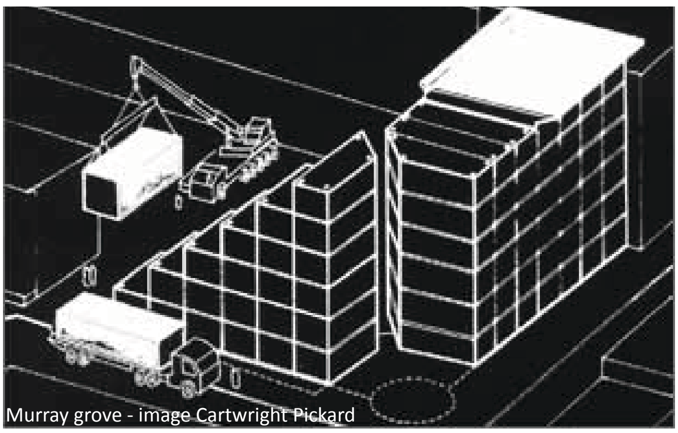

Hilton Palacio del rio, San Antonio


Murray grove

Few truly new concepts are emerging today that have not been tested in the past. Tall buildings have been built from of modules and panels since the middle of the 20th century.

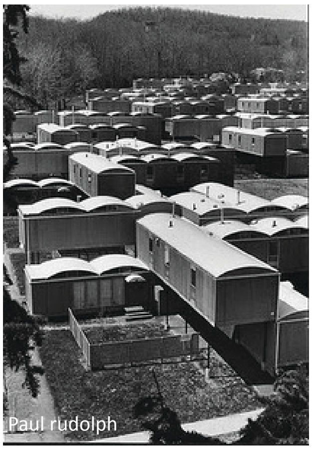
Many of the practices today are merely incrementally improving on practices of the past or at worst repeating the same mistakes. This is not to say that there are no new improvements, there are, but we need to be temper our enthusiasm with a critical eye on the past and make sure the mistakes have been learned.


Murray grove - image Cartwright Pickard


Murray grove - image Cartwright Pickard

playing with space and modules

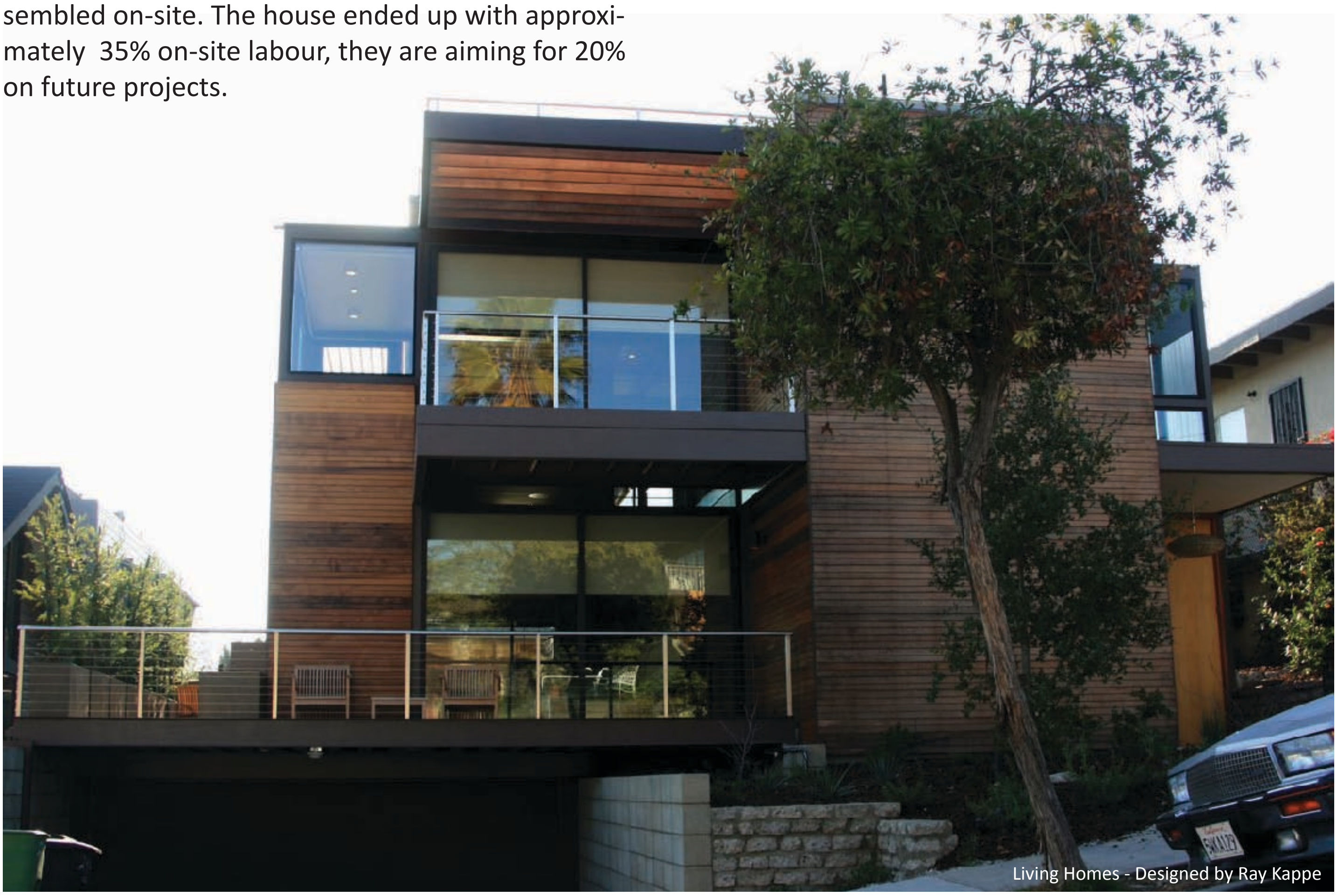
This project in Santa Monica, California designed by Frank Kappe for Living Homes was by far the most aesthetically spectacular of any house or building visited during the tour and so deserves special mention. Although I will describe only its physical aspects here, it should also be noted that architects also demonstrated excellent sustainability initiatives.



Paul rudolph

The project is modular prefab construction with modules stacked perpendicular to each other creating double height spaces, the building was detailed in such a way as to make the spaces float into one another through the use of high level glazing, opening up the building in very interesting ways. Despite being the first house that living homes had completed, this house completely disperses the notion that a prefabricated house should anything less than the best of what is possible with site built construction.

Despite statements that say the house was installed in 8 hours, there was however a substantial amount of on-site work, before and after the 8 hour installation. The slab, basement and garage were all built on site, windows, internal cladding and the kitchen were also installed after the modules had been assembled on-site. The house ended up with approximately 35% on-site labour, they are aiming for 20% on future projects.



Living Homes - Designed by Ray Kappe

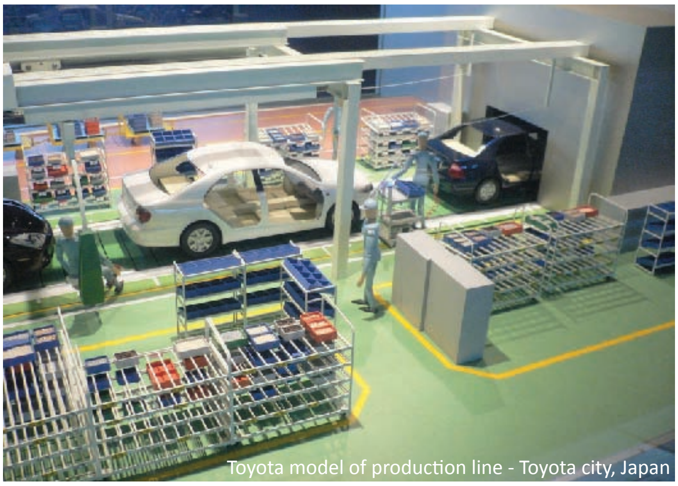
Living Homes - Designed by Ray

so what does it all mean?

"It is important to draw the product just once and continue to extract the data over and over......... if you do a comprehensive 3D model you have a much better chance of extracting whatever you need at any time that you need it." Australian Ship building engineer

understanding the differences

In order to develop a deeper understanding of the current paradigm of the prefabrication sector, especially the opportunities and constraints, it was necessary to study its practice outside the construction industry as well as within it. The best way to critically understand the practices of individual companies (which were generally leaders in their field) was to visit them and to observe fabrication and assembly of their products first hand, in order to cut through the hype and spin used to promote their products.


Toyota model of production line - Toyota city, Japan

It was then also necessary to identify the similarities and differences between the construction industry and the parallel industries studied (automotive, shipbuilding and aerospace), in order to understand which alternative practices could be appropriate to adopt from other industries and those which would not.

The main difference between the construction industry and especially the prefabrication sector and the parallel industries is company size, the parallel industries are highly consolidated with few companies dominating, whereas within the construction industry smaller companies predominate. This has big implications on R&D budgets and the ability to adopt long term strategies. Companies within the construction industry are in many cases competing on cost, within a bench mark of competency (design, quality, performance, durability etc).

Although the expenditure of the construction industries globally out-stips those of the parallel industries, there is little comparison between cost per kg (in the aerospace industry) or engineering hours (automotive or shipbuilding) to the construction industry. The dilemma is that, so much money is spent, producing products that are in many cases largely similar, yet refinement of practices through process engineering and R&D is limited. Largely because profit margins are low and research budgets are split through a multitude of companies rather than within a few. Collaborative research with other companies, through partnership with universities or government agencies seems to be the only way around this issue.

lessons learned?

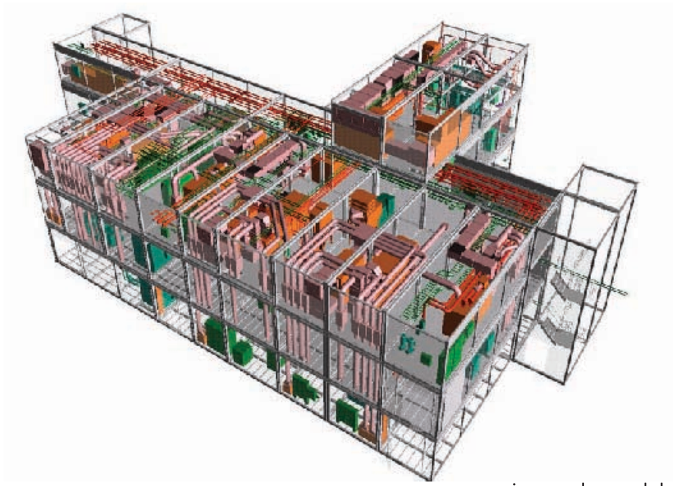


image pharmadule

The question of prefabrication is very much a question of 'have the lessons of the past been learned', there is no point adopting new practices from other industries unless we are aware of the current practices within the construction prefabrication sector. Interestingly many of the practices of the parallel industries are already being implemented, in most cases by only one or two companies in isolation within a national context.

Prefab is popular again, but can we say with any conviction that we know why it failed in the 60's and 70's? Can we point to the really successful examples without being influenced by what the architectural critics said? What is our method of judging prefabricated buildings in the future?

The research presented here has attempted to dispel some of the myths about prefabrication, to cast a clearer light on the fundamental aspects that are so important to its success and to indicate where it may all be heading in the near future in the ever 'brave new world'.

One of the major issues has been the looseness of the use of the term prefabrication, with alternative terms such as "off site fabrication" now being used as an alternative. If we are building a house in a factory, using exactly the same methods used on site, can this be called prefab? If a project is almost entirely built on-site using pre-cut materials and the architect calls it a prefab house, is that prefab.

If we are to learn one lesson from the past, it should be to be clear about what is and isn't a prefab building, lest the name becomes sullied again by poor practices and marketing spin.

"The impact of the adoption of innovative technologies in those industries (shipbuilding, automotive and aerospace) has been profound....today various appliances, cars, airplanes and ships are entirely designed, developed, analysed and tested in a digital environment."
(Kolarevic, 2003)

the virtual prototype

The most interesting revelation emerging from this research is that architects are not, by any means, the leaders in this digital revolution. We like to think we are, but the really hard work has already been done by companies in the automotive and aerospace industries.

As stated earlier every aspect of the product can now be modelled, the real benefit comes from taking full advantage of the 3D model throughout the business, so that the model can pay for itself through the added value it provides. I call this 'leveraging the model'.

Very few architects or engineers that I interviewed in Australia had been able to truly leverage the model in their practices. A simple example; if you are using Revit or Archicad is have I used the bill of materials functions? I can say personally I have used both programs for a number of years each and rarely accessed this functionality.

Why would that be? The question here is not in the example of whether or not we use a particular function, but rather why not. The lack of motivation here is the key to understanding the issue. Architects and engineers will usually not get paid extra for providing this information and they may expose themselves to risk.

Part of realising the potential of the 3D model is first identifying the potential, second educating others of the value of what can be done and the third and most important aspect, selling that value to make it worth doing.

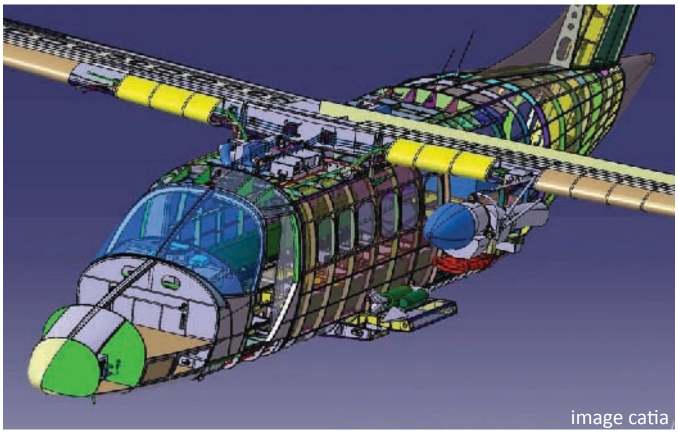


image catia

a systematic approach

Creating a 3D model that has value is not necessarily a given. From my own experience and that imparted by those in other industries, the expression 'garbage in, garbage out' is alive and well in the world of virtual prototyping. As with any other important action, one needs a systematic approach.

As with 2D model if you do not follow conventions, setup within your company or industry, others will find it difficult to work with that model and to use it effectively. When scaling up to a 3D model, that holds all of the information that could be held in a 300 page 2D contract document set (and in many cases potentially much more), the odds are stacked against you if a systematic approach is not used.

Take for example a simple example of a simple wall assembly, perhaps there are three different wall types in a project. If when modelling, each separate wall is created individually, without a centralised definition referring to the 3 wall types. If one needs to change the one of the wall types, one would need to find each instance and either update them separately or force a definition onto it.

This is the simplest example, models of complex buildings can have hundreds of thousands of objects that are tied in with other objects through complex dependencies, without a systematic approach updating and revising these models would be in orders of magnitude more complex and time consuming.

Imagine trying to take the same unsystematic approach when dealing with a project such as the Watercube by PTW and Arup. Could you conceive changing or analysing each structural element individually?. The potential of systems on large projects is enormous, Steve Downing from Arup stated that through the use of scripting within the Arup CAD model; the parametric model could be analysed and changes made through the entire structural frame. This process instead of taking months, could be made in less than a day.

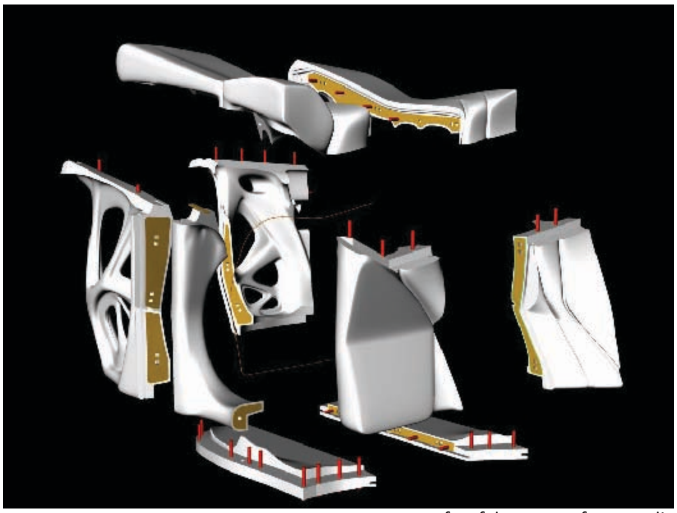

watercube unattributed image

the system

Quite different from the systematic approach is the system in prefab. One of the interesting aspects that has arisen through researching prefab is the question 'is it a product or a the product of a system'. A number of architects and companies visited sell a product, which can be modified as required to suit the clients needs. Each of these changes essentially becomes a variation from the standard and incurs additional costs.

This is equivalent to the Ford expression "Any customer can have a car painted any colour that he wants so long as it is black" meaning there is no or very little choice. This comes from the mass production principle, that efficiency comes from repetition.

This principle was transformed from the 1950's within the automotive industry with the gradual phasing in of mass-customisation. This method of producing a standard product which can be tweaked i.e. would you like bluetooth and alloys? has been adopted around the world by various companies building prefabricated houses. At Misawa in Japan I was told there are approximately 100,000 possible variations to their standard product.



freefab system faan studio

Other companies are going even further, concentrating instead on the system rather than product. There is a long history of development of housing systems, such as that developed by Gropius and Waschman after world war II. The System approach is however not the dominant method used by the prefab companies or architects today. The automotive industry uses this approach integrating standard subassemblies across their whole vehicle range, although this is still applied to standard products.

Many architects use 'standard details' which they will refine and re-use from project to project. Construction fabricators, such as pre-cast concrete companies and steel fabricators, also apply this approach to post rationalising buildings to generate their products.

With the increased use of 3D CAD packages, their is now far greater ability to apply standard details and methodologies to highly individual projects, such as the 'exhibition assembly' freefab system developed and designed by Faan Studio.

design to fabrication

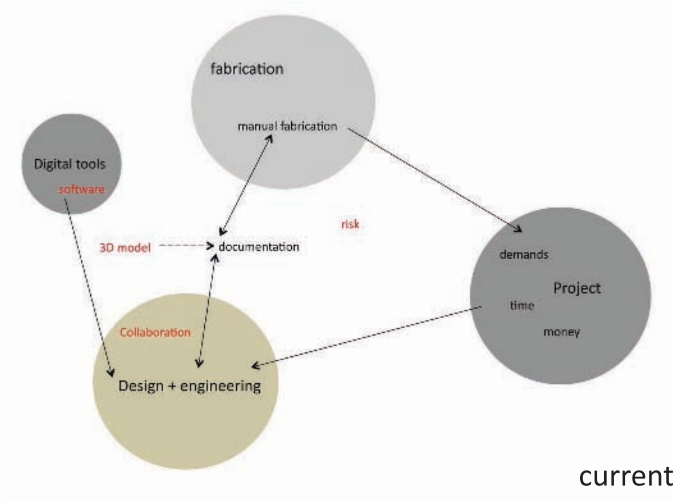
As stated above architects are not leading the field in digital design to fabrication, although the most striking projects often emerge from this field.

As observed from the interviews in Australia and abroad, there is a growing trend toward fabricating directly from 3D data. Within architecture in Australia this is still an exception rather than the rule. However interestingly there is a much greater uptake of this approach within the construction fabrication sector.

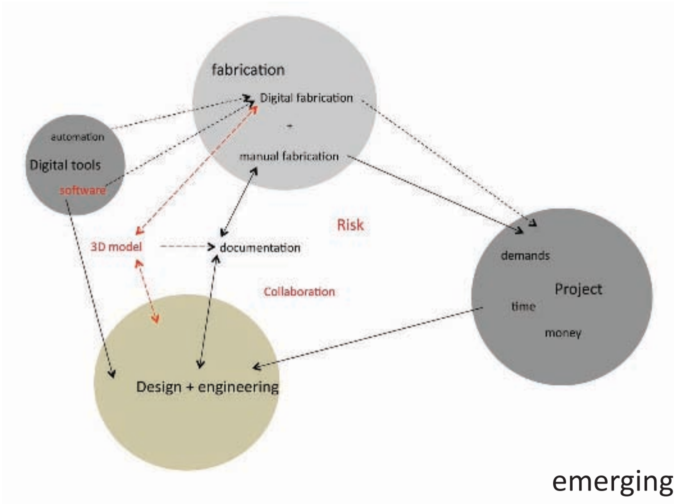
Metal fabricators lead the way in this sector, using CAD packages such as Tekla and Xsteel to model entire structural assemblies in 3D which is then automatically broken down for digital automated fabrication using machines such as the 'beam line'. Instead of working from 2D drawings many of these companies send the data directly to the machine which can cut, punch, drill and weld materials with almost no human intervention.

Where 3D models have largely been used for presentation and design purposes by architects, the model is now being increasingly used to overlay into the engineer or fabricators model for checking purposes. The barrier at present for using the architects model directly for fabrication is largely due to risk. In each instance of handover of data from one consultant to another and then to the fabricator, the re-drawing process is used as the checking mechanism: no-one is prepared to warrant their model for accuracy due to aversion to risk.

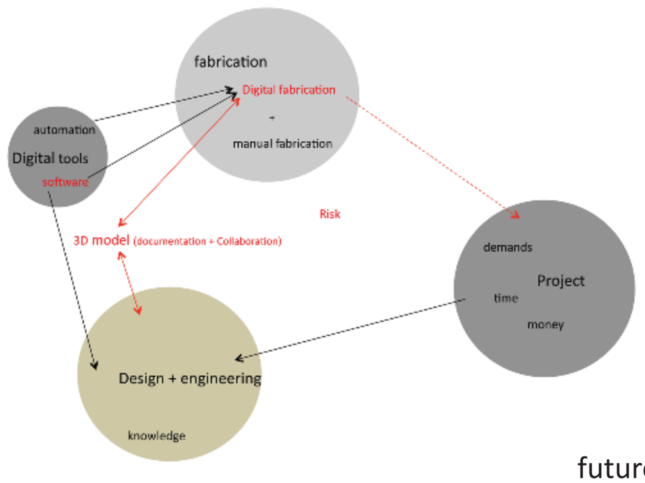
This comes back to the point made earlier regarding leveraging the 3D model. If the architect or the engineer is not paid to model the building to the level of accuracy required to build from there is little incentive to do so. This results in a large amount of duplication, when the client can be convinced (as is increasingly slowly, particularly on large fast track projects) that it is worth paying for one very well managed model that is produced collaboratively. There can be substantial gains in time, accuracy and reductions in rework caused by errors in coordination.



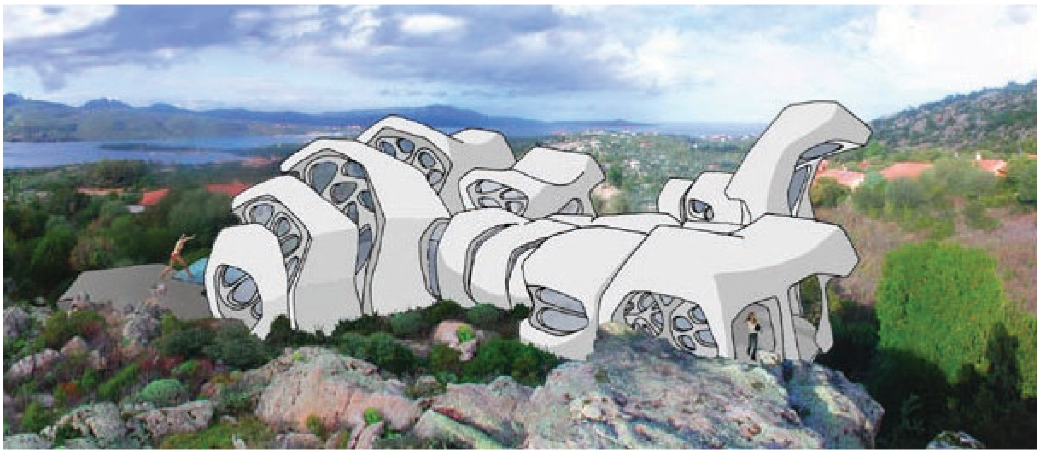
current

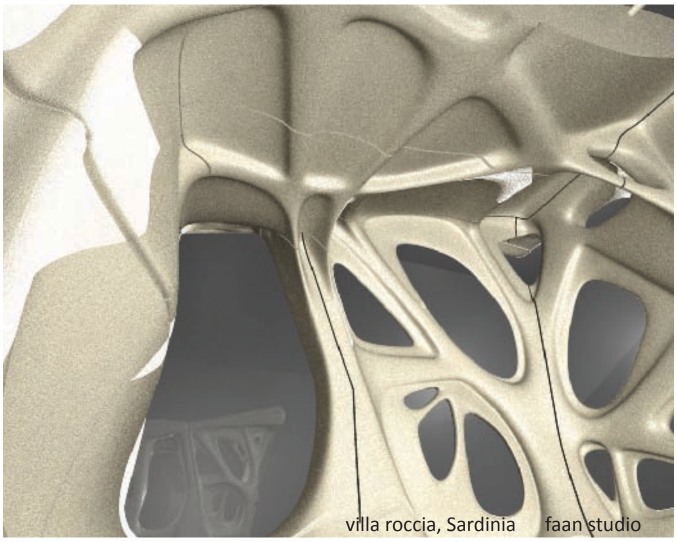


emerging



future





villa roccia, Sardinia faan studio

what's next?

One of the principal reasons for investigating prefabrication to understand the current limitations and best practices worldwide. Although prefab is often hailed as the answer to the problems of construction it also has its limitations. As mentioned above there are very significant new techniques and technologies which are emerging that I believe will be the 'silver bullet' in unlocking the potential of prefabrication.

The main two areas are the development of the 3D prototype, which can be used to create the primary source of data for all aspects of a project, from design, engineering and analysis, client presentation, costing through to direct fabrication using digital automated fabrication techniques.

These digital automated fabrication techniques, which include beam line, CNC milling and laser cutting have proven to considerably increase efficiency, reduce human labour errors and speed up production. Emerging fabrication techniques based on 3D printing (rapid prototyping) techniques, such as contour crafting, freeform construction and particularly D_Shape are proving to be a viable new technique for additively fabricating buildings using materials equivalent to concrete.

These techniques will add a substantial freedom to the shape and complexity possible using automated fabrication techniques and when combined with best practice prefabrication techniques could offer a truly viable alternative to current construction practices.

acknowledgments

New South Wales Board of Architects, Australia	trustees Byera Hadley travelling Scholarship
University of Technology, Sydney Australia	trustees Jack Greenland travelling scholarship
Australian Research Council	funding the delivering digital architecture project
Faan studio	providing funding above scholarship allowances
Arup Sydney - particularly Richard Hough	for support and assistance
SIAL RMIT - Mark Burry	providing PhD scholarship funding
Company participants as listed on pages 10 & 11	interviews and site visits
Pui-yu Lee	for support and encouragement

biography

James Gardiner

James is a registered architect, who heads Faan studio (est. 2005) with a broad range of ongoing projects and experiments, from balloon inspired lighting, prefabricated buildings and the Villa Roccia project for the worlds first 3D printed house. The practice specialises in employing prefabrication, emerging digital design and automated fabrication techniques to realise highly responsive buildings.

James Gardiner is a 1st class honours UTS architecture graduate with a Diploma of Arts in interior design for which he was awarded a commendation of Excellence.

James Gardiner is currently completing a PhD at SIAL, RMIT, teaches at a number of Australian Universities and gives regular public lectures including an interview on By Design on ABC radio national, His work is also regularly featured in international publications.

He was awarded the 'Jack Greenland travelling scholarship' and the Byera Hadley travelling scholarship and will soon exhibit his latest project in the open agenda exhibition at Customs house between October 2010 and January 2011.