CONSTRUCTION SYSTEMS

COMPARATIVE ANALYSES

AN EBOOK BY DR. EYTHAN CHETRIT

CONSTRUCTION SYSTEMS COMPARATIVE ANALYSES

COMPERING THE ALTERNATIVES CONSTRUCTION SYSTEMS, IN ORDER TO POINT THE PREFERABLE ONE, REQUIRE DEEP UNDERSTANDING OF EACH OF THE MAIN CONSTRUCTION SYSTEMS; THE CONVENTIONAL, THE HYBRID AND THE 3D PREFABRICATED MODULAR SYSTEM. WEIGHTING THE PROS AND CONS OF EACH SYSTEM TO BE USED AS A STATISTICAL MEASUREMENT TOOL, IN ORDER TO MEASURE THE RELATIVE SIGNIFICANCE OF EACH PARAMETER, IS FEASIBLE, ONLY AFTER CLOSE RELATIONSHIP AND EXPERIENCE AT EACH OF THE COMPERED SYSTEMS. THE NEXT PART WOULD BE FOCUSED ON PRESENTING THE OPTIONAL SYSTEMS ON THEIR TYPICAL CHARACTERISTICS.

DR. EYTHAN CHETRIT

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CONVENTINUAL CONSTRUCTION

DEFINITION AND CHARACTERISTIC

According to Webster's American Heritage Dictionary conventional means conservative. Conventional system or also known as traditional system is the first construction system used in construction industry. In this system, all construction work done by using traditional method which is in-situ method.

All materials used are cast in-situ and no pre-cast or pre-fabricated panels are used.

In-situ cast construction is a quite complex process with many inputs and flows; e.g. material, components, and equipment have to be transported to and on the site and tasks have to be performed in certain sequences.

Conventional or also known as traditional system has its own characteristics which are the basic construction method in construction industry in the world. The characteristic of conventional method includes:

Ⅰ. Use cast in-situ system all building components are being built and cast on site with high usage of construction materials and load of site works.

Ⅱ. Labor-intensive practices

Ⅲ. Conventional system is known with the 3-D syndrome which is Dirty, Difficult and Dangerous. All site work that being done which involved many types of construction materials and machineries and high number of workers will make the construction site messy and crowded. This will lead to Dirty and Dangerous environment. Advantages and Disadvantages of Conventional System are: Conventional system gives both advantages and disadvantages in construction industry .The advantages of using conventional system in construction include:

Ⅰ. Easy transportation (the wet concrete)

Ⅱ. It is flexible when it comes to geometric shapes

Ⅲ. It is relatively easy to do late changes to the structure

Ⅳ. The structure becomes monolithic

While the disadvantages of using conventional system are:

Ⅰ. It is produced in an 'unprotected' environment

Ⅱ. Additional time is required for the drying out process

Ⅲ. It requires more temporary works (like propping)

Ⅳ. Many projects are built by different subcontractors without past shared experience.

THE HYBRID

CONSTRUCTION SYSTEM

Hybrid construction (HC) is a method of construction which integrates precast concrete and cast in-situ concrete to make best advantage of their different inherent qualities. The accuracy, speed and high-quality finish of precast components can be combined with the economy and flexibility of cast in-situ concrete.

Hybrid construction produces simple, buildable and competitive structures. The client is given better value and the contractor benefits from increased off-site component manufacture, safe and faster construction and consistent performance..

Benefits of using Hybrid Construction system are:

Although the structural frame of a building represents only 10-15 per cent of the total construction cost, the choice of material for the frame has dramatic consequences for subsequent processes. HC is able to offer greater speed, quality and overall economy on a project.

As precast and cast in-situ concrete are used where most appropriate, construction becomes relatively simple and logical.

The use of HC encourages design and construction decisions to be resolved at design stage.

The use of HC also means that a percentage of the frame is manufactured by a skilled workforce in a weatherproof factory, resulting in faster construction and better quality.

A high proportion of the work for a hybrid construction project is carried out in the precast factory. On site, the use of HC helps ensure that each safety plan is drafted on the individual project's merits. HC can reduce the potential for accidents by providing successive work platforms on a generally less cluttered site.

HC offers the opportunity to exploit the inherent thermal mass of concrete by exposing the soffit of precast concrete floor slabs. This fabric energy storage (FES) of the structure can help to control temperatures in the context of a naturally ventilated low-energy building. The finish and shape of exposed concrete units can also be used to help with the even distribution of lighting and to reduce noise levels.

MODULAR PREFRABRICATED

CONSTRUCTION SYSTEM

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First, let's describe what the modular prefabricated construction is. This is a process that constructs a building off site, under controlled plant conditions, using the same materials and designed to the same codes and standards as conventionally built facilities.

Buildings are produced in 3D (dimensional) "modules" that when put together on site, reflect the identical design intent and specifications of the most sophisticated traditionally built facility - almost, without compromise.

Structurally, each module is engineered to independently withstand the rigors of transportation and craning Structurally, each module is engineered to independently withstand the rigors of transportation and craning onto foundations. Once together and sealed, the modules become one integrated wall, floor and roof assembly.

Manufacturing plants have strict QA/QC programs with independent inspection and testing protocols that promote superior quality of construction every step of the way. Modular construction remove at least 90% of the building construction activity from the site location significantly reduces site disruption, vehicular traffic and improves overall safety and security. Modular construction techniques are analogous to assembly line car manufacturing. Typically, four stages make up a modular construction project. First, **Design development** by the developer and plan approval by the regulating authorities; second, **Production & assembly** of module components in a factory; third, **Transportation** of modules to the project site; and fourth, **Erection of modular units** to form the building.

Modular contractors manufacture buildings at off-site locations. They may also operate as general contractors on projects, coordinating the delivery, installation, site work and finish of the building or the modular contractor will be responsible for construction, delivery and installation of only the modules and an overall general contractor will be responsible for the entire project. Construction primarily occurs indoors away from harsh weather conditions preventing damage to building materials and allowing builders to work in comfortable conditions.

Unique to modular construction; while modules are being assembled in a factory, site work is occurring at the same time or in some cases prior to construction.
This allows for much earlier
building occupancy and contributes to a much shorter overall construction period, reducing labor, financing and supervision costs. Compared to traditional onsite construction, more coordination of design and engineering of the modules is required before construction of the modules can be completed; however, this requirement is also changing as the modular manufacturing industry is maturing and evolving to accommodate fast track construction techniques and the variety of modern construction delivery methods. Everything from traditional general contracting to design-build-operate- transfer has been utilized in the modular industry. In fact many schools, hospitals and prisons are built with modular technology. However, the off- site modular construction requires more coordination during the design/ construction process and forces developers to make decisions earlier.

For example in the module steel frame in a high rise project, it's possible to make decisions on foundations and some structural elements, but precise size and depths of the modules will be needed to dictate necessary structural supports. Similarly the exterior finishes, material specs and elevations need to be decided before modules can be fabricated. Even if the building exteriors will be built onsite the module volumes will be impacted by the elevations. Thus a traditional design-bid-build model is possible, but more challenging. **It would be more appropriate to incorporate modular constrains into the projects at an earlier date to ensure the project time and cost savings are realized.** Through
techniques that have been around for decades, prefabrication/ modularization is seeing a renaissance as technologies, such as BIM (Building Information Modeling), have enabled better assembly and precise design of modular components.

Changes in design such as the emergence of environmentally sensitive design have also increased the opportunity for permanent modular buildings. Additionally in light of the long recession, more contractors are looking for ways to build for less and thus the growth of prefabrication and modular construction. Although the trend for greater use of off- site construction has been growing slowly for years, the recession and new technologies could increase their use. Changes in design such as the emergence of environmentally sensitive design have also increased the opportunity for permanent modular buildings. Additionally in light of the long recession, more contractors are looking for ways to build for less and thus the growth of prefabrication and modular construction. Although the trend for greater use of off- site construction has been growing slowly for years, the recession and new technologies could increase their use.

THE FACTORY

After the client architect design is finalized, the preliminary plans are sent to a factory where the majority of the building parts are designed. Contractors use prefabricated elements for as many building components as possible. Everything from walls and mechanical systems to painting and carpet can be completed on the assembly line. Steel studs are usually cut to a standard length and shipped to a jobsite where they're cut to the needed size. Instead of wasting metal, the studs are created on the factory line to the exact length required. Modular building factories maintain a high level of quality control with inspections at each station, eliminating "on-the-fly" decisions or unexpected complications that can occur in the field.

Factory construction of modular components varies greatly from static factory floors to conveyer belts to even robotic construction of modules. Toyota Motor Corporation known for its automobiles successfully transferred robotic assembly line manufacturing technology from the automobile sector to the construction industry. (Bock, 2007)

TRANSPORTATION

Normatively, it is quite challenging to ship the modules extremely far due to road size/load restrictions. Most modular deliveries are made over the highway\roads net and governed by a national and international regulation.
It is not rare for a transporter to have to deal with several different territories agencies to get reach its destination site. Several issues remain that one needs to be aware of such as: potential time delays due to delayed transportation permits for oversized loads, potential delays due to customs issues along the n borders and most importantly, dimensional restrictions on modules being transported. Rules regarding dimensional limitations vary from place to place, so a modular manufacturer would want to understand the route the modules must travel. A general rule of thumb to understand the most basic size limitations is that the maximum width allowed anywhere is around 16 feet, the maximum height is 13'6" including trailer and the maximum length feasible for transport is around 45 feet long. Within these limitations there are varying levels of specific regulations and added expense mostly relating to width. Modules less than 4.0 m wide are mostly allowed to travel with no restrictions. When the size increases to between 4.1- 4.35 m wide there is an accompanying increase in the restrictions and often a requirement for police escort. Once a module reaches the 4.35-4.70 m width it is almost universally declared a special wide-load that requires police escorts and can often be required to travel overnight as to not impede local traffic.

Additionally, the ceiling height must also be considered, since most highway height restrictions are 4.2 m and with a trailer height that leaves less than 3.0 m for the module. In this cases a flatbed module transport allows for taller modules to be transported, up to 3.40 m or to find a road with no bridges or other height limiting obstacles. However the additional cost of the transportation must be carefully balanced with the additional square area gained per trip and crane lift cost in a wider load. If there is a sufficient economy of scale the larger volume modules will actually reduce the total transportation cost even though the per trip cost is higher with the larger volume modules.

Shipping costs are billed separately on a per mile basis and these costs must be weighed against the savings in modular technology. Modular builders have begun utilizing both sea delivery to remote locations. Despite the obvious difficulty inherent in such complicated transport it may often be a more cost effective alternative than utilizing a site built method in expensive labor markets or locations will poorly trained construction trades.

ON SITE ACTIVITIES

Once the modules are ready, they are shipped to the site and fastened together. Module installation includes line connections for mechanical and electrical systems, exterior finishes and interior finishes, where are needed. The final construction stage includes completing exterior systems such as cladding and roofing components and internal spaces like lobbies, stairwells, and elevator shafts.

The crane is the most expensive part of the installation process with expected costs of $1500-$2500 per day, not counting police details or road closures. Therefore, careful planning needs to be undertaken so the crane is never idle. Since cranes are classified by tonnage, the larger the crane the more operational flexibility one has, especially on challenging small sites where one might be forced to place the crane in a less than ideal position for efficiency which can negatively impact the number of sets per day. When selecting the type of crane it is also important to consider operational maneuverability of the crane and airspace of surrounding uses.

THE MODULAR CONSTRUCTION INDUSTRY

US commercial construction market was $201 billion in 2010 and only $2 billion accounted for modular construction or 1%, but the industry has been growing at 20-25% annually over the past few years. (Modular Building Institute, 2011). International market for modular construction is larger than the US, but even well accepted markets only have 2-3% market share. The UK is an example of a well- accepted market that had approximately a 2% share since 2005. (AMA Research, 2007) However, wide adopt of this technology with its potential advantages in schedule and cost could be a partial answer to building housing for over 2 billion people in Scandinavia, England and central Europe (due to natural growth needs and Refugees) not to mention China & India, with their huge residential needs, Over the next 20-30 years.
Customers served by modular construction industry include federal, provincial, school boards, corporations, non-profit organizations, retail establishments, healthcare providers. Other uses include, military installations, hospitals, dormitories, hotels, and remote telecommunications stations. These uses reflect the highly repeatable nature of modular construction that lends itself well to repeatable assembly line construction.13

Larger facilities employ between 140-150 workers during their peak production, while smaller plants employ between 60-70. The typical modular manufacturer produced about 158,000 square feet in 2010, producing an average of 232 “modules.” This production is about 7% less than reported in 2009, which reflects the challenging economic climate. Each module is roughly 30-40 square meter , commonly 3.6 m wide by 9-12m m, in length. Transportation regulations are commonly the limiting factor in module size. Depending on the level of customization required by the owner and architect, most modules leave the factory 80%-90% complete, with wiring, plumbing, structural, and mechanical systems inspected and approved before arriving at the site. (Modular Building Institute, 2011)

Many including the National Research Council of the US National Academies believe greater use of the modular construction techniques could greatly improve both the efficiency and competitiveness of the construction industry. This need is further exacerbated by the lack of skilled onsite construction workers (McGraw Hill Construction, 2011)

DESIGN CONSIDERATIONS AT THE MODULAR CONSTRUCTION

The decision to use modular construction must be made from the onset of the design; however there are a many examples of conventional site built designed projects being later converted to modular construction. The advantages of modular also wane considerably if your intended building doesn't have repeating spaces. The prefabrication of entire rooms lies at the heart of modular construction, so a building with very large open spaces is not the best candidate. For example, an office building shell designed with unfinished interiors and intended for multiple tenants who would finish out their own individual space would not be a good option; however a build-to-suit office building could be viable. In addition finish customization, as required in most residential projects, can be possible and will yield very similar costs as traditional site built customization.

Challenges that arise from customization might deal with limited opportunity to change structural of the modules and unit plans. In a site build project it may be possible to make such changes in the field and modify MEP connections to accommodate a buyer's needs, but such changes are more challenging in a factory. If such market demands are necessary, it may be more appropriate to provide a shell module with exterior finishes and allow onsite construction to complete the finishes. This example highlight the fact that modular construction is not a binary condition in that many projects use both onsite and offsite construction on projects. The question is more about how much offsite construction is appropriate for a particular project.

Modular construction is not necessarily a barrier to creativity. The architects for the Victoria Hall Wolver Hampton project readily admit that the challenges of converting a traditional building to a modular building arises from planning issues, which require structural changes to the design. However, none of those changes critically impacted the overall aesthetic of the buildings. (Modular Building Institute, 2010) Modular rooms or pairs of rooms or room/corridor modules can be used to create a variety of unit layouts. These layouts can be put together to make most desired unit mixes and ultimately any combination of exterior elevations.

The nature of high-rise buildings is such that the modules are clustered around a core or stabilizing system. The particular features of the chosen modular system have to be well understood by the design team at an early stage so that the detailed design conforms to the limits of the particular system, particularly the structural integrity of the design.

The design of high-rise modular buildings is strongly influenced by structural, fire and services requirements. From a building layout viewpoint, two generic floor plans may be considered for the spatial relationship of the modules around a stabilizing concrete core:

- A generally square configuration where the corridor surrounds the central core on all sides and units are access off the corridor or a traditionally single loaded, central corridor.
- A generally rectilinear configuration where the corridor extends in opposite directions from the core and units are access on either side of the corridor or a traditionally double loaded corridor.

The addition of external balconies, cantilevers or other architectural features can be used to create a layer of architectural interest, while still maintaining structural integrity. Balconies can be attached at the corner posts of the modules or the loads can be directly transferred to the ground. Integrated balconies within the modules may be provided by bringing the balcony end wall within the configuration of the module. However, curvilinear forms, multiple exterior materials, and new window-wall systems add additional layers of complexity. It is important to understand how cost and time advantages to modular construction might erode with more complicated architecture or completely eliminate the option to utilize modular technology.

BENEFITS OF MODULAR SYSTEM

SUSTAINABILITY CONSIDERATIONS

Modular building offers significant opportunities for environmental improvement, economic opportunity, LEED certification and market penetration in this area. Material handling, optimal construction conditions and environmental control during construction, all can contribute to attaining LEED credits. It is quite challenging to identify specific LEED criteria or points that favor modular construction, since each project will be different and the extent of modular construction and other decisions will change the certification level. However, what is clear is that the market desire for LEED approved and sustainable buildings will only benefit the further adoption of modular construction.

Modular construction provides several opportunities to improve the sustainability of the project during the construction process and maintain superior operating performance within the completed building.

• Construction waste is substantially reduced from 15% to 20% in a traditional building site to less than 5% in a factory environment. It is estimated that modular construction can achieve the highest level of waste reduction relative to both traditional construction and any other modern construction techniques, such as panelized or pre-fabricated pods. (AMA Research, 2007) The majority of waste in traditional construction projects is generated from the concreting process and the related wet trades, which constitutes over 80% of construction waste. Concrete waste is generated mainly from both the direct work, steel from the cutting of reinforcement bars, surplus or spilled concrete, etc. Rework, the need to replace, remove or extend work previously considered completed also results in construction waste.

• With steel modular units, the wall and roof frames are typically constructed using the stud and track method of connection, whereby sections are joined together using self-drill/tap fasteners and bolts. Consequently, at the end of life, these should be easy to disassemble. The floor and ceiling joists have service conduits in the form of holes that allow for the running of cables and pipe work, which are easily removed. With the facade and roof covering elements, the facade panels and insulation boards are all connected using a system of brackets, rails and self-drill/tap fasteners. As no mortar, is used, disassembly of these components should be straightforward. The steel components are all **highly recyclable** and are metal facade materials such as aluminum, and zinc and also brick slips. (AMA Research, 2007)

Benefits of a modular building are largely due to additional materials used in the construction. Several manufacturers estimate that anywhere from 10-25% more structural materials are used in a modular home. So, while fewer natural resources are "wasted" during the modular construction process, more are being consumed to create the same square footage of livable area. The net usage of total building materials in a modular project is only slightly less than that utilized by a conventional onsite project, but more materials are used to the benefit of the building than wasted and result in landfill.

- The number of **visits to site by delivery vehicles** is reduced by up to 70%. The bulk of the transport activity is moved to the factory where each delivery provides more material in bulk than is usually delivered to a construction site.
- **Noise and disruption** are reduced on site, further diminished by the 30% to 50% reduction in the construction period, which means that neighboring buildings are not affected as much during a traditional building process.
- **The air-tightness and the thermal performance** of the building fabric can be much higher than is usually achieved on site due to the tighter tolerances of joints that can be achieved in a factory environment which reduces the need for higher utility expenditure.
- The efficient use of lightweight materials and the reduced waste means that **embodied energy** of the construction materials is also reduced.
- **Safety on site** and in the factory is greatly improved and it is estimated that reportable accidents are reduced by over 80% relative to site of intensive construction. The modules can be installed with pre-attached protective barriers or in some cases, a protective 'cage' is provided as part of the lifting system. (Lawson R. M., 2011)
- **Theft is** also greatly **reduced** as most finishes and expensive exterior elements are set in the factory and tied to the module before its arrival to the site.

Modular manufacturers and early adopters of this technology do not consider there to be any limitations in this technology due to the **building codes**. All countries require that the modular manufacturers have an approved quality-assurance program and that it be monitored by an accredited, third- party agency. These third-party agencies make inspections on both the modular builder's plant and the building under construction. Where a third-party agency is not a local requirement, building department officials and/or certifying engineers typically assume the same inspection role. (Hardiman, Dispelling the Myths of Modular Construction, 2008) .**Any building code issues** can be effectively addressed in the design process and the building code itself prescribes design guidelines and tolerances, not construction techniques. Additionally, the modular process presents both opportunities and challenging for the developer during the entitlement process. The construction advantages specifically the reduced environmental impact, traffic, noise and construction time will likely engender substantial support amongst the community and adjoining neighbors, all else equal. Additionally, the reduced construction timeline will yield quicker revenue streams. There is also speculation that more affordable construction techniques could yield lower rents and sale prices as derivative advantage to the community. (Kastenbaum, 2011) .

SCHEDULE CONSIDERATIONS

One of the greatest benefits is the ability to dramatically reduce the time needed for construction. Factory efficiencies allow building components to be completed quickly and without weather delays. The factory has all of the key player's onsite to handle multiple building requirements and multiple subcontractors are not always required. This makes modular construction suitable for owners who need buildings quickly, properties with hard dates for occupancy, and areas where seasonal weather restricts or even halts construction. (Morton, 2011) Additionally, modular construction allows horizontal construction on the factory floor rather than vertical construction in high rise buildings onsite, thus saving additional time for all trades to move throughout the building.

Although modular construction that integrates MEP (mechanical, electrical and plumbing) into the module allows the manufacturer to employ multiple trades and provide near finished modules to the site, both the manufacturer and onsite contractor must coordinate schedules and module installation. Delays and lack of schedule coordinate either onsite or in the factory could mitigate much of the time and cost savings. Additionally the access to cranes and the timely arrival of modules to efficiently utilize the crane is important in maintaining the schedule. An idle crane or too many modules onsite could change the financial dynamics of the project. Typically the modular manufacturer is responsible for delivery and assembly of the modules. MEP connections can be the responsibility of the general contractor or the modular manufacturer depending the project scope. It is important to know the liability of the manufacturer during and after installation of the module. These schedule coordinates are further complicated by the inability of the general contractor to control the manufacturer, but some projects have resolved this conflict by requiring the general contractor to subcontract the manufacturer and thus eliminating any conflicts of interest and keeping complete control at the general contractor level.

FINANCIAL CONSIDERATIONS

Modular construction takes most of the production away from the construction site, and essentially the slow unproductive site activities are replaced by more efficient faster factory processes. However, the infrastructure for factory production requires greater investment in fixed manufacturing facilities, and repeatability of output to achieve economy of scale in production.
An economic model for modular construction must take into account the following factors:
• Production volume (economy of scale)
• Proportion of on-site construction (in relation to the total build cost)

• Transport and installation costs
• Benefits in speed of installation versus limited change order opportunities
• Savings in site infrastructure and construction management

Materials use and wastage are reduced and productivity is increased, but conversely, the fixed costs of the manufacturing facility can be as high as 20% of the total built cost. Even in a highly modular project, a significant proportion of additional work is done on-site.

Limited data is available on multifamily modular construction, but some guidance can be provided may be taken from a UK government report on modular home construction. This report estimates that the proportion of on-site work is approximately 30% of cost for a fully modular building, and can be broken down into foundations (4%), general services (7%), exterior finishes (13%) and interior finishes (6%). However, in many modular projects, the proportion of on-site work can be as high as 55%, as was the case in the Victoria Hall Wolverhampton case study. Modular construction also saves on commissioning and change order costs that can be as high as 2% in traditional construction. (Lawson R. M., 2011)

The financial benefits of improved construction timing are:
• Reduced interest charges
• Earlier inception of rental income.

The tangible benefits due to reduced interest carry can be 2 to 3% over the shorter building cycle. The UK report estimates that the total financial savings when using modular construction are as high as 5.5%. However, the scalability of single family homes is limited and commensurately so are the savings. (Lawson R. M., 2011) Additionally, all trades and consultants on the project are also likely to be in support of modular construction if the reduce project time also equates to a quicker release of fees upon project completion.

Perhaps more important than any quantifiable difference between modular and traditional construction costs is the value in an accelerated construction schedule relative to market changes. With a quicker delivery time the developer reduces the risk of market changes and can more efficiently meet just in time market demand.

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