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Sustainability in modular design and construction: a case study of ‘The Stack’

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The goals of sustainability are to meet people’s basic needs and improve their quality of life while simultaneously ensuring that the natural systems, resources, and diversity upon which they depend are maintained and enhanced, both today and for future generations. Construction activities over a facility’s life cycle are also connected with the broader problems and issues affecting the environment, including global warming, climate change, pollution and the depletion of valuable resources. Built facilities significantly impact human health, comfort, and productivity. Modular building is becoming increasingly popular in many countries due to its many benefits, including greater construction efficiency and productivity. This study investigated how modular building can support sustainability goals in the built environment via a deep case study of ‘The Stack’, a recently completed modular rental housing block in New York City. The building’s architect and manufacturer were interviewed for the case study and the design, manufacturing and construction process analysed to examine how modular processes can contribute to achieving the goals of sustainability. The ultimate goal of this study is to improve the processes involved in modular construction to help all stakeholders to achieve the goals of sustainability.

Keywords: modular design; modular fabrication; modular construction; sustainability; case study

Introduction

The construction industry is one of the largest contributors to pollution and waste when a building’s entire life cycle is taken into account [1,2]. In the US, activities such as developing, maintaining and operating facilities in the built environment are responsible for 17% of fresh water withdrawals; 40% of the energy, 72% of the electricity and 50% of the fossil fuels consumed; 30–50% of the total waste generation; and 39% of all CO_2 emissions [3–5]. Sustainability in the built environment is therefore rapidly becoming a serious consideration in the construction industry due to the widespread recognition of the many negative environmental issues and problems associated with its operations [2,6,7]. The concept of sustainability encompasses a wide range of goals, enabling people to meet their basic needs and improve their quality of life, while at the same time ensuring that the natural systems, resources, and diversity upon which they depend are maintained and enhanced, both for their benefit and for that of future generations [2]. One of the best ways to achieve sustainability is to implement sustainable design and construction practices such as energy efficient design and the reduction of construction waste throughout the building’s life cycle. Current practices in construction are very labour intensive, with low productivity rates compared to other industries, and are surrounded by significant risks associated with the market, site and weather conditions and relatively low profit margins. To achieve sustainability and improve construction quality while simultaneously fulfilling the occupants’ need for affordability, comfort, and flexibility, modular construction, where much of the work is completed off-site in a controlled factory environment and the resulting modules transported to the site for the final assembly, promises to be a revolutionary new and innovative approach that will provide high value and quality for every part of the useful lifespan of the building [8]. Modular construction offers many benefits compared to conventional construction approaches including: 1) shorter overall project schedules, 2) better product quality, 3) less need for skilled workers on the site, 4) a reduction in the negative environmental impact caused by construction activities, 5) better onsite safety, and 6) a reduction in overall construction costs [9–12]. Reports in the literature clearly demonstrate that modular construction can help the industry to achieve the goals of sustainability alongside the many benefits listed above. The purpose of this study is to examine how modular construction can achieve the goals of sustainability by improving the efficient use of resources, boosting product quality, reducing the project duration, and lowering overall construction costs. A case study of ‘The Stack’ building in New York City is included as a practical example. The study findings confirm that modular construction can indeed improve the triple bottom line of sustainability.

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Background study/literature review

To establish the background for this study, a literature review was carried out to examine the current status of sustainability in the construction industry. The literature on modular building was also examined to identify connections between sustainability in the built environment and modular construction.

Sustainability in the built environment

Construction activities, including developing, maintaining and operating facilities in the built environment, are major consumers of the nation's fresh water, energy, electricity and fossil fuels as well as being responsible for creating a significant fraction of its waste and CO_2 emissions [3–5]. Overall, the construction industry is one of the largest contributors to pollution and waste throughout the building life cycle, from the initial design phase through construction and occupation to its final demolition [1,2]. Construction makes a significant contribution to our society and its economic prosperity. The implementation of sustainable practice in all activities in the built environment can thus have a major impact on efforts to achieve the 'three pillars of sustainability' (the so-called Triple Bottom Line) that make up the three parts of the framework: social, environmental and financial. In construction, sustainable practices can play a significant role in mitigating the environmental problems associated with construction activities while at the same time contributing to a higher quality of life for clients and boosting economic profits [2]. The underlying purpose of sustainable practices is to protect and preserve land and sites, enhance indoor environmental quality, reduce the environmental impacts of materials, reduce construction waste, optimise energy performance and protect and conserve water [6,7,13,14]. Through implementing sustainable practices in the built environment, it is possible to achieve a wide range of social, environmental and economic benefits, as shown in Table 1 [2,7,15].

By implementing sustainable practices, the construction industry can meet the overall definition of sustainability: 'Meeting the needs of the present without compromising the ability of future generations to meet their own needs' [16].

Modular construction

The term *modularisation* refers to construction processes that the industry has used for centuries, although this approach has gained momentum as a result of the rise of Building Information Modelling (BIM) and the increased popularity of green building techniques [17]. In this study, a 'modular building' is composed of a number of factory-built volumetric units which are transported to the site on a flatbed trailer and joined together at the job site to create a larger structure [18]. The primary advantages of this modular building approach are:

- Economies of scale in manufacturing multiple repeated units
- Improved construction efficiency and productivity

Table 1. Environmental, social, and economic benefits.

Environmental Benefits	Social Benefits	Economic Benefits
• Protecting air, water, land ecosystems	• Improving the quality of life for individuals and society as a whole	• Improving economic growth
• Conserving natural resources (fossil fuels)	• Alleviating poverty	• Reducing energy consumption and costs
• Preserving animal species and genetic diversity	• Satisfying human needs	• Raising real income
• Protecting the biosphere	• Incorporating cultural data into development	• Improving productivity
• Using renewable natural resources	• Optimising social benefits	• Lowering infrastructure costs
• Minimising waste production or disposal	• Improving health, comfort, and well-being	• Decreasing environmental damage costs
• Minimising CO_2 emissions and other pollutants	• Having concern for inter-generational equity	• Reducing water consumption and costs
• Maintaining essential ecological processes and life support systems	• Minimising cultural disruption	• Decreasing health costs
• Pursuing active recycling	• Providing education services	• Decreasing absenteeism in organisations
• Maintaining the integrity of the environment	• Promoting harmony among human beings and between humanity and nature	• Improving the Return on Investment (ROI)
• Preventing global warming	• Understanding the importance of social and cultural capital	
	• Understanding multidisciplinary communities	

- Improved quality and accuracy in manufacture
- Reductions in both costs and budgets
- Improvements in construction workers' safety
- Greener building methods and reduced waste (lower job-site environmental impacts) [17,19,20].

Modular buildings are also relatively easy to dismantle and reuse, thereby maintaining their asset values and preserving the planet's overall resources [19].

Sustainability and modular construction

Although sustainability is not yet a major driver for the adoption of modularisation techniques [17], modular building inherently achieves the goals of sustainability in the built environment (Table 2).

According to a report by McGraw-Hill, 72% of contractors surveyed believe that using modularisation shortens project schedules by more than a week, with over one third (37%) believing that usage can cut schedules by more than four weeks. In addition, 74% of the contractors surveyed believe that modularisation can help decrease project budgets and 37% believe that this process improves site safety. Finally, more than 83% of the contractors surveyed believe that modularisation reduces onsite waste and 66% also believe that modularisation reduces the amount of materials used on a project [17]. The evidence published in the literature thus confirms that modularisation does indeed contribute to efforts to achieve the goals of sustainability during the building construction phase. In addition, concepts such as BIM and Lean Construction also support the benefits of modularisation for construction stakeholders by facilitating the building process [1,17,20].

Research methods and objectives

The primary objective of this study was to determine whether the modularisation of buildings can play a role in achieving the goals of sustainability. To achieve this objective, a qualitative research method was adopted that utilised the case study research method via a series of in-depth semi-structured interviews with representatives from the architecture firm responsible for the project (architect & CM) and the module manufacturer. The authors developed an interview guide that listed the questions and topics to be covered during the interview. These questions covered the overall goals of the project; the relationships among stakeholders; the modular design, manufacture, and assembly processes; the challenges associated with these processes; and sustainability practices and modularisation. The resulting case study of 'The Stack' in New York City, presented below, illustrates how building modularisation can help achieve the goals of sustainability in the built environment.

Case study of 'The Stack'

Project description

The Stack project is located in Inwood, New York City, NY. The Stack is the first of New York City's affordable buildings to utilise the modular building approach. The project was developed by Jeffrey Brown of Brown Hill Development, Huntingdon, PA, and Kim Frank, the owner of the real estate finance company MCA, working with a design team and construction manager from the architecture firm Gluck + and the module manufacturer Deluxe Building Systems in Berwick, PA (Figure 1). The Stack is composed of 28 housing units (6 studios, 6 one-bedroom, 14 two-bedroom and 2 three-bedroom units), with retail spaces on the first floor. In total, the building is 37,710 sq.ft, which includes 26,138 sq.ft of modular spaces assembled in the form of 56 modules. The Stack is a mixed residential development that provides 22 rental housing units and 6 affordable housing units for low- and medium-income citizens, allocated via a lottery. The new building addresses New York City's severe lack of affordable housing units, as the price of housing in the city continues its dramatic rise.

Modular design process

One of the first steps in the building procurement process is to choose a project delivery system, which is the system

Table 2. Sustainability and modularisation.

Triple Bottom Line	Benefits	Modular Building Processes
Economic	• Increased efficiency and productivity • Compressed project schedules • Reduced construction costs • Improved product quality	• Manufactured in a controlled space (Over 60%) • Modules assembled at the site • Reduced requirement for on-site material storage • Option to disassemble modules and re-use them
Social	• Increased worker safety (fewer accidents) • Healthier lifestyle for workers	• Work with all stakeholders • Stream construction process
Environmental	• Reduced construction wastes • Reduced air and water pollution, dust and noise, and overall energy costs • Reduction in quantity of materials • Reduction in site disturbances	

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- Owner/Developer: Jeffery Brown and Kim Frank
- Designer/Construction Manager: Gluck +
- General Contractor: Jeffrey M Brown and Associates
- Manufacturer: Deluxe Building Systems
- Building square Footage: 37,710 Sq. Ft
- Modular Square Footage: 21,160 Sq. Ft
- Housing Unit Mix (Monthly Charge)
  - o Studio (6): 484 Sq. Ft ($1755)
  - o One Br (6): 682 Sq. Ft ($2400)
  - o Two Br (14): 875 Sq. Ft ($2850)
  - o Three Br (2): 1160 Sq. Ft ($3990)

Figure 1. Project description of The Stack in New York. (Courtesy of Gluck +)

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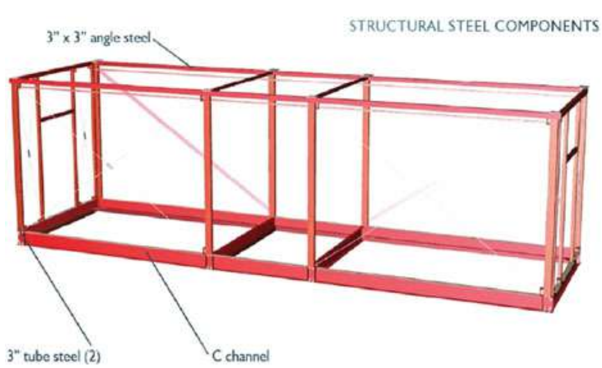
used by an owner to organise the design, manufacturing, and construction services for a building. As a modular building, the procurement process for The Stack was different from that for conventional custom-design and construction projects. Developers Jeffrey Brown and Kim Frank hired the innovative architecture firm Gluck + to deliver this project using a modular building approach, seizing the opportunity to create an existing design for living while enjoying the benefits and efficiencies of controlled, offsite fabrication. The Stack is designed with both elegance and durability in mind. The residential units feature stained concrete floors, high performance aluminium windows and tenant-controlled heat and air conditioning. Kitchens are equipped with solid surface Corian countertops with under-mounted stainless steel sinks, maple cabinetry with stainless steel pulls, GE stainless steel appliances and WaterSense fixtures, while the bathrooms offer contemporary vanities with storage and mosaic tiled walls. In addition, all residents have access to a common outdoor terrace; 10 of the units have additional private terrace space. Upon entering The Stack, residents are greeted by a 'virtual doorman' to ensure safety. When developing the overall design for The Stack, the developers and Gluck + collaborated with Deluxe Building Systems, a modular manufacturer in Pennsylvania, at the design stage. The major criteria for selecting the modular manufacturer was their experience with steel modular manufacturing, their specialisation and expertise in modular engineering, their financial strength, the location of the manufacturing facility, and references from other design and development firms. Since Deluxe Building Systems was selected at a relatively late stage of the design process, the collaboration between architects, clients, and modular manufacturer was necessarily limited, but once they joined the project team, Deluxe collaborated with the design team in pricing the manufacturing process, value engineering, logistics between the plant and the job site, any structural and engineering issues involved in the modular construction, prototyping/mock-ups, construction documents, shop drawings, lean approaches for fabrication, material procurement, and module erection. Gluck + and Deluxe adopted the modular system shown below in Figure 2.

The modular manufacturing process

All the project stakeholders, consisting primarily of the architects, engineers and module manufacturer, collaborated in the design of The Stack. In addition, Deluxe



- Structural steel frame – point load system
- Light gauge infill framing
- 4.5" composite concrete floor deck
- Structural columns that are typically buried within the wall framing

Figure 2. The modular system at The Stack. (Image source: Deluxe Building Systems)

Figure 3. Steel slab frame and poured concrete on the slab form. (Courtesy of Deluxe Building System)

Building Systems developed shop drawing packages for the manufacture of the modules for the 28 residential units at their factory in Pennsylvania. The shop drawing packages included the details for each part being produced and a bill of materials for the project. Deluxe Building Systems also adopted lean fabrication practices to improve the module production efficiency and reduce potential waste during production. The production began with framing a steel slab frame with a metal deck (Figure 3). Since the concrete slab was poured at the factory, it was possible to eliminate much of the construction waste normally created in conventional construction methods. The cured concrete slabs were stacked at the yard ready to install in the steel chassis of each module when needed.

The members of each module's steel chassis were cut via computer numerical control (CNC) cutters using a laser and water jet (Figure 4). Bending was performed by hammering with press brakes and similar tools. The steel chassis was assembled by manual and robot welding (Figure 4). Since the metal fabrication was completed at the factory with efficient tools and expert welders, it was possible to increase the process efficiency and reduce steel waste.

The internal walls were assembled using cold-formed steel (CFS) made by rolling or pressing the correct gauge of sheet steel. CFS walls in the module were created by working the sheet steel using stamping, rolling, or presses to deform the sheet into a usable product. Figure 5 shows the cutting and rolling process using a CNC cutting machine and cold-formed steel channel forming machine. Using those tools can significantly improve the production efficiency compared to those available for field production. The more

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Figure 4. Cutting and assembling a steel chassis. (Image sources: Deluxe Building Systems)

Figure 5. Cold-formed steel wall manufacturing. (Image sources: Deluxe Building Systems)

precise cutting and forming procedures made possible by these precision tools also reduces construction waste.

Gypsum board was cut by an automatic gypsum board cutting machine (Figure 6). The pre-cut gypsum board was nailed to the cold-formed steel walls using the fully automatic drywall board manufacturing machine shown in Figure 6. These tools significantly improved production efficiency, with minimal waste due to precise cutting and nailing. As these procedures were all conducted inside a factory building, there was also no danger that the gypsum board would suffer from water damage due to exposure to the elements, which is often a problem on conventional building sites.

The preassembled walls were assembled into the structural chassis using a crane (Figure 7), after which insulation, plumbing pipes and electricity conducts were fitted on the wall and ceiling. In addition, Heating, Ventilation, Air Conditioning (HVAC) ducts and sprinklers and fire-extinguisher pipes were installed before the drywall was installed on the other side of the CFS walls.

Once all the module's walls were assembled, windows and doors were installed and crew members completed the interior finishes and installed the cabinets, fixtures and appliances (Figure 8). The crew members also tiled the bathroom at this point (Figure 9). Once the inspector had inspected the quality and signed off on each module, the certified third party issued the complete certification. After passing this inspection, the module was ready for delivery to the job site. Note that it was deemed vital to provide temporary weatherproofing for each module at this point since it would be exposed to weather for the first time during transportation.

Figure 6. Drywall board manufacturing and installation machines. (Image sources: Deluxe Building Systems)

Figure 7. Assembling walls and HVAC ducts. (Image sources: Deluxe Building Systems)

Figure 8. Window and cabinet installation in a module. (Image sources: Deluxe Building Systems)

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Figure 9. Tiling a bathroom and weatherproofing the module for transport. (Image sources: Deluxe Building Systems)

The modular construction process

A modular construction process starts in the same way as a conventional construction project with digging the foundation of the new building (Figure 10). In general, conventional construction methods are utilised up to the first floor slab construction, which provides a base for laying the first floor modules (Figure 10).

Once the first floor slab is ready, the modules are transported from the factory to the jobsite for module erection. In this project, the modules were manufactured at Deluxe Building Systems' factory in Berwick, PA, and then transported to the job site in (Figure 11). The transportation of the modules was crucial for the efficiency of the module assembly and erection procedure at the job site as continuous erection processes were implemented. Deluxe Building Systems adopted a lean concept for just in time delivery and production that allowed the project team to eliminate 'muda', the Japanese word for waste, i.e. any activity that wastes time and effort. Once they arrived at the job site, the modules were assembled by a crane and experienced crews who were highly qualified in module erection. All modules were lifted directly from the flatbed trailer into their final location. The use of highly skilled and specialised work crews significantly reduced errors and mistakes in the module assembly process and achieved a very tight tolerance in modular construction. For The Stack project, the crew assembled the 56 modules into a 7-storey building within 19 days. This could have been reduced to 10 days if government regulations had allowed more modules to be delivered each day; there was a government-imposed limit for the delivery of modules to the job site as part of the city's effort to reduce traffic congestion.

Once all modules had been erected to create the main building structure, only minimal field finishing was

Figure 10. Conventional construction for the foundation and first floor slab. (Image sources: Deluxe Building Systems)

Figure 11. Module transportation and installation. (Image sources: Deluxe Building Systems)

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required. Applying as much of the finishes as possible in the factory ensured a high value-to-volume ratio and maximised the financial benefits of modular construction, but some field work was still required in order to cover the interfaces between the modules and the mate-lines. In The Stack, the following tasks were required to complete the modules (Figure 12):

- HVAC systems
- Plumbing and sprinklers
- Electrical connections
- Mate wall carpentry and drywall trim out
- Floor finishes across the mate line
- Corridor and common areas completion
- Exterior skin.

After the 56 units were stacked, the facade was installed. Workers also made the horizontal and vertical connections and set up the mechanical and electrical systems; the modules arrived on the site already equipped with kitchen appliances and tubs, showers and toilets in the bathrooms. Since many of the work tasks had been completed at the factory, it took a little over two months to complete the field work, including assembling the modules, from August 2013 to the end of October 2013. The overall project took less than a year to complete, including the conventional construction of the foundation and first floor and all the field work after the module assembly.

Sustainability in modular buildings

Modular building benefits from inherent qualities and opportunities that improve the sustainability of the building project. For example, modularisation can significantly reduce the project duration by improving the productivity and efficiency and minimising weather-related delays, reducing carbon emissions by transporting only the finished modules to the site, and minimising material wastage, and the natural resources used in the building. This section looks in more detail at how The Stack project achieved the goals of sustainability in the building's design, manufacturing, and construction.

First, the first pillar of the triple bottom line is economic prosperity. The Stack's shorter project duration, 30% faster than a conventional construction project would have been, was achieved due to modularisation and off-site construction. This reduction in the construction period due to high efficiency and productivity contributes to the economic pillar of sustainability via the cost savings from the project's indirect and financing costs. In addition, as the modules were manufactured at the factory, it was possible to improve worker efficiency via easier access to tools, fewer material deliveries, and better sequencing of crews. Since over 50% of the project was completed in the factory, this supported the provision of high quality housing units to the occupants that will considerably reduce the energy consumption of each unit over the operational phase of the building's life. This reduction in energy consumption will reduce both occupants' energy bills and the carbon emissions from energy consumption.

The second pillar of sustainability is social sustainability. The use of modular construction enhances worker safety by reducing their exposure to inclement weather, temperature extremes, and ongoing or hazardous operations, while at the same time providing better working conditions. Modular construction also reduces traffic congestion as well as noise and dust at the job site, both of which will reduce conflicts with local residents. As some of the housing units were assigned to low- and medium-income residents, this addresses the need for affordable housing in New York City.

There are many environmental benefits in a modular building. Compared to conventional building sites, The Stack minimised job-site environmental impacts because of the reductions modularisation achieves in material waste, air and water pollution, dust and noise, and overall energy costs, although prefabrication and related technologies also entail higher transportation costs and energy costs at off-site locations. Two of the major benefits of modularisation are to reduce construction waste and lower the need for resources. Finally, when they reach the end of their operational lives, modular buildings can be dismantled and recycled in other projects, after renovation. The reduced energy consumption once occupied also

Figure 12. Finishing The Stack. (Image sources: Deluxe Building Systems)

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Figure 13. Exposed mass concrete. (Image source: Gluck +)

reduces carbon emissions during the building's operational phase. The exposed mass concrete on the floor in The Stack modules will also reduce the need for additional materials such as carpet (Figure 13).

Conclusion

Sustainability is very important in the built environment to preserve our environment and enable our society and economy to prosper. The Stack project in New York City clearly demonstrates that modular building can provide high quality housing units for low- and medium-income residents. The main advantage of The Stack project was its speed of construction, with a project duration of only six months on site, much lower than that possible with conventional construction projects. In addition, the architect reported that the project cost for The Stack was 15% lower than that which would have been needed for conventional construction with the same quality. Since building modules were manufactured at the factory in Pennsylvania, prefabrication made it possible to optimise construction material purchases and usage while minimising on-site waste and offering a higher quality housing unit to the renters. In addition, residents living close to the job site also appreciated the reduced traffic congestion compared to conventional building approaches during the construction period due to the high percentage of prefabrication. Off-site construction also subjected residents to less site disturbance and other noise and dust problems. Since almost all workers on the site worked inside the building once the modules had been erected, the construction workers enjoyed a safer work environment that did not leave them exposed to temperature extremes, rain, wind or any combination of natural conditions. Modular building with its integrated design, manufacturing and construction process has been shown to be inherently advantageous in several major areas, including reductions in material waste, the exposure of materials to inclement weather, costs, site disturbances, and energy and carbon emissions, as well as a safer and speedier construction process. In particular, the speedy construction of higher quality housing units supports efforts to address the shortage of affordable housing in big cities around the world. The lower construction cost also reduces the financial burden of rental housing for low- and medium-income residents in New York City. This case study demonstrates that modular construction can indeed help achieve the three pillars of sustainability by improving social, environmental, and economic properties. In addition, modular construction also addresses the issue of the shortage of affordable rental housing units in New York City.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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