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Modular Disruption in Construction Industry—The Environmental Benefits

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Abstract: The impact of Covid-19 on every aspect of life is undeniable. As the pandemic began to spread throughout February 2020, no one could have foretold the ways in which this disease would change society. One of the key things that the Covid-19 pandemic has accelerated is off-site manufacturing and the different ways in which modular construction can be utilized to deal more effectively with the demands of a crisis. The rapid erection of modular hospitals across the globe has been critical in fighting the outbreak of Covid-19, not least the modular hospital in Wuhan that was built in just 10 days. Modular construction was already a hot topic for the industry, the pandemic has simply enhanced this—and the last few months were given the opportunity to explore the options in more detail. There is no doubt that modular construction will continue to play a part in construction projects in the longer term and construction industry should adapt to accommodate this change. Since construction industry is the largest consumer of natural resources, this article would emphasize on the sustainability dimensions of modular construction and its performance during the whole lifecycle. A thorough literature review of the sustainability benefits of modular construction compared to its tradition counterpart is presented.

Key words: Off-site construction, modular construction, environmental benefits, sustainability.

1. Introduction

Modular construction may seem like a new building method, yet it is actually been used for a long time. Its roots can be traced to the Rome in AD-43, where the Romans used modular building elements to build their forts quickly and efficiently as they realized that these forts and stockades used a large number of same and repeating components. However, not only the Romans, but the Britishers also transported simple modular houses by ships to their new settlements in the colonies to provide comfortable European Style living to its officers in these colonies. In 1840s modular construction made its way to the United States in response to the housing needs of the California Gold Rush, prefabricated houses were transported from New York to California [1].

One of the most famous examples of early modular construction is Crystal Palace, built for Britain's Great Exhibition of 1851. Designed in less than two weeks, it utilized light and inexpensive materials such as iron, wood and glass, and was constructed in only a few months [2]. Afterward, Crystal Palace was dismantled, moved, and rebuilt at another location [3]. Another example of modular construction is the Eiffel Tower. Eiffel Tower was built as a temporary exhibit structure for the Centennial Exhibition in Paris in the year 1889 for the celebration of the French Revolution of 1789. The Eiffel Tower consists of modular iron parts that were mass produced at an off-site location on the outskirts of Paris [4]. Each of the 18,000 iron parts used to construct the Tower was specifically designed and calculated, traced out to an accuracy of a tenth of millimeter and then put together forming new pieces around 5 m each. These pieces were then taken to the site and assembled to build a 300-m tall structure which completed in a time period of just over two years.

Corresponding author: Dimitra Tzourmakliotou, Ph.D. in civil engineering, associate professor in Democritus University of Thrace, steel structures, space structures, design for deconstruction, sustainability of steel structures.

However, the first true catalyst for modern modular construction happened shortly after the turn of the 20th century. Starting in 1908, Sears, Roebuck, and Co. sold modular houses through its Sears Modern Home Program. The concept was simple: Order one of the 400 house plans from the catalog and receive it in easy-to-construct sections [5, 6]. In the mid-1940s, the industry turned to modular when faced with skyrocketing demand for new homes after World War II and, in the late 1950s, modular expanded into the construction of schools and medical facilities [7, 8]. In the 1960s and 1970s high rise concrete modular construction was introduced. The Hilton Palacio del Rio Hotel was among the first concrete high rise modular buildings in the world. The 500-room hotel was designed, completed and occupied in an unprecedented period of 202 working days. The hotel's room modules were pre-cast from light-weight structural concrete [9]. Nowadays, based on the spread of modular construction we can categorize countries into three groups: those that have an acknowledged high application of prefabricated housing such as Sweden (84% of all detached homes) and Japan (28%); those that have been identified as having both relatively high levels of prefabrication and highly efficient traditional or "craft based" house-building industries such as Germany (9%) and the Netherlands (20%) and major economies that have an infrequent application of prefabricated housing such as the United States (5%), United Kingdom, and Australia [10].

2. Sustainability in Construction Industry

The construction industry strongly affects the economy, the environment and society as a whole. It touches the daily lives of everyone, as quality of life is heavily influenced by the built environment surrounding people. The construction industry accounts for 13% of global GDP (Gross Domestic Product) and is using the natural resources 1.5 times faster than the world can replenish itself. The construction industry is the world's largest consumer of energy, resources and raw materials as it consumes about 50% of the total global raw resources for the manufacturing of building products worldwide [11, 13, 15]. Also, it accounts for more than 40% of the world's energy use and is attributable for 30% of global greenhouse gas emissions [11, 12, 14]. In Europe, the construction sector uses by far the greatest amount of resources in the economy on a mass basis, and consumes between 5% and 10% of total energy only for the production of construction materials [16-19]. Moreover, a large volume of CDW (construction and demolition waste) is generated by the construction industry each year, which in industrialised countries can be up to 60% of the total amount of solid waste generated by mass [20-24]. In Europe, CDW accounts for 38% of Europe's total solid waste generated, excluding wastes from the mining and quarrying activities [18, 21, 25, 26]. Also, the construction industry in EU generates 40% of the carbon dioxide CO_2 emissions and uses 50% of all-natural resources. Furthermore, global demographic and lifestyle changes, growth in the world's population and, in particular, its middle classes, which will expand from two to five billion by 2030, are increasing the existing demand in construction industry while it is under increasing pressure to minimize its environmental impact.

Sustainability could help the construction industry to reduce its environmental footprint, and to avoid rising costs, labour shortages, delays, and other consequences of volatile commodity markets but that is something that has been put somewhat on the backburner for the time being due to disruption caused by the Covid-19 crisis. As an industry, so often the focus is on cost and designing to meet the minimum standards rather than considering the longer-term impact of the construction on the environment. Modular construction would involve reshaping the way projects are procured, designed, constructed, operated and repurposed.

3. Modular Construction

Since its introduction stateside, the process of constructing structures off-site, then transporting and assembling them in half the time compared to traditional techniques, has undergone significant technological innovations, including advances in associated software, automation and building information modeling. This blend of technological prowess plus modularity is a key feature for enhancing sustainability in construction.

Modular construction is more of a manufacturing process than it is a typical construction. The modules (frames, walls, ceilings, floors, etc.) are all produced in a factory, or what we would call "off-site". Compared to a traditional construction site, where hundreds of processes are happening at the same time, this highly centralized process allows for closer inspection and quality assurance. Flaws in material quality are flagged directly at the source of manufacturing and resolved before ever reaching the site, ensuring the minimization of waste on site, the strictest compliance to building codes and higher safety standards once the construction phase has begun. Moreover, because modular components are so highly standardized and predictable, it is possible to model and pre-optimize facilities in the virtual 3D space with total detail and accuracy, simulating everything from airflow and human movement to asset performance and energy consumption.

The terms off-site construction, prefabrication, and modular construction are used interchangeably and cover a range of different approaches and modular systems. These modular systems vary depending on the complexity of the elements being brought together as explained below.

4. Categories of Modular Systems

Panelized Systems ("2-Dimensional"): also regarded as "non-volumetric preassembly" these are either classified as "open" or "closed". The open panels normally delivered to site purely as a structural element with services, insulation, cladding and internal finishes installed in situ while the closed panels apart from the structural elements usually include more factory-based fabrication such us lining materials and insulation and may even include external cladding, internal finishes, services, doors, and windows [27, 28]. Using this panelized system's parts of the walls, ceiling or roof can be constructed in a factory and rapidly assembled on site by an experienced construction team to form the completed building. These are components that can be flat packed, that is grown up into a full-sized building.

Modular or Volumetric System ("3-Dimensional"): involves three-dimensional modules that can be in isolation or in multiples to form the structure of the building. These systems are pre-engineered and pre-assembled units in the factory which can be transported to site and fitted into an existing building or incorporated into a traditional construction project with limited amount of work on site [29-32]. A 3D volumetric approach delivers the potential for maximum efficiencies and time savings—but the trade-offs include transportation costs and size limitations. The time savings onsite need to be substantial for volumetric systems to be chosen over panelized. The most common volumetric system is a bathroom pod. The bathroom pod contains all the sanitary ware, electrical and plumbing fittings and even the finished tiles. This entire unit can then be transported to the construction site, installed and can be made instantly ready for use. Additionally, this can include "complete buildings" where the completed useable space forms part of the completed building or structure finished internally (lined) and externally (clad). A 3D volumetric approach is most suitable for projects with a high level of repeatability and a high ratio of wet to dry rooms.

Hybrid System (2D + 3D). A hybrid system is a combination of more than one discrete system or approach and is normally a combination of both volumetric and panelized systems. This approach combines the flexibility and logistic advantages of 2D panels with the productivity benefits of 3D modules [29, 31, 33, 34]. Typically, wet areas are manufactured as bathroom pods, while the remainder of the building is made from 2D panels. However, the manufacturing process required to deliver both solutions becomes more complex, as does coordination of the supply chain.

Sub-assemblies (Component Systems 2D or 3D). Any major part of a building made in a factory and brought to the construction site can be classed as a sub-assembly, which forms part of a component system [29, 34-36]. These do not form the primary structure of the building. Foundation systems and cassette panels are typical examples. Sub-assemblies can be as small as locks and handles for the doors, or they can be larger components such as pre-assembled roof trusses. Sub-assemblies are likely to be used in a construction project that predominantly uses onsite techniques but enables some of the trickier components to be built in a factory that allows for more precision than the building site.

5. Benefits of Modular Construction

5.1 Schedule

The most important benefit of modular construction is the ability to substantially reduce the time needed for construction (Fig. 1). This diagram shows a side-by-side comparison of a timeline for a site-built construction vs. a timeline for a modular construction. The first two stages of construction are the same. The first major difference in timeline comes when the actual construction begins. With site-built construction, all site preparation and foundation work must be completed before the actual house can be built since the framing for the house must be built on top of a finished foundation. Using modular construction on the other hand, work on the factory can take place at the same time as the foundation is being prepared [37, 38].

Numerous projects have demonstrated that schedule savings are the most easily documented and noticeable savings that occurs because of modular construction. Parallel scheduling for off-site and onsite construction schedules saves 30% to 50% of project duration compared to stick-built traditional construction processes [39-41]. This is due to concurrent site and factory work, as well as factory production being faster than on-site framing, removing weather delays and subcontractor sequence delays associated with on-site construction [42-44]. This makes modular construction suitable for owners who need buildings quickly, properties with hard dates for occupancy such as the educational and health sectors, and areas where seasonal weather restricts or even halts construction [35, 45, 46]. Additionally, this time saving can reduce significantly the final cost

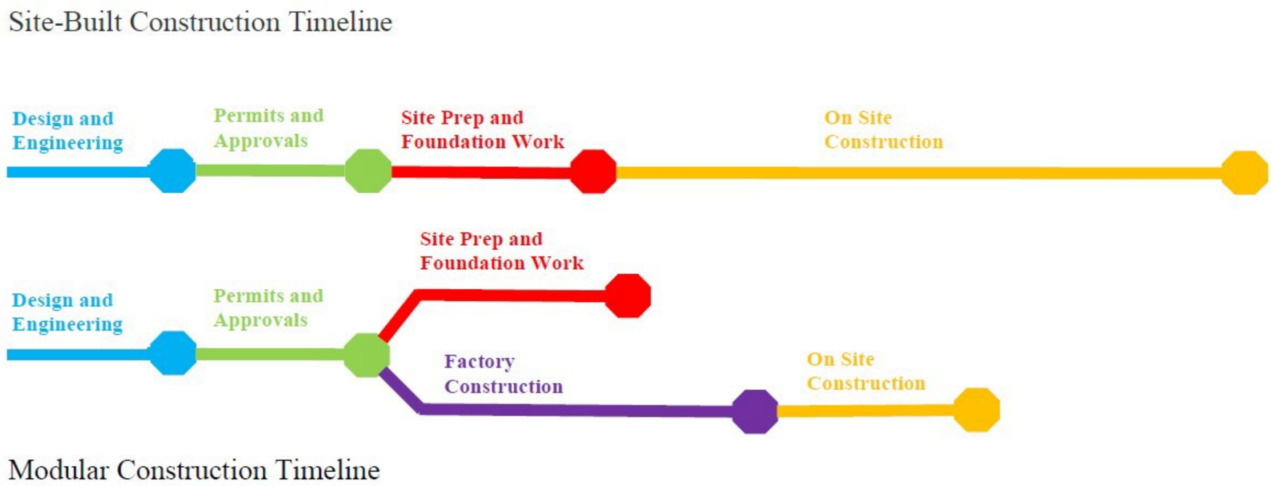

Fig. 1 Timeline of site-built construction vs. modular construction.

Table 1 Potential modular construction savings/cost (%).

	Pre-construction phase	Estimated savings/Cost (%)
Design	Preferably, a modular-based design philosophy should be adopted from the start, ensuring that various considerations—including those related to geometry and material strategies, transportation logistics, and issues related to shared scope and coordination—are fully integrated into the process. However, there is often an additional fee in the design due to a lack of experience in designing modular projects. But as the industry gains more experience in such projects and adjusts to producing repeatable designs that can be used and adapted multiple times, this cost will likely drop. The development of digital tools such as BIM (building information modeling) will also help in this direction [58]. In modular construction design includes structural design, detailing, 3D modelling, service layouts, soap drawing and is usually carried out by the modular supplier. So, the cost of design finally might be reduced by 3%-4% compared to traditional design cost [55, 65, 74, 75].	-3% to -4%
Site Overheads	Modular construction has already a proven track record of decreasing project timelines and construction risk which in turn minimizes the cost of site overheads and financial carrying costs (such as insurance, weather related issues). In traditional construction site preliminaries may account for 12% to 15% of overall cost while in modular construction it may be taken 7% to 8% [65, 75].	-5% to -8%
	Construction Phase	-8% to -10%
Materials	There are numerous factors which either increase or decrease the cost of materials for off-site manufacturing compared with onsite. Cost increase factors •As manufacturing facilities become more automated greater precision in the tolerances of the quality requirement for the materials needed which in turn can increase costs. •Due to transportation from the manufacturing facilities on-site some duplication of key structural elements such as beams and columns, is required in order to be structurally sound in situ whilst being raised and lowered throughout the handling process (transportation and assembly). This can substantially drive-up material costs depending on the material choice and level of design optimization. • The need for "standardization" means that some economy in use of materials is sacrificed for production efficiency. Cost decrease factors • Optimizing procurement for a factory rather than for individual projects the contractor can save the cost of material. Utilizing different methods, the cost can be decreased by about 20%. • By direct procurement and cut out of intermediaries. • Efficient ordering and optimized deliveries to reduce logistic cost. • Economies of scale for the purchasing of all units going through a factory versus individual projects. • Manufacturing process has far lower wastage rates than a construction site. Because of this it is difficult to be clear on whether material costs will be higher.	-3% to -4%
Labor Force (On- and Off-Site	The construction industry is experiencing a clear shortage in skilled and semi-skilled labor. Fewer younger workers are coming into the construction trades to replace those who are aging out. One of the most disruptive aspects of modular construction is the reduced labor force required during the construction phase as in a modular building, up to 80% of the traditional labor activity can be moved off-site to the manufacturing facility. Modular, construction lays the framework to optimize a shrinking labor force and maximize productivity. A modular construction company usually employs a group of full-time employees in the manufacturing facility to address all required off-site construction and manufacturing of the modules; a consistent workforce tends to make modular construction faster and of higher quality than traditional construction methods. In addition, as a modular construction approach requires more standardized, automated, and controlled operating environment of a factory and a high level of coordination and collaboration among project team members, it promotes a more integrated process that can in turn lead to increased productivity [75]. Conversely, onsite assembly of modules requires a lower-skilled and thus lower-cost labor force. Overall, it is expected transition to modular manufacturing to lower the labor cost on a project by up to 15%. Saving can be even more significant up to 10%, when high-value activities such as mechanical, electrical and plumbing (MEP) installation done off-site. Nowadays, modular manufacturers are growing, and 25% of firms in the 2018 Associated General Contractors (AGC) Workforce Survey [66, 67] reported adopting or increasing the use of methods like off-site fabrication to deal with labor shortages.	-15% to -25%

Table 1 to be continued

Logistics	Modular construction possesses the characteristic of both construction and manufacturing and a new tailored logistic process is necessitated for its future coherent operation. The modular components leaving the factory can be either 2D panelized systems or 3D volumetric or modular systems. In the case of 3D volumetric systems, the components are typically large and cumbersome requiring specific transportation considerations that might cause delays, incur extra cost and add complexity to the construction process [60, 62, 63, 64]. Therefore, a well-coordinated transportation plan, via specific routes at specific times, with adequate and specialized vehicles should be carried out in advance [60, 61]. Additional caution should be taken when they are carried out across public roads and urban areas [60]. Consequently, the contractors should take special care that the productivity gains offset this cost, carefully weighing wage differentials between the manufacturing facility and the product's end destination, as well as the distance involved in delivery. The total cost of a modular project can increase by up to 10% in locations with restrictive transport regulations [63, 65].	+10%
Rework	Quality assurance is one of the most vital aspects in almost every industry, and, when it comes to construction, it is "the" most vital aspect. Higher quality can be attained with the use of modular construction due to better manufacturing facilities in which the components are built, than on a construction site which has a big impact on rework. Rework refers to re-doing a process or activity that was incorrectly implemented. Rework is usually pure waste and substantially affects the schedule, cost, and quality of construction projects [68, 69]. A significant proportion of rework is caused by errors made during the design process [70]. The direct costs of rework on site are projected to be 2%-12% of the overall construction cost; therefore, rework should be managed effectively [71-73]. Modular construction due to stringent quality checks at every stage and much more restrictions in the design and construction can reduce or eliminate rework significantly improving construction schedules, potentially by up to several months and ensuring project cost. Moreover, as the modules should have enough strength and load bearing standards when transported by trucks, high quality materials which are durable, lightweight, and resistant to weather are required. This elevated material quality and manufacturing process is reflected in cost savings of 1% to 2% [75].	-1% to -2%
Financing	Modular construction is a relatively new concept and thus, the financing industry is just beginning to explore the opportunity and make themselves aware of this new system. But as they are in the early stages of their learning curve proposed lending schemes for projects utilizing modular construction tend to be higher since it is different from the stick-built construction and not always fully understood by the financing industry. However, this will change over time as a substantial track record and scale are established and greater research and development (R&D) is undertaken. As it is mentioned previously the most important benefit of modular construction is speed of construction and since time equals money, the ability to accelerate projects can lower costs. Even though upfront payment can be higher in modular construction, financing would be required for short time which in turn would reduce the project's financial cost by 2% to 5% [76, 77].	-2% to -5%
Factory Costs	The initial capital investment for the construction of the manufacturing facility and the running expenses of the production facility should be considered against the above-mentioned savings. Depending on the production facility the factory cost to be allocated can be between 5% and 10% of overall cost on a modular construction project [65].	+5% to +10%

of the project [47]. However, it should be mentioned that, when the number of stories in modular construction increases, the time savings decrease considerably as the project becomes more complex and subsequently additional engineering and communication as well as more work in the jobsite is required [48]. Nevertheless, the completion time of modular construction is still less than that of conventional ones even though the project is a high-rise modular construction [38].

5.2 Construction Cost

Although the costs of modular construction are often more predictable than with traditional construction methods this does not mean it will automatically result in savings in overall project cost. There are a series of factors that could result in modular construction savings as are referred in Table 1 [38, 49, 50]. Saving in modular construction costs can come either from the pre-construction (design and site preliminaries) or the construction phase (sub-structure, materials, on- and off-site labor, logistics) [42, 51-53]. Moreover, the manufacturing process involved in off-site construction eliminates the demand for subcontractors and the margins that they incorporate in their quotations. Nonetheless, the main trade-offs are among the savings in onsite labor compared to possibly higher costs for materials and the increase in logistics costs. Modular construction also tends to have higher upfront design costs against lower costs for rework and redesign [54]. However, apart from the construction costs, there are two more aspects regarding the cost that are significant to consider: the full life-cycle costs and the impact that modular construction can have on them and the cost of the factory investment itself and how this influences the overall savings of modular construction.

6. Sustainability Benefits of Modular Construction

The implementation of modular construction in the built environment can have a substantial impact on efforts to achieve the "three pillars of sustainability, the so-called TBL (triple bottom line) that make up the three pillars of the framework, environmental, economic and social. These sustainability benefits of modular construction have been reported in many studies and are presented in Table 2. The benefits arise from the more efficient manufacturing and construction process [56, 57, 59], the improved in-service performance of the completed building, and the potential reuse at the end of the building's primary life due to the flexibility and durability of modular construction.

Table 2 Sustainability benefits of modular construction.

	Description	References
Economic Benefits	Speed of construction. Several activities can be performed simultaneously;	[37, 74, 75, 78, 79, 85, 86, 87]
	Economy of scale in manufacture, especially in larger projects (dependent on the production volume) or in repeated projects using the same modular specification;	[74, 75, 82, 83, 84]
	Saving in design costs due to the client as most of the detailed design is carried out by the modular supplier;	[74, 75]
	Reduced overheads in-site infrastructure and management of the construction process (known as site preliminaries) due to speed of construction;	[73, 75, 78, 79, 81]
	Compressed project schedules, leading to reduced site management costs for the main contractor and early return on investment for the client;	[32, 75, 78, 79, 81, 84, 85]
	High levels of consistency and higher product quality achieved by the factory based construction process and predelivery checks, leading to reduced rework or "snagging" costs;	[32, 58, 74, 75, 78, 97]
	Costly delays due to severe weather conditions can be eliminated;	[79, 88]
	Higher productivity in manufacture and less work on site, leading to reduction in labor costs and transportation per unit completed floor area;	[32, 58, 74, 75, 78, 89, 90, 97]
	Savings in material use due to rationalization of material orders;	[74, 78]
	Savings in disposal costs due to the reduced amount of waste;	[74, 78, 92]
	Receiving volume discounts by ordering materials in bulk;	[79]
Environmental Benefits	Reduced site and neighborhood disturbance during construction, which is important in urban areas where the adjacent buildings have to function without disruption;	[75, 78, 79]
	Reduced air & water pollution, dust & noise;	[78, 94]
	Better energy performance and decrease in CO_2 emissions due to reduced transportation of labor, materials and machinery on site;	[32, 78, 79, 87, 89, 90, 94]
	Lightweight, less material use and less waste generation compared to site intensive construction;	[37, 75, 78, 79, 80, 87, 95, 96]
	Efficient land resource use. Foundation excavation is minimized and there are fewer potential wasteful site activities;	[78, 79, 87]
	Reduction in quantity of materials delivered on site with considerable economy of use in production than is achievable on site;	[78, 79, 87]
	Potential for waste management;	[79]
	Modular buildings can be easily reused or relocated at reasonable cost;	[75, 87, 93]
	Wider use of recycled materials (like timber, steel, aluminum, etc.) and greater opportunities for recycling in factory production;	[75, 78, 79, 80]

Table 2 to be continued

Social Benefits	Increase workforce health & safety;	[78, 79, 86, 91]
	Improved working conditions on site;	[32, 78, 84, 86]
	Reduced on-site risks by reducing elevated work and dangerous activities;	[32, 79, 84, 86]
	Excellent acoustic, thermal insulation and fire safety due to double skin nature of the construction, which means that each module is effectively isolated from its neighbours;	[75, 86]
	Health comfort and well-being of the occupants;	[75, 86]
	Affordability;	[86, 98]
	Reduced community disturbance;	[75, 78, 79, 86]
	Aesthetic options and beauty of the building;	[86]
	Influence of local social progress.	[86]

7. Conclusions

The construction sector needs more natural resources and generates more waste than any other industry in the world. These place the construction sector in the spotlight as changes in the design, construction, use and life cycle assessment of the sector can result in major improvements in the overall sustainability impact of the sector. Designing and constructing in the built environment with sustainability in mind can bring long-term benefits not only in terms of reduced material use and related environmental issues, but also in long-term economic and social wellbeing.

The potential for using modular construction is acknowledged by the construction sector. Technical, economic, and organizational factors currently hinder this potential from being utilized, rendering modular construction largely untapped. Despite the several initiatives to unlock modular construction, a lack of quantitative information restricts the demonstration of the real advantages to be gained. A key aspect that must be addressed in promoting modular construction is a change in the cultural mind-set towards this method of construction, and the wider collaboration between all actors involved in the planning, construction, maintenance, refurbishment of a modular building. Research that can better highlight the economic, environmental, social and technical benefits of modular construction would enable designers, contractors and real estate agents to get a better understanding of how changes in their current practices could be optimised through modular construction. Education and training in the wider skillset associated with modular construction, combined with the right policy incentives and opportunities for market development would empower their active participation in modular construction. This would provide the right conditions for modular construction to become a mainstream practice. In addition, political strategies that foresee the provision of incentives to boost modular construction, and the promotion of legislation for their usage, will help to realize the potential of this method as an alternative to traditional construction.

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