Abstract

Modular or prefabricated construction has gradually replacing the traditional on-site construction due to the benefits provided, notably faster time, reduced costs, better work quality, and less environmental impacts. Prefabricated construction guarantees more control over the quality of components and safety of the construction process. However, some other concerns such as design considerations and coordination of factory and on-site activities, may be easily undermined if an appropriate procurement method is not selected. In a precast concrete construction, for instance, precast members require highly skilled workers, more complex techniques, and a more complex design. Because the design professionals need to concentrate on perfecting the modular design, the intensive administrative work may be neglected. To include these managerial task in a modular construction’s equation, this study presents a fundamental understanding of modular and/or pre-fabricated systems and suggests a construction procurement method based on project type to satisfy this short coming and to achieve sustainable modular construction.

Keywords: Modular Construction, Prefabrication, AEC Industry, Environmental Impact, Modularization, Adaptable Construction

1. Introduction

The construction industry is one of the most lucrative fields of work worldwide, and it is becoming more complex as technology improves capabilities and standards become more stringent. There are many factors for an owner to consider when deciding to embark on a construction project. Ultimately, the owner wants the project to increase the long term economic prosperity of his organization. Typically an architect will make all the design decisions as the owner’s agent to provide the optimal end result. The architect has the responsibility to decide what materials and components are best for the specific building. Many of the parts of a building are common among many buildings, while others are unique to a specific project. The typical parts of a structure offer the opportunity to take advantage of off-site fabrication. It saves the owner time and money to have components constructed off-site and later incorporated into the building at the project site. The ultimate cost of some assemblies is lower using off-site construction because less labor is necessary in a factory setting without the obstacles of a construction site. Also, the ultimate length of a project can be reduced because prefabricated components are produced much more quickly and efficiently. A major
disadvantage of modular construction is a lack of quality control over structural integrity and aesthetic performance. These are some of the issues architects consider to determine whether to use off-site fabrication.

2. Literature Review

Over the last twenty-five years, there have been many publications on the issues that modular building present to project delivery. In 1994, civil engineering graduate student Mayra L. de la Torre presented a thesis titled “A Review and Analysis of Modular Construction Practices” to the Graduate and Research Committee at Lehigh University. In this paper, Torre offered advantages and disadvantages of modular construction, a review of modular construction activity at the time, and an industry survey of modular construction [1]. An excellent source for information for prefabricated construction components is a textbook titled Off-site fabrication: Prefabrication, pre-assembly, and modularization, published in 1999. The author of this book is Alistair G. F. Gibb from the Department of Civil and Building Engineering at Loughborough University in the United Kingdom. Gibb’s book describes the principles of off-site construction, numerous applications and case studies, and the implications this method has on the construction industry. The information contained there is useful to understand the basics of modular building [2]. Because much has changed in the construction industry in the new millennium, it is important to include a modernized perspective of modular building in the repertoire of source information. A thesis by architecture graduate student Joseph M. Schoenborn titled “A Case Study Approach to Identifying the Constraints and Barriers to Design Innovation for Modular Construction,” was submitted to the faculty at Virginia Polytechnic Institute and State University in 2012. That paper is meant to provide information to architects based on a research study from five construction companies, which identifies the problems inherent in modular construction [3].

2.1. Applications (Gibb)

Gibb’s book offers many examples of modular building applications, some of which are applicable to prototype office building. In the first chapter, a commercial building model “demonstrates the possible extent of off-site fabrication for a major multi-stored commercial building.” For the substructure, the applications listed include: precast concrete piles or mats for the foundation, precast concrete basement walls, and large pipe lengths for underground services. For the frame, the synopsis includes structural steel with preassembled connections, pre-stressed precast concrete floor units, precast concrete frames, and structural timber. Suspended ceilings, raised access floors, and mobile partitions are mentioned for the building interior. Examples of facility and service modular components include office bathrooms, elevator and lift shafts, preassembled electrical and mechanical distribution systems, and prefabricated electrical or mechanical rooms. This model offers a preliminary perspective of some potential modular components. The third chapter includes many modular applications, including two that apply to buildings similar to the hypothetical office building. The first of these, referred to as a “Modified Roof Erection System,” “involves the assembly of large roof sections at ground level…and then hoisting them into place. These steel frame roof sections also included mechanical, electrical, and fire protection components attached before the sections were raised. This system was tested on a construction project of an industrial building in Kentucky, where half of the roof was constructed using conventional techniques and the other half used the MRES. This experiment concluded the following for MRES compared to in situ construction: improved safety due to a vast decrease in work at height, increased productivity due to less weather delays, a 15% decrease in total labor, and a slight increase in cost. The other example about the Embankment Place office development in London includes several relevant modular applications. The structural steel frame was composed of large beam and column pieces, but further preassembly was limited by the project site. The external wall cladding consisted of metal and glass curtain wall panels which, “incorporated granite stone facings, fully glazed windows, all weather barriers and radiant heating panels.” Other modular components for this building included precast concrete panels, restroom units, and air-handling units.

Chapter 4 offers even more relevant case studies. The first one considers the Scottish Widows corporate headquarters building in Edinburgh, United Kingdom. This project is notable for using a high volume of precast concrete elements, consisting of structural beams and columns, pre-stressed hollow core slabs, and external cladding panels. The design of this building shows the advantages in using precast concrete for many different applications. One supplier can potentially supply all precast concrete elements for a job and one specialty contractor can install them, which simplifies project delivery. The fabrication of the concrete units requires extensive planning by the supplier to prepare the units in a timely manner. This is crucial to the success of this type of project, in order to take advantage of the time savings that precast concrete offers. The contractor must also be well prepared for the means and methods necessary to complete the work quickly. This example project also stresses the ability of a competent supplier to provide concrete units that are structurally and architecturally sound and easy to connect to other building elements. Another example focuses on Crown House Engineering, a mechanical and electrical subcontractor in the United Kingdom specializing in building service modules. One schematic drawing shows a module with electrical conduits and piping for chilled water, sprinklers, and rainwater. Others show modules for air handling units in a network and continuous riser bundles that include electrical piping and air ducts. Service modules are beneficial if there is legitimate duplication of electrical, plumbing, and mechanical components throughout a building. Prefabrication of these components can remove the difficulty that is often
2.2. Implications (Gibb)

Part 5 of Off-site fabrication is titled “Implications” and raises some different points than Torres’ essay. Several suggestions are offered for the procurement strategy. Strategic partnering refers to an owner working repeatedly with reliable suppliers and contractors. Two-stage tendering refers to these suppliers and contractors submitting initial offers early in the project to help the owner and architect make better selections. Nominated suppliers are chosen by the owner and architect to help guide the design plans before a contractor is chosen. All three of these concepts facilitate faster project delivery using off-site fabrication because they improve planning and procurement. The last suggestion is to choose construction management or design-build as a project delivery method due to the technicalities involved with prefabrication. The next section on interface management stresses the importance of considering how building elements interrelate and require coordination between different companies. The design implications mentioned provide some important architectural issues to consider with modular building. The key to module size and dimensional coordination is to find the largest feasible module size in order to simplify construction processes. The structural tolerances provided by prefabricated units have been proven beneficial considering factory manufacturing environment. Prefabrication often requires that performance specifications be used more often over prescriptive specifications. The architect must use a safety factor to account for the uncertainty of modular units. Exterior cladding can disguise the construction and design limitations of prefabricated assemblies. Information technology enhances prefabrication due to virtual reality and three dimensional software, automated and digitally controlled manufacturing and fabrication, and decision support software. Pre-installation trial assemblies can demonstrate how modular assemblies will interrelate with other components. Finally, maintenance and operating procedures of prefabricated units may require special consideration. Despite the many constraints, innovative design opportunities are more practical with modular techniques than with conventional techniques.

2.3. Implications (Torre)

Now that many prefabricated building applications have been identified, the conceptual issues related prefabricated construction must be evaluated. Torre’s essay describes the distinct advantages and disadvantages of modular construction. The cost factor can be an advantage or a disadvantage, depending on the situation and the assemblies involved. Cost advantages related to the factory nature of prefabrication include avoidance of construction site hindrances and cheaper labor rates for factory workers as opposed to site workers. Less on-site work contributes to cost savings from a reduction in labor hours, decreased management costs, and less extensive mobilization and demobilization. A faster project delivery typically provided by modular building systems decreases construction overhead costs and financial liability. Another potential cost advantage is an increase in competition for fabrication and assembly contracts. There are also cost drawbacks to modular construction, which include increases in design engineering, contract administration, and procurement costs. The factory prefabrication environment can improve product quality. Factory workers are more permanent and reliable than site workers, so they can be much more consistent. Modules can be routinely tested more easily in a factory than on the job site. The factory environment is also safer than the construction site environment. Inclement weather risks and the dangers of aerial work are eliminated by shop fabrication. Another major advantage of modular practices is the reduction of overall job length. The efficiency of factory workers contributes to faster production, and factory work can progress simultaneously with site work while reducing clutter on the job site. Tasks in the schedule that are performed in factories are also much more predictable and have less risk of delaying the project. An important point raised by Torre is that an overlap of design and procurement activities is highly desirable in modular construction. This may put traditionally delivered projects at a disadvantage because the contractor cannot be involved in the design phase. Modular projects have a smaller impact on social and environmental factors because the project site causes less disturbance and fewer workers need to be imported. The last advantage explained by Torre is the ability of modular construction methods to deliver a project to a site that is not conducive to conventional construction.

The disadvantages of prefabrication may be given more importance than the advantages because of the desire to avoid problems. The first drawback to modular building offered by Torre is a need for more material. In order to provide the necessary structural performance, modular members may be larger and may require more extensive connections than conventional techniques. Also, the transportation and installation of modular components may require extra material to ensure proper stability and placement. Another problem with prefabrication is an increase in some construction management responsibilities. Planning and scheduling will be more complex due to the extensive amount of fabrication, transportation, and intensive erection procedures. Modules also require more design effort to ensure that structural and architectural integrity will be maintained throughout these processes. Trustworthy procurement of modular components
is much more difficult to achieve because specialty suppliers and subcontractors must be heavily involved early in the project. Inspection can be harder to perform because the modules are built at factories rather than the construction site. Another major constraint of modular construction is the difficulty to coordinate the following activities: planning, design, fabrication, transportation, handling, and installation. Delivery and construction processes place restrictions on modular design because large and heavy components require heavy equipment and complex installation. Intense coordination is necessary to ensure that fabrication, transportation, and erection occur in sequence with minimal delays. Additionally, original modular assembly design must be accurate because changes can devastate the interrelated processes involved. All of these constraints places significant risk on the project, as the reliability of modular methods is much harder to guarantee than conventional work. There may be a lack of competent project management or a scarcity of contractors and suppliers available to perform the work. Because the parties to the contract may be unfamiliar with the procedure, there is a high potential for problems to arise. Modular construction can be very beneficial to a project, but only if everyone involved has the proper experience and ability to perform such activities [1].

2.4. Implications (Schoenborn)

Schoenberg’s essay offers a different and more modern perspective of the design implications in modular construction. During the literature review, charts list the most crucial perceived benefits and constraints of prefabrication. The listed benefits are for on-site labor conditions, safety, site conditions, manufacturing conditions, craft productivity, volume of on-site construction, quality, environmental impact, project duration, ground level work, overall cost savings, and labor savings. The constraints relate to the amount of preplanning, the amount of project coordination, transportation, inflexibility, procurement, and changes in impact risk. The data analysis portion of the essay highlights the most important modular construction topics gathered from interviews with industry companies. Suggestions to improve the market perception of modular techniques include LEED certifications application and increased communication of new technology from manufacturers to architects on new modular technologies. The scope of work applicable to each contractor or supplier involved implies advantages and disadvantages for different types of project delivery methods. The latest in building information modeling and computer aided drawings improves delivery of shop drawings, coordination of different assemblies, and prefabrication production. The latest software allows greater automation of fabrication factory processes. Schoenberg’s last point is that life cycle costs are given more consideration than initial costs for modular units.

3. Methodology

In order to investigate architectural considerations for modular building, the approach for this study is to devise a hypothetical construction project with specific options to include modular building components. The first part of the research process is to define the hypothetical project, and explain why that project will provide the best insight into the factors that affect decisions regarding modular building components. The second step is to discover several specific options for modular components that are applicable to the chosen project type. Alistair Gibb’s textbook provides many examples of these components, and these examples will be used as an introduction to the potential options for the project. Then, the overall conclusions described in all three major sources will reveal the major factors that affect architectural decisions. After all this information has been described, the design options can be evaluated considering the most important contributing factors. Final conclusions about the hypothetical project will follow this process, which will lead to overall evaluations for modular building techniques.

4. Scope

Residential building is a specialized industry that differs greatly from the rest of the construction industry. Because residential developments are built with a high degree of repetition, construction has become very standardized. The benefits of using these standard methods greatly outweigh the drawbacks, and there is not much room for innovation in specific projects. Industrial construction projects focus much more on the processes occurring within the building than on aesthetic factors. The goal of industrial construction is to provide the highest economic benefit, which will ultimately overcome all construction costs. The focus in civil engineering projects is utilities and infrastructure rather than building occupants. There is not an extensive opportunity to choose modular components as there is in building construction. Remaining types of construction includes a wider range of building types such as high-rise construction, shopping centers, and institutional buildings. Modular building design decisions are more significant for these buildings because the long term aesthetic, structural, and performance factors are more pronounced than for residential, industrial, and civil projects.

Institutional buildings include school and university buildings, health care facilities, and other government facilities. These projects are typically funded by federal and state governments and owned by state and local governments. There are a lot of
opportunities for innovation in these buildings, especially because public projects encourage competition by requiring contractor bidding. However, a private project with a wider range of discretion will better demonstrate the factors involved in decisions regarding modular components. Horizontal commercial construction includes large shopping centers and strip malls as well as individual retail outlets. These buildings are typically located in light urban or suburban settings, where the coordination and logistics of construction are at moderate difficulty and the safety implications are manageable. On the other hand, taller structures in urban areas are more difficult to build because of the difficulty inherent to work at heights with minimal room to maneuver. These buildings require sophisticated construction methods that involve a lot of expensive equipment and labor hours. The safety of construction workers and the general public is extremely important in vertical construction, which requires extra precautions. A lot of planning and coordination is necessary to ensure that the project operates efficiently and safely. Despite these constraints, urban locations are very profitable for businesses because of the close proximity to employees and amenities. Because urban vertical construction offers the opportunity to assess many factors of construction that modular building components can influence, the hypothetical structure will be a twenty story office building in a highly populated urban area.

5. Design Options

Now that several relevant design applications and implications for modular building techniques have been researched, some major building components can be analyzed to determine the feasibility of incorporating modular techniques. The most relevant assemblies are structural components, exterior cladding, and service modules. Research has shown that precast concrete can improve a project most effectively if used exclusively for structural framework, so the discussion will consider the advantages and limitations of precast concrete. Following the conclusions for the structural members, the exterior cladding will be analyzed. This assembly must be aesthetically appealing and contain a lot of glass, but also connect sufficiently with the framework. The repetitive nature of an office building offers opportunities for modularization of electrical, mechanical, and plumbing components. A portion of the study will be dedicated to determining the feasibility of using such modules.

6. Precast Concrete (Structural)

The structural framework of the twenty story office building will likely consist of steel, concrete, or a combination of both. The concrete components can be either cast in place on the job site or precast in a factory. Advantages of precast concrete over site cast concrete include a drastic reduction of shoring and formwork costs, and better quality control over concrete strength and surface finishes. On the contrary, precast members require more highly skilled workers, more complex techniques, and a more complex design. Architectural precast concrete applies to exterior walls and will be analyzed for the exterior cladding. Structural precast concrete can combine with another material in mixed precast construction or used exclusively in total precast construction. In mixed precast construction, precast concrete is used for horizontal slabs while vertical elements are composed of steel, masonry, or site cast concrete. This is common because precast concrete roof and floor slabs reduce costs due to the lack of formwork. Hollow-core slabs, solid planks, double-tee units, and inverted-tee beams are typical for horizontal members in mixed precast construction. Total precast concrete construction consists of double-tee units, inverted-tee beams, columns, and walls. This is similar to steel frame construction because both require heavy rigging equipment and efficient procurement coordination.

The Precast/Pre-stressed Concrete Institute has published an electronic brochure promoting the use of total precast concrete structures. The main purpose is to describe numerous advantages for the owner, architect, contractor, and structural engineer that contribute to the rising popularity of total precast projects. The most significant advantage to the owner is a reduction in overall project length due to the following: one contractor for all structural framework, early fabrication, design simplicity, winter construction, quick installation, and more efficient fire resistance. Fabricators supply higher quality and lower maintenance products that improve logistics and promote safety. An earlier relationship with precast concrete manufacturers simplifies project coordination and cost estimation. The architect enjoys efficient and sustainable design advantages from total precast construction due to coordination with the manufacturer and the environmental benefits of using precast concrete. Precast manufacturers are also able to provide samples and mockups more easily than is possible with site cast concrete.

The architect has more interior design freedom due to the ability of precast sections to cover large spans and fit into tight spaces. Total precast structures are also beneficial to the contractor and engineer due to increased workability and performance compared to steel or site cast concrete. The major benefits summarized for precast concrete that do not exist with steel or site cast concrete are the potential for expedient construction year-round, factory controlled production, and labor savings. Costs are lower for precast construction than the other methods for general conditions, structure and enclosure work, fireproofing, and caulking. Site cast concrete is only cheaper for decks and toppings, and steel is only cheaper for shear walls. The final chart of this brochure is especially relevant to the prototype building because it considers multi-story office buildings. The overall savings in construction time for total precast construction compared to a mixed steel and precast design amounted to five weeks. Site cast concrete, mixed steel and precast, and mixed steel and brick designs all ultimately cost about six dollars more per square foot than total precast construction.
7. Precast Concrete (Architectural)

Since the advantages of total precast concrete construction have been identified, it is appropriate to determine the potential of precast concrete panels to serve as exterior cladding for the office building. The benefits of using one manufacturer to produce all the structural members and one contractor to install them may extend to the exterior walls if they are also made from precast concrete. Precast concrete pieces fit together more easily with other precast concrete pieces than with steel or site cast concrete components. Exterior precast concrete walls can adequately provide both structural integrity and aesthetic appeal. The advantages of the factory production environment for structural components also apply to architectural precast concrete. Using panelized exterior walls is more efficient because construction is possible in weather unfavorable to site cast concrete, and because the danger of scaffold work is eliminated. The ability to produce panels with openings for windows makes precast exterior wall panels popular for office buildings. The aesthetic advantage of producing concrete panels at ground level allows for better control over the surface finishes desired. The most crucial details for precast concrete curtain walls are the connections to the structural frame, which is achieved through bearing supports and tiebacks. The main disadvantage to these wall panels is the difficulty transporting, connecting, and erecting panels that may be numerous due to structural limitations [4].

8. Precast Concrete (Implications)

The popularity of the total precast concrete method for office building construction is favorable to the architect because of the familiarity and experience of owners, contractors, suppliers, and engineers. It would not be difficult to find qualified manufacturers and workers that specialize in precast concrete to join the project team. Because this method is common for office buildings, a higher degree of predictability can be expected for the project since all parties improve their performance with experience from previous projects. If the owner or architect has worked on projects with a specific contractor or manufacturer, contract administration and project management become easier to tasks. This is an important advantage, because the administrative responsibilities especially during the design phase are more extensive in precast concrete construction than with conventional techniques. This places severe limitations on the type of project delivery that is appropriate for the situation. A design-bid-build process is undesirable because early involvement with the precast manufacturer and the installation contractor is necessary. An architect may be unable to form an agreement with the manufacturer or specialty contractor before a general contractor is chosen because the general contractor is free to contract with any subcontractor or supplier. The design-negotiate-build method is a slight improvement because only competent and experienced general contractors can be selected, and the chosen general contractor likely will have previous experience with the other parties. One way for the owner to eliminate the potential for problems between companies is to form separate contracts with a supplier and specialty contractor to perform the precast concrete work. The owner can then hire a general contractor or several contractors to perform the remaining work.

Because the design firm needs to concentrate on perfecting the modular design, the intensive administrative work should be delegated to a construction management firm. These professionals are better prepared to handle the rigor of procurement, planning and scheduling, and project engineering than architects or building engineers. Most of the complications between construction, procurement, planning, and fabrication are especially apparent for office buildings. The congestion of a busy city imposes severe limitations on the movement of large cranes and the storage of precast panels on site. The means and methods of construction must be well planned by the contractor; and the production, transportation, and installation coordination for large precast concrete components must be equally well planned by the project management team. The best solution for a total precast concrete construction project is to implement integrated project delivery. Under this method, the designers and contractors are determined before the final concept of the project is realized. A working relationship with the contractor responsible for the precast concrete installation is crucial to the success of the project. Structural modular building requires all parties to the project to coordinate their efforts from the beginning, since the remaining work relies on the building being enclosed. Although manufacturer’s representatives and other design consultants may be involved from the beginning of the design phase in traditional project delivery, complete cooperation between the manufacturer and architect is the only way to fully realize the shortened project length possible with precast concrete. A twenty story office building will require extensive time to erect regardless of the construction techniques. The precast manufacturer can produce components for the upper stories of the building while the lower stories are being erected. These processes can occur while the design for the service systems and interior architecture is finalized. Because it allows many project tasks to occur simultaneously, integrated project delivery is the best method to maximize time and cost savings that precast concrete construction offers.

9. Service Modules
The total precast concrete construction method in the prototype project is the most effective way to incorporate modularization into the building. There are other opportunities to reduce cost and time in the project by using additional prefabricated elements. One other relevant modular system for this office building project consists of prefabricated modules containing electrical, mechanical, plumbing, and fire protection components. Typical office buildings contain many floors that are very similar to each other and have very similar design layouts. Nearly identical floors can have the same plans for lighting, electrical service, heating and cooling, plumbing, and fire protection. Overhead ductwork, electrical conduits, and sprinkler lines will run above a typical drop ceiling and can be installed modularly before the ceiling. Those components, which are routed nearly identically from floor to floor, can be combined into cohesive modules that can be replicated for each floor. Vertical plumbing and sprinkler pipe mains and electrical conduits between floors can also be constructed in modules. The only difference between these vertical modular units may be pipe or conduit sizing, which may decrease as the height increases. There are several advantages of using service modules, but there are also complications they present to design and project delivery. Prefabricated components offer time and financial benefits because less and cheaper labor can perform the work than is typically necessary. Most projects plan electrical and mechanical work near the end of the project, when other interior construction can delay or obstruct this work. Many labor hours are necessary for installation in spaces confined by the ceiling grid and other contractors attempting work in the same areas. If the more difficult aspects of the assembly are completed at a factory, labor costs are significantly reduced. The obstacles that cause high labor costs in conventional construction also constrict the project schedule, but modular techniques can eliminate this.

10. Conclusion

Adequate planning for modular service construction is necessary to capitalize on the advantages identified by Torre in section 2.2. In an ideal situation, contractors or suppliers should be involved during the design phase to ensure that fabrication, transportation, storage, and installation occurs in a timely and cohesive manner. Service modules should only be used if the owner and his agents are satisfied that the contractor is competent to perform the work. The best scenario is to contract with suppliers and contractors that can build and install modules that combine electrical, mechanical, and plumbing elements. This will simplify project management for the service divisions and boost confidence in the project because of contractor experience. Specialty contractors are familiar with the construction procedures required for service modules. These processes include proper handling and storage, adequate equipment for hoisting and swinging, and cautious positioning and installation in exact locations. The precast concrete construction system can aid the service module construction process if both modules types are installed in a highly coordinated manner. Vertical modules can be easily positioned and connected before walls are added to a slab. After a slab is poured, modules that run horizontally below can be installed before the building is enclosed by all walls. If service modules are installed at a consistent pace with the precast concrete elements, the entire construction process is simplified. The advantages of using multiple modular construction methods is contingent upon early and complete communication between all contractors and suppliers involved.

References


