sustainability

MDPI

Review

Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways

Fred Edmond Boafo [1], Jin-Hee Kim [2] and Jun-Tae Kim [3,*]

[1] Zero Energy Buildings Laboratory, Graduate School of Energy Systems Engineering, Kongju National University, Cheonan, Chungnam 330-717, Korea; febs@kongju.ac.kr

[2] Green Energy Technology Research Center, Kongju National University, Cheonan, Chungnam 330-717, Korea; jiny@kongju.ac.kr

[3] Department of Architectural Engineering & Graduate School of Energy Systems Engineering, Kongju National University, Cheonan, Chungnam 330-717, Korea

* Correspondence: jtkim@kongju.ac.kr; Tel.: +82-41-521-9333

Academic Editor: Marc A. Rosen
Received: 9 May 2016; Accepted: 13 June 2016; Published: 15 June 2016

Abstract: Even though tightened building energy efficiency standards are implemented periodically in many countries, existing buildings continually consume a momentous quota of the total primary energy. Energy efficiency solutions range from material components to bulk systems. A technique of building construction, referred to as prefabricated architecture (prefab), is increasing in reputation. Prefab encompasses the offsite fabrication of building components to a greater degree of finish as bulk building structures and systems, and their assembly on-site. In this context, prefab improves the speed of construction, quality of architecture, efficiency of materials, and worker safety, while limiting environmental impacts of construction, as compared to conventional site-built construction practices. Quite recently, a 57 story skyscraper was built in 19 days using prefabricated modules. From the building physics point of view, the bulk systems and tighter integration method of prefab minimizes thermal bridges. This study seeks to clearly characterize the levels of prefab and to investigate the performance of modular prefab; considering acoustic constrain, seismic resistance, thermal behavior, energy consumption, and life cycle analysis of existing prefab cases and, thus, provides a dynamic case study-based review. Generally, prefab can be categorized into components, panels (2D), modules (3D), hybrids, and unitized whole buildings. On average, greenhouse gas emissions from conventional construction were higher than for modular construction, not discounting some individual discrepancies. Few studies have focused on monitored data on prefab and occupants' comfort but additional studies are required to understand the public's perception of the technology. The scope of the work examined will be of interest to building engineers, manufacturers, and energy experts, as well as serve as a foundational reference for future study.

Keywords: prefabricated architecture (prefab); modular; energy; thermal behavior; acoustic constraints; seismic resistance; life cycle analysis

1. Introduction

1.1. Background

Vis-à-vis the automobile, shipbuilding, and aerospace industries, the building construction industry has been the slowest to change over the years. That premise may be about to change at a startling pace. Quite recently, a Chinese company has built a 57 story, 800 apartment skyscraper (called Mini Sky City) in just 19 working days in the Hunan provincial capital of Changsha. Mini Sky City was roofed on 17 February 2015. The builders, Broad Sustainable Building, were able to get Mini

Sky City ready so quickly for occupants by assembling the skyscraper out of prefabricated sections using modular methods; fabricating the building's 2736 modules for 4.5 months before construction began at an installation rate of three floors per day [1,2]. Inside Mini Sky City is the world's first indoor spiraling sky street 3.6 km upwards from the first floor to the roof garden on the 57th floor [3]. Time savings attributed to prefabricated construction revolve around the fact that on-site foundation construction can be done in parallel to offsite component fabrications, while restraining weather delays on the construction schedule [4,5].

From a single prefabricated window system to an intricate prefabricated building module, almost all contemporary buildings integrate prefabrication to a degree. Particularly, prefabricated architecture is an offsite manufacturing process that takes place at a specialized facility in which various materials and building systems are joined to form a component or part of a larger final assembly on-site, or a unitized building system to be installed on-site. Industrialized building, offsite construction, offsite fabrication, prebuilt construction, and prefabricated building are some terms used interchangeably in literature to describe prefabricated architecture—hereafter referred to as prefab. Significant research activities have focused on various aspects of prefabricated buildings, namely: realizing lean construction through off-site manufacturing [6–8], surveying the perspective of housebuilders on offsite construction trends [9], opportunities and constraints of offsite construction [10–12], policy-making [13], design solutions [14], software implementation potential [15–17], and future perspectives [18,19]. The recent UNFCCC COP 21 resolved to restrain increases in global average temperature to below 2 °C by reducing emissions, among others, towards sustainable development [20]. Prefabrication is said to be a sustainable building technology [21]. The benefits of adopting prefabrication in building construction can be quantified through survey and comparative analysis from stakeholders and selected existing buildings. Studies support that construction quality and safety can be increased with prefabrication, while time spent for construction completion, overall costs, material waste, and the impact on the environment can be reduced [11,22–25]. Designing with prefab components is not a barrier to creativity; conversely, by standardizing prefab components and providing mass customization options, ultimately lowers final costs through economies of high volume work [26,27]. For instance, in Hong Kong, the construction industry generates a huge quantity of waste and this amount reaches 40% of the total waste intake at the landfill areas; space for waste disposal is running out and prefabrication in construction is being turned to with a promising waste reduction of 84.7% [28]. The benefits of applying prefabrication were considered as having different levels of significance to construction, and a survey was conducted to identify the level of recognition of these beneficial aspects.

Better supervision on improving the quality of prefabricated elements ranked as first with an average value of 4.09. The respondents claimed that prefabrication of building components achieved better quality products with better supervision, as the prefabricated elements were tested and inspected before site installation. Frozen design at the early stage for better adoption of prefabrication and reduced overall construction costs were ranked second and third, respectively, with average values of 3.91 and 3.63, respectively. Additionally, the respondents argued that other than the cost that can be saved from the early standardized design layout, time can also be reduced as the prefabrication can increase the productivity and efficiency of building construction; this interpretation is in line with the survey's result of ranking fourth of the advantages of prefabrication with an average value of 3.50 [28]. A further study reiterated that adopting prefabrication demonstrated significant advantages, such as improved quality control, reduction of construction time (20%), reduction of construction waste (56%), and reduction of dust and noise on-site, as well as labor required on-site (9.5%) [29]. For a 25 story student residence in Wolverhampton, UK, with 16, 340 m^2 total floor area worth of modules, the installation period was 32 weeks for 824 modules and the total man-hours of on-site work was estimated as 170,000 (or approximately 8.2 man-hours per m^2 of the completed floor area). It was estimated that the reduction in the construction period relative to site-intensive concrete construction was over 50 weeks (or a saving of 45% in construction period). In addition, a 70% reduction in waste relative to site-intensive concrete construction was estimated [30]. Post-occupancy and indoor monitoring surveys of prefabricated timber housing showed that the indoor temperature rose above the comfort range when external temperature was above 19 °C [31]. To comprehensively understand the actual performance of prefab, monitoring and measurement of existing prefab needs to be quantified and declared, which will also boost the confidence of all stakeholders involved. The objective of this study is to examine the general performance of modular prefabricated buildings based on existing cases and, thus, provide a dynamic case study-based review. As a precedent, an overview of the different levels of prefabrication in buildings and its historic development is clearly presented. Ultimately, this study seeks to identify performance boundaries of prefab based on an analysis of selected cases. Most literature on prefab focused on their architectural designs, general descriptions, and construction specifications. This study will be knowledgeable to stakeholders involved in the building industry and, as such, serve as a foundational reference for future work on the subject. However, unpublished or inadequate data of numerous existing prefab limits the scope of this work.

1.2. Brief History of Prefab

Prefabrication in the construction industry is evolutionary, not revolutionary, based on successful and unsuccessful experiences [4]. The earliest prefabricated cases was recorded in 1624, when houses were prepared in England and sent to the fishing village of Cape Ann, in what is now a city in Massachusetts. In 1790, simple timber-framed shelters were shipped from England to Australian settlements in New South Wales as hospitals, storehouses and cottages. Years later, a similar system was erected in Freetown, Sierra Leone and Eastern Cape Province of South Africa; these structures were simple and shed-like, with timber frames, clad either with weatherboarding or board-and-batten siding. Although these structures were not extensively prefabricated, they represented a significant reduction in labor and time compared to on-site methods then. In 1830, the Manning Portable Colonial Cottage for emigrants, an improvement of the earlier system, was developed. The house was an expert system of prefabricated timber frame and infill components, designed to be mobile and easily shipped. 1833 was the beginning of the light balloon frames in the United States; buildings were erected so quickly that Chicago was almost entirely constructed of balloon frames before the infamous Chicago fire. The light wood construction caught fire quickly. The earliest, most extensive example, of prefabrication is Britain's Great Exhibition of 1851, featuring a building called the Crystal Palace. Designed by Sir Joseph Paxton in less than two weeks, the building used light and cheap materials: iron, wood, and glass. The construction period lasted only a few months and consisted of assembling the prefabricated components. After the exhibition, the palace was taken apart, piece by piece, and moved to another location. Through the 1930s, the Aladdin "built in a day" house became common in the United States, boasted by lower cost per foot in material due to its "ready cut" system that maximized yield from standard lengths of timber. In 1932, a metal sandwich panel wall system was developed, followed by George Fred Keck's "House of Tomorrow" and the "Crystal House" for the Chicago World's Fair in 1933. The House of Tomorrow comprised a three-story with steel frame and glass infill walls that resembled an airplane hangar, and the Crystal House improved the steel frame concept. The House of Tomorrow was focused on cost effectiveness, passive heating, and modulation of daylight. From 1954–1968, mobile homes, built as a module on a chassis in a factory, accounted for 25% of all single family houses in the United States. The Hilton Palacio del Rio Hotel in San Antonio, Texas, was built in 1968 for the Texas World's Exposition of 1968 (still in use); it is a 500-room deluxe hotel designed, completed, and occupied in 202 working days. Of the Palacio del Rio's 21 stories, the first four were built of conventional, reinforced concrete for support facilities. At the same time, an elevator and utility core, also of reinforced concrete, were slip formed to a full height of 230 feet. From the fifth floor to the 20th, 496 modules were stacked and connected by welding of steel embedment; the 496 rooms were placed by crane in 46 days. In 1976, the building code was changed to distinguish permanent homes as being those designed to the standard code (*i.e.*, International Building Code (IBC)) and mobile homes to the HUD (U.S. Department of Housing and Urban Development) code. Up until the 1990s, numerical control was restricted to those who could afford it; but today, small manufacturers and fabricators use Building Information Modeling (BIM) tools, Computer Numeric Control (CNC), and 2-D laser cutting devices. This requires full scale modeling of components to effectively prove that all elements fit together with appropriate tolerance [4,5,11,32,33].

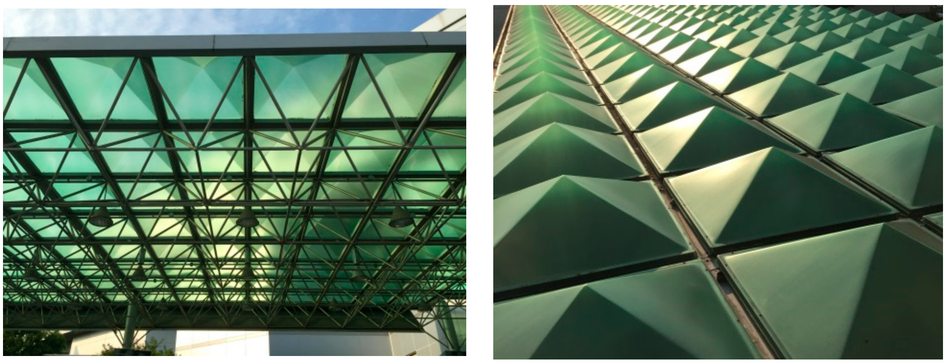
2. Prefabricated Building Concepts

2.1. Degree of Prefabrication

Degree of prefabrication refers to the size and complexity of prefabricated components or configuration of the final product. Decreasing the size of prefabricated components increases the degree of on-site construction labor and vice versa. Prefabrication can be categorized into:

2.1.1. Components

Components allow for the greatest degree of customization and flexibility within the design and execution phases, but they become numerous on construction sites and laborious to account for. Componentized systems also require more joints and connections, and require more careful alignments and infiltration checks. They are single fabricated elements such as stairs, gable ends, roof trusses (see Figure 1), wall frames, wood kits, and precast concrete.



(a) (b)

Figure 1. Roof truss system: structural framework (**a**) and roof (**b**).

(a) (b)

Figure 2. Customized curtain wall with glazing vision and building-integrated photovoltaic spandrel: macrograph (**a**) and sectional view (**b**).

2.1.2. Panelized Structures

Panels are 2D planer elements used to build structural walls, floors, and roofs, alongside columns. Panels enhance the speed and convenience of delivery of walls to a site. Included in this category are structural insulated panels (SIPS), metal frame panels, and curtain walls (see Figure 2). A typical example of panel system is the 30-story hotel near Dongting Lake in the Hunan Province of China, that was built in 15 days [34].

2.1.3. Modular Structures

Modules are made in complete 3D boxlike (volumetric) sections, multi section units, and stack-on units (see Figure 3). Unlike in panelized or component levels of prefabrication, in modular construction most of the interior and exterior finishes are put into place in the factory. They are up to 80–95 percent complete when they leave the factory [4,35]. Modules are designed for ease of assembly. The size of a module is a factor of module location in the building, manufacturing constraints, and transportation limitations. It is worth mentioning that a category of prefab called a mobile home uses the modular concept, but generally employs lighter construction and with a metal chassis as part of the floor system; thus, as the name implies, it can be moved around quite often and easily. The air-tightness and thermal performance of modular buildings can be much higher than previous prefab levels due to tighter tolerances of joints [30]. A typical modular building is the Mini Sky City, a 57-story apartment skyscraper constructed in 19 working days (previously described under Section 1.1) and the One9 modular building (will be described under Section 2.3).

Figure 3. Modular system.

2.1.4. Hybrid Structures

Hybrids usually combine panel and modular prefabrication systems to construct a whole building. An example is the Meridian First Light House, depicted in Figure 4. The house is a net zero energy dwelling designed to maximize energy drawn from the natural climate using a combination of passive and active energy strategies. The house is made up of six independent prefabricated modules and wooden decking surrounds the house linking the interior to the surrounding environment. The building ranked third in the 2011 US Department of Energy's Solar Decathlon [36–38].

(**a**)

(**b**)

Figure 4. Hybrid structure–First Light House: completely installed building (**a**) and installation procedure (**b**).

2.1.5. Unitized Whole Buildings

Whole buildings are standardized building units prefabricated to the highest degree of finish as compared to components, panels, modules, and hybrids. More work is done under controlled factory environment (with larger building structures), providing the opportunity for the manufacturer to take control of quality and speed of the final product. However, sometimes their bulk size and weight presents difficulties in transportation from the factory to the building site.

2.2. Load-Bearing Material Classification

Prefab can broadly be classified based on the type of load-bearing material. A plethora of materials are employed for prefab purposes, however for load-bearing structures, steel, wood (for small buildings), and precast concrete are generally used for their properties, availability, and cost. A typical wooden structure prefab is the First Light House illustrated in Figure 4. The building was inspired by the traditional Kiwi Bach (a New Zealand holiday home), designed with a strong connection to the landscape. The buildings structural support and facades were wood-based. Wood is natural, biodegradable, easy to machine, and a recyclable or reusable material [39]. For steel structure prefab, a simple case is shown in Figure 3; a classic case would consist of a number of steel modules (usually shipping containers) stacked on top of each other, such as the cantilevered shipping container coffee shop in Johannesburg, South Africa [40]. Steel is known for its strength-to-weight serviceability and durability. Unlike wood and steel, precast concrete are generally used up to the panelized level of prefabrication because of weight constraints. For a decade (*i.e.*, 1985–1995), wooden structure, steel structure, and concrete structure prefab averaged 18%, 74%, and 8%, respectively, of the total prefabricated housing in Japan [41]. The trend may be different today and plausibly change with the development of lightweight concrete that fulfills strength requirements [42,43]. Moreover, due to its high compressive strength, precast concrete is used as load-bearing stabilizing systems for high-rise modular prefab. For instance, 36 modules were clustered around a precast concrete core (see Figure 5). Shifting away from conventional concrete/cement clinker production towards energy-efficiency and CO_2 emissions reduction, high-activation grinding, oxygen-enriched combustion, the use of carbide slag and low lime saturation factor, geopolymer cement, among others, have been proven to reduce the carbon footprint of cement use [44]. Based on optimal mix designs, CO_2 emissions of a low-carbon concrete were reduced by 7% as compared to an actual mix design [45]; a potential 45% reduction in global warming potential of concrete was also reported in [46] depending on mix proportions. Concrete made with Portland cement, 35% fly ash (35% FA), and 80% blast furnace slag blended cements (80% BFS) captured 47%, 41%, and 20% of CO_2 emissions, respectively, during the life cycle of a 3 m high building column with 30×30 cm^2 cross-section. The blended cements emitted less CO_2 per year during the life cycle of the structure, although a high cement replacement reduced the service life notably. For instance, the service life of blended cements with high amounts of blast furnace slag blended cement replacement was about 10% shorter, given the higher carbonation rate coefficient [47].

2.3. Prefab Methodology

2.3.1. General Approach

Some aspects of prefabricated construction are identical to conventional practices, such as site preparation, excavation, and installation of the foundation. Simultaneously, detailed design and offsite fabrication of building components, under controlled factory conditions, using the same materials and designing to the same local building codes and standards as site-built facilities take place. The prefab components are then delivered and assembled on-site to reflect the identical design intent and specifications of the most sophisticated site-built facility, without compromise [48]. The ensuing section features an example of on-site prefab assembly.

2.3.2. On-Site Assembly Case Study

One9, developed by the Moloney Group, is located at 19 Hall Street, just 7 km northwest of Melbourne's central business district in Moonee Ponds, a thriving hub of commercial, office, and retail activity, bordered by quality residential dwellings and excellent lifestyle amenities. Designed by the Amnon Weber architecture firm and constructed by Vaughan Constructions using Hickory Group's prefabricated building systems, One9 comprises 34, one- and two-bedroom contemporary apartments over nine stories. The manufactured apartments were erected by Vaughan and Hickory using 36 unitized building modules in just five days; the daily schedule and progress are shown in Figure 5. Vaughan subcontracted Hickory to deliver the 36 modules, complete with the facades and fully fitted with a combination of natural timber floors and high grade carpets, built-in wardrobes, and full-length balconies. The nature of tall buildings is such that the modules are clustered around a precast concrete core or stabilizing system; the modules are generally designed to resist vertical loads and horizontal loads are transferred to the concrete core [30,49]. The Hickory manufactured apartments offer light-filled and functional spaces for everyday living. Unique, modern design highlights the capability of the modular technology to adapt to complex architectural concepts, and features cantilevered terraces on all levels and clean framing on the front façade. One9 was completed in November 2013 [50].

Figure 5. One9 modular building stabilized by a concrete core.

3. Performance of Modular Prefab Cases

3.1. Thermal Behavior

Hundreds of modular housing units were built as shelter after the 2008 Wenchuan earthquake, in the Sichuan province of China. The prefab envelope was composed of 40 mm polystyrene foam board sandwiched between two 0.5 mm stainless steel layers. In situ measurement of the prefab houses showed that indoor air temperature reached 30 °C, while inner surface temperature could escalate to 55 °C. Solar heat gain affected the indoor thermal environment significantly. The prefab envelope was found to be of low thermal resistance and thermal inertia; occupants complained of the poor indoor thermal environment [51,52]. To limit solar radiation heat gain, a model of the prefab housing units was fabricated with a 1 mm retro-reflective material integrated as the outermost layer of the prefab building envelope. The thermal behavior of the prefab with and without retro-reflective material was studied considering peak summer days and contrasted. The reflectivity of the retro-reflective material was 0.543.

The maximum outdoor air temperature difference was up to 10 °C in the daytime, and solar radiation peaked at 850 W/m^2 around 14:00 during the day. Generally, the indoor air temperature of the modular housing unit without retro-reflective material (Model 1) and modular housing unit with retro-reflective material (Model 2) fluctuated nearly in sync with the outdoor air temperature due to the low thermal resistance and the small thermal inertia of ultrathin envelope. It was observed that the indoor air temperature for Models 1 and 2 was almost the same with the outdoor air temperature on the first day, when the total horizontal radiation was generally low, due to cloud overcast. However, the indoor air temperature for Models 1 and 2 was higher than the outdoor air temperature when the total horizontal radiation was high. Additionally, it was deduced that the peak air temperature of Model 2, compared to Model 1, reduced by 7.1 °C for the second day and 7.4 °C for the fourth day [51].

Furthermore, at the microclimate scale, the use of reflective material could contribute to reducing the ambient air temperature due to the heat island effect [53]. However, unless the retro-reflective material is removable, this approach is only suitable during the summer, when the sun is high and incident total horizontal radiation would be high. Alternatively, a phase change material (PCM) used in passive latent heat thermal energy storage can control the temperature fluctuations of both winter and summer [54]. Two models of the prefab housing units were fabricated; Model 1 was a similar replica of the modular housing units in Wenchuan, while Model 2 had an exterior layer of PCM. The phase transition temperature range, latent heat, specific heat capacity, density, and thermal conductivity of the PCM were 18 °C–26 °C, 178.5 kJ/kg, 1785 J/kgK, 1300 kg/m^3, and 0.25–0.5 W/mK (depending on the phase state), respectively. The theoretically calculated thermal resistance and thermal inertia index of Models 1 and 2 were 1.282 (m^{2}K/W) and 1.374 (m^{2}K/W), 0.783 and 1.916, respectively [55]. Based on a validated simulation model with less than 5% error, Table 1 shows the results for Models 1 and 2 for different climatic zones in China.

Table 1. Temperature fluctuations based on climatic conditions [55].

Climate Zone	City	Season	T_{out}	T_{in1}	T_{in2}	ΔT_{day}	ΔT_{night}
Severe cold	Harbin	Winter	−25.1–11.0	−26.9–11.0	−18.7–14.7	5.7	8.7
		Transition	13.2–24.2	12.4–32.3	22–25.2	7.7	10.0
		Summer	14.4–28.4	14.8–35.9	25.0–29.5	7.4	9.9
Cold	Beijing	Winter	−7.3–8.4	−8.3–15.4	−0.5–5.1	11.5	8.4
		Transition	11.8–29.4	11.9–38.5	24.2–29.6	9.7	13.9
		Summer	27.2–34.8	27.2–42.0	33.6–37.4	4.9	7.5
Hot summer and cold winter	Shanghai	Winter	0.9–14.9	0.5–21.6	7.7–12.6	9.8	7.4
		Transition	17.4–20.7	16.2–27.6	23.7–25.3	2.7	8.1
		Summer	27.2–32.8	26.1–41.3	31.5–36.6	7.3	6.7
Hot summer and hot winter	Guangzhou	Winter	6.0–14.9	4.4–31.5	15.4–21.18	11.0	11.6
		Transition	13.8–25.8	12.7–36.3	22.1–27.9	9.7	9.8
		Summer	27.1–35.6	27.1–43.6	35.4–38.8	5.2	9.4
Temperate	Kunming	Winter	1.9–17.8	1.7–28.6	12.5–18.5	11.2	11.6
		Transition	13.3–23.7	12.0–32.5	21.2–25.3	8.1	9.8
		Summer	13.9–25.8	13.8–36.1	24.4–36.1	7.7	10.3

Where T_{out} is the outdoor air temperature, T_{in1} is the indoor air temperature of Model 1, T_{in2} is the indoor air temperature of Model 2, ΔT_{day} is the maximum temperature difference between Models 1 and 2 during daytime, and ΔT_{night} is the maximum temperature difference between Models 1 and 2 at night. Generally, the indoor air temperature fluctuations of Model 2 were smaller than those of Model 1. This was attributed to the PCM's heat storage performance. That is, the total attenuation degree of the wall-integrated PCM was 32.233 compared with a total delay time of 3.705 h; which is nearly 3 h longer than the wall without PCM. Furthermore, the indoor air temperature fluctuations in Model 1 for the five cities were higher than 10 °C, while the maximum indoor air temperature fluctuations in Model 2 was only 5.8 °C. For instance, in Beijing where the outdoor air temperature difference is the largest, the indoor air temperature difference of the two models was up to 13.9 °C at night and 9.7 °C during the day, in winter [55].

3.2. Acoustic Constraints

Consumers favor multi-unit dwellings in Korea. Weight impact sounds generally occur in multi-unit dwellings and are often caused by young children running or jumping. Such sounds are irregular noise that is unpleasant for the person living in the floor below. Based on computer simulations and mock-up models, the characteristics of vibration in floor structure and floor impact sound applicable for apartment houses with common modular structure were studied in [48].

It was found that the flooring with double concrete slabs had the highest performance in reducing heavyweight impact sounds. The use of mortar for insulation increased the vibration reduction effect. Heavyweight impact sound was affected significantly by the load on the flooring structure, whereas for lightweight impact sound the performance was higher with dry construction insulation structures compared to wet construction structures. Lightweight impact sound was caused by less impact on the floor, which could be why dry insulation construction had a better ability to absorb smaller vibrations.

3.3. Seismic Resistance

Modular steel buildings (MSBs) are being used increasingly for two- to six-story schools, apartments, dormitories, hotels, and in similar buildings where repetitive units are required. The lateral resistance of this unique building type is often achieved by adding diagonal braces [56–58]. In MSBs, modular units made of high strength and durable steel sections are built and finished under a controlled manufacturing environment and connected horizontally and vertically. Lateral loading on each floor is transferred through the horizontal connections (HC) to the modular-braced frame and then through the vertical connections (VC) to the foundation.

The following features specifically distinguish the MSB-braced frame from a regular steel-braced frame: (1) the existence of ceiling beams (CB) and ceiling stringers (CS) in the MSB frame system; (2) the floor beams (FB) may be set directly above the ceiling beams (CB) without mechanical connections, except at column locations; (3) the brace members in a typical modular steel frame do not intersect at a single working point which may lead to high seismic demands on the vertical connection (VC) between different units/modules; (4) the horizontal connections (HC) of separately-finished modules, shown in section A-A, are achieved by field-bolting of clip angles which are shop-welded to the floor beams; (5) the vertical connection (VC) between modular units, shown in section B-B, typically involves partial welding of the columns of a lower and an upper modules which may lead to independent upper and lower rotations at the same joint [59]. An experimental testing under repeated cyclic loading involved specimen of a one story MSB braced panel extracted and scaled from a typical four-story modular building frame.

The MSB structure showed stable ductile behavior up to very high drift levels; there was no significant strength and stiffness degradation with cycling and showed superior energy dissipation per cycle in each of the load steps. Seismic performance of a framed structure can be measured by its energy dissipation characteristics.

3.4. Energy Consumption

The existing building stock consumes a momentous quota of the total primary energy in many countries [60,61]. Additionally, many of the buildings that will exist in 2050 are the ones that exist today; thus, it is logical to focus on minimizing this energy demand. The refurbishment of the existing buildings has a fundamental role to meet stringent building standard requirements such as the recast Energy Performance of Buildings Directive within the European Union (EPBD 2010/31/EU) [62]; and without any doubt their great numerical superiority in relation to the new buildings represents an opportunity for achieving overall goals for energy savings and reduction of CO_2 emissions level globally. By combining modular construction with passive house standard, a modular passive house dorm that drastically reduced energy consumption was built. The building's heating and cooling was about $350/month as compared to $1200–$1400/month for a similar building according to use and floor area [63].

3.5. Life Cycle Analysis

Energy and materials are used, and corresponding environmental impacts incurred in large quantities throughout the life cycle of a building. While the occupancy phase of a building has been reported to account for about 70%–98% of a building's energy use, the construction phase has been found to account for about 2%–26%, depending on the reference building's design and intended use [64–69]. A survey of modular construction facilities revealed that practically all building materials were reused, with the exception of some gypsum (3.4–3.9 kg/m^2) and copper wire (0.15–0.48 kg/m^2), which are impractical to use in small sections. The life cycle analysis (LCA) for greenhouse gas (GHG) emissions considering materials production, transportation, and construction phases only for three modular and five on-site companies was investigated in [32], considering materials production, transport, and construction phases of the building life cycle. Mod1, Mod2, and Mod3 are LCA results based on data of modular construction companies, while Conv1, Conv2, Conv3, Conv4, and Conv5 are LCA results calibrated using data of on-site construction companies. Most data were reported as amount per week or year; thus, the authors scaled down annual production estimates of the construction companies to a common functional unit of 186 m^2; a two-story home model. The analysis showed that impacts from modular construction were, on average, lower than those from on-site construction, but that there were significant variations within each. For instance, in the case of Mod1, the company's emissions were significantly higher than the other two modular cases, and also higher than one of the five on-site companies. This particular facility was located in a rural area with a commute that is more than twice as long as for the other modular facilities, when normalized for production volumes. This factory also reported higher levels of electricity use than the others and was heating with fuel oil, again leading to increased levels of emissions. Energy use on-site and worker transport to the site were the most important categories for GHG emissions from conventional construction, which is intuitive as both represent direct combustion of fossil fuels. Therefore, reducing unnecessary worker trips, idling of equipment, and temporary heating through effective management practices remain the most important goals of low-carbon construction of homes. For example, Conv2 homes had low impacts relative to the set of conventional homes. In this particular case, the contractor worked with a local crew and so reported relatively short distances for worker transport to the construction site. This contractor also reported lower consumption of all fuels and electricity on-site than reported by other contractors. On average, GHG emissions from conventional construction were about 40% higher than for modular construction [32]. That said, depending on a reference building's design and use, the maintenance or occupancy, demolishing and rebuilding have large impacts in terms of embodied energy and LCA [67–70]; nonetheless, in [32] the authors did not consider whole cradle-to-grave LCA, the results could be different should other stages and environmental impacts been factored into the LCA. Over a 50 year life span LCA of modular and conventional housing (floor area of 135 m^2 in each case), it was found that the conventional home produced 2.5 times more construction waste than the modular home; additionally, the latter had 5% less total life cycle energy consumption and 5% less global warming potential than the former due to higher air tightness, although the study simplified assumptions [71].

4. Future Pathways

Prefabrication is a promising strategy to realize lean construction. Nowadays, prefabricated buildings are more focused on harmonization of various systems, minimizing thermal bridges, material efficiency, automation and optimization of production, time efficiency, and mass customization potentials, as compared to the earliest prefabricated buildings, which were more focused on satisfying a need for a booming housing demand within a short time limit. Among the various degrees of prefabrication, modular buildings maximize the most gain in time savings, because they are prefabricated to a greater degree of finish. Modular buildings are constructed based on local building codes and standards, in the same way as on-site built construction; thus, of equal quality to an on-site built construction. The materials and building envelope U-value requirements for both modular and on-site built construction are exactly the same for the same building use, with the exception of added structure to ensure that the modular building can be transported to the site without being damaged. Over the years, modular buildings have been designed astutely and constructed in such a manner that sometimes, it is impossible to tell the difference between a modular building and a conventional building. However, modular buildings are just not limited to design, manufacturing, and construction stages, but also maintenance during occupancy, deconstruction, and recycle or reuse [72]. Thus, similar to other industrialized products that usually bears a date of expiry or terms of use, a product lifecycle management or monitoring concepts needs to be implemented in modular buildings. Limited information and real-time data of modular buildings, covering all stages of the prefab has hampered a comprehensive cradle-to-grave LCA. In countries like Japan where modular buildings are advanced and hold a considerable market share, energy monitoring systems are often installed. Owners can choose to install photovoltaics for energy generation; this, of course, comes with an extra cost. In particular, the lack of uniform definition for various levels of prefabrication, and contextual differences surrounding mobile or manufactured homes and modular buildings, has contributed to misunderstandings of the technology [73]. Often confused with mobile or manufactured homes, modular buildings are built to IBC code, without chassis, and are set on-site permanently. The mass public needs to be educated on the clear difference between the two. Local building codes are often adopted for modular buildings; this hampers performance comparison of modular buildings with different geographic locations. A universally-binding standard for modular buildings, that factors geographic location, is clearly needed. Although often pricy, integrative 3D modeling software and project management software, which enable prompt sharing of designs, information, and results, are crucial to the success of prefab; more so are multi-objective algorithms that use mathematical approaches to solve real-time challenges [74], such as artificial neural networks used to predict the energy use of buildings [75]. Numerous projects incorporating prefab (on various levels) have already been completed successfully, and many more are planned. For instance, a 100-story tower using unitized system has been granted permit to be constructed in Melbourne; completion is due in 2019. Additionally, Chinese constructors have proposed a 220-story 838 m vertical city using modules; if permit is granted, it would become the world's tallest building. The potential for growth in the building economy; embracing greater productivity, total sustainability, improving workplace and workforce safety, was theoretical some ages ago, but is a practical realization today and hereafter, through prefab.

5. Summary and Outlook

The building industry is refabricating architecture through prefabrication. Similar to the automobile, shipbuilding, and aerospace industries, the construction industry aims to deliver an integrated prefab architecture that meets design requirements according to budget, quality specifications, as well as being on time. Using a case study based methodology, this study was designed to review the classification and actual performance of assorted prefabricated architecture. The earliest prefabricated buildings date back to the early seventeenth century, when houses were fabricated in England and shipped abroad. From literature, there are numerous benefits that can be realized by adopting prefabrication; notably, material and time efficiency, as well as reduced impacts of construction on the environment. Some authors have described prefabricated architecture on the modular scale as a sustainable approach. Nonetheless, there are some hindrances to prefabrication; notably, transportation restrictions due to module size and weight, high level of project coordination, negative market perception, and lack of general knowledge on prefab. Contrary to the general perception, designing with prefab components is not a barrier to creativity; rather, by standardizing typical prefab components and providing mass customization options, final costs are lowered through economies of high-volume work. The building envelope of prefabricated architecture should be tailored to suit local climatic conditions and building codes to ensure a comfortable indoor environment. On average, greenhouse gas emissions from conventional construction were higher than for modular construction. Measuring seismic performance of a modular steel brace frame structure by energy dissipation characteristics showed that the structure was stable and behaved in a ductile manner up to very high drift levels; there was no significant strength and stiffness degradation with cycling and showed superior energy dissipation per cycle in each of the load steps. For better implementation of prefabrication, early design stage should be considered and included in the construction methods. For the future, there is need to improve assurance of stakeholders by making known to the public performance data of existing prefabricated architecture; only then can prefabricated and conventional architecture be juxtaposed and quantified. Further, reducing costs through mass customization, promotions, and policies will be an important factor to widen the commercialization of prefab.

Acknowledgments: This work was supported by the Human Resources Development (No. 20134010200540) and the International Cooperation (No. 20148520011270) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea Government Ministry of Trade, Industry and Energy.

Author Contributions: This paper was a collaborative effort by all the authors. The authors contributed to different aspects of the research methodology and development, literature review, discussion and analyses.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chairman Zhang's Flatpack Skyscrapers. Available online: http://www.bbc.com/news/resources/idt-3cca82c0-af80-4c3a-8a79-84fda5015115 (accessed on 21 December 2015).
2. Blink and You'll Miss It 57-Storey Skyscraper Built in 19 Days. Available online: http://www.theurbandeveloper.com/build-skyscraper-19-days/ (accessed on 21 December 2015).
3. Broad Sustainable Building. Available online: http://www.61.187.123.140/enbroadcom/uploads/pdf/enhzdj.pdf (accessed on 21 April 2016).
4. Smith, R.E. *Prefab Architecture: A Guide to Modular Design and Construction*; John Wiley & Sons: New York, NY, USA, 2011.
5. Permanent Modular Construction. Annual Report. Available online: http://www.modular.org/ (accessed on 20 April 2016).
6. Pasquire, C.L.; Conolly, G.E. Leaner construction through off-site manufacturing. In Proceedings of the 10th Annual Conference, International Group for Lean Construction, Gramado, Brazil, 6–8 August 2002.
7. Bertelsen, S. Lean construction: Where are we and how to proceed. *Lean Constr. J.* **2004**, *1*, 46–69.
8. Höök, M.; Stehn, L. Applicability of lean principles and practices in industrialized housing production. *Constr. Manag. Econ.* **2008**, *26*, 1091–1100. [CrossRef]
9. Pan, W.; Gibb, A.G.; Dainty, A.R. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Constr. Manag. Econ.* **2007**, *25*, 183–194. [CrossRef]
10. Goodier, C.; Gibb, A. Future opportunities for offsite in the UK. *Constr. Manag. Econ.* **2007**, *25*, 585–595. [CrossRef]
11. Schoenborn, J.M. A Case Study Approach to Identifying the Constraints and Barriers to Design Innovation for Modular Construction. Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 27 April 2012. Available online: https://theses.lib.vt.edu/theses/available/etd-05082012-010848/ (acccessed on 14 June 2016).
12. Velamati, S. *Feasibility, Benefits and Challenges of Modular Construction in High Rise Development in the United States: A Developer's Perspective*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2012; Available online: https://dspace.mit.edu/handle/1721.1/77129 (accessed on 14 June 2016).
13. Park, M.; Ingawale-Verma, Y.; Kim, W.; Ham, Y. Construction policymaking: With an example of singaporean government's policy to diffuse prefabrication to private sector. *KSCE J. Civ. Eng.* **2011**, *15*, 771–779. [CrossRef]
14. Delfani, M.; Ibrahim, R.; Raschid, M.Y.M. Towards designing modular of industralized building systems. *J. Teknol.* **2016**. [CrossRef]
15. Patlakas, P.; Menendez, J.; Hairstans, R. The potential, requirements, and limitations of BIM for offsite timber construction. *Int. J. 3-D Inf. Model.* **2015**, *4*, 54–70. [CrossRef]
16. Ramaji, I.J.; Memari, A.M.; Solnosky, R. Integrated BIM platform for multi-story modular building industry. In Proceedings of the PHRC 2nd Annual Residential Building Design & Construction Conference, State College, PA, USA, 19–20 February 2014.
17. Vernikos, V.; Goodier, C.I.; Gibb, A.G. *Building Information Modelling and Offsite Construction in Civil Engineering*; ARCOM: Loughborough, UK, 2013; Available online: https://dspace.Iboro.ac.uk/dspace-jspui/handle/2134/14483 (accessed on 14 June 2016).
18. Nadim, W.; Goulding, J.S. Offsite production in the UK: The way forward? A UK construction industry perspective. *Constr. Innov.* **2010**, *10*, 181–202. [CrossRef]
19. Blismas, N.G.; Pendlebury, M.; Gibb, A.; Pasquire, C. Constraints to the use of off-site production on construction projects. *Archit. Eng. Des. Manag.* **2005**, *1*, 153–162. [CrossRef]
20. UNFCCC COP 31, Adoption of the Paris Agreement. Available online: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf (accessed on 21 December 2015).

21. Matoski, A.; Ribeiro, R.S. Evaluation of the acoustic performance of a modular construction system: Case study. *Appl. Acoust.* **2016**, *106*, 105–112. [CrossRef]
22. Arif, M.; Egbu, C. Making a case for offsite construction in China. *Eng. Constr. Archit. Manag.* **2010**, *17*, 536–548. [CrossRef]
23. Jaillon, L.; Poon, C. Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Autom. Constr.* **2014**, *39*, 195–202. [CrossRef]
24. Jaillon, L.; Poon, C.; Chiang, Y. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Manag.* **2009**, *29*, 309–320. [CrossRef] [PubMed]
25. Musa, M.F.; Mohammad, M.F.; Mahbub, R.; Yusof, M.R. Enhancing the quality of life by adopting sustainable modular Industrialised Building System (IBS) in the malaysian construction industry. *Proced. Soc. Behav. Sci.* **2014**, *153*, 79–89. [CrossRef]
26. Noguchi, M.; Hernàndez-Velasco, C.R. A mass custom design approach to upgrading conventional housing development in Mexico. *Habitat Int.* **2005**, *29*, 325–336. [CrossRef]
27. Benros, D.; Duarte, J. An integrated system for providing mass customized housing. *Autom. Constr.* **2009**, *18*, 310–320. [CrossRef]
28. Tam, V.W.; Tam, C.M.; Zeng, S.; William, C.Y.N. Towards adoption of prefabrication in construction. *Build. Environ.* **2007**, *42*, 3642–3654. [CrossRef]
29. Jaillon, L.; Poon, C. The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Autom. Constr.* **2009**, *18*, 239–248. [CrossRef]
30. Lawson, R.M.; Ogden, R.G.; Bergin, R. Application of modular construction in high-rise buildings. *J. Archit. Eng.* **2011**, *18*, 148–154. [CrossRef]
31. Adekunle, T.; Nikolopoulou, M. Post-occupancy and indoor monitoring surveys to investigate the potential of summertime overheating in UK prefabricated timber houses. In Proceedings of the 8th Windsor Conference, Windsor, UK, 10–14 April 2014.
32. Quale, J.; Eckelman, M.J.; Williams, K.W.; Sloditskie, G.; Zimmerman, J.B. Comparing environmental impacts of building modular and conventional homes in the United States. *J. Ind. Ecol.* **2012**, *16*, 243–253. [CrossRef]
33. Kelly, B. *The Prefabrication of Houses; The Technology Press of The Massachusetts Institute of Technology*; John Wiley and Sons, Inc.: New York, NY, USA; Chapman & Hall, Ltd.: London, UK, 1951.
34. Lauren, H. High Speed High Rise: The Earthquake-Proof Skyscrapers Built in 15 Days. Available online: http://www.wired.co.uk/article/high-speed-high-rise (accessed on 21 December 2015).
35. WoodWorks, Putting Pieces Together; Technical Report. Available online: http://www.woodworks.org/ (accessed on 20 April 2016).
36. The Meridian First Light House. Available online: http://www.firstlightstudio.co.nz/the-meridian-first-light-house/#top (accessed on 20 April 2016).
37. US Department of Energy Solar Decathlon. Final Results. Available online: http://www.solardecathlon.gov/past/2011/final_results.html (accessed on 20 April 2015).
38. Bell, P. *Prefabrication in New Zealand: New Housing Types + Case Studies*; Prefab NZ, Presentation Material: Seoul, Korea, 2014; Available online: www.prefabnz.com (accessed on 14 June 2016).
39. Falk, R.H.; McKeever, D.B. Recovering Wood for Reuse and Recycling: A United States Perspective. In Proceedings of the European COST E31 Conference : Management of recovered wood recycling bioenergy and other options Construction, Thessaloniki, Greece, 22–24 April 2004; pp. 29–40. Available online: www.treesearch.fs.fed.us/pubs/7100 (accessed on 14 June 2016).
40. Lori, Z. Cantilevered Shipping Container Coffee Shop Pops Up in Johannesburg. Available online: http://inhabitat.com/cantilevered-shipping-container-coffee-shop-pops-up-in-johannesburg/ (accessed on 31 May 2016).
41. Noguchi, M. The effect of the quality-oriented production approach on the delivery of prefabricated homes in Japan. *J. Hous. Built Environ.* **2003**, *18*, 353–364. [CrossRef]
42. Kurt, M.; Gul, M.S.; Gul, R.; Aydin, A.C.; Kotan, T. The effect of pumice powder on the self-compactability of pumice aggregate lightweight concrete. *Constr. Build. Mater.* **2016**, *103*, 36–46. [CrossRef]
43. Martins, P.F.; de Campos, P.F.; Nunes, S.; Sousa, J.P. Expanding the material possibilities of lightweight prefabrication in concrete through robotic hot-wire cutting-form, texture and composition. In Proceedings of 33rd Annual Conference, eCAADe, Vienna, Austria, 16–18 September 2015.

44. Hasanbeigi, A.; Price, L.; Lin, E. Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6220–6238. [CrossRef]
45. Kim, T.; Tae, S.; Roh, S. Assessment of the CO_2 emission and cost reduction performance of a low-carbon-emission concrete mix design using an optimal mix design system. *Renew. Sustain. Energy Rev.* **2013**, *25*, 729–741. [CrossRef]
46. Miller, S.A.; Horvath, A.; Monteiro, P.J.M.; Ostertag, C.P. Greenhouse gas emissions from concrete can be reduced by using mix proportions, geometric aspects, and age as design factors. *Environ. Res. Lett.* **2015**, *10*, 114–017. [CrossRef]
47. García-Segura, T.; Yepes, V.; Alcalá, J. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. *Int. J. Life Cycle Assess.* **2014**, *19*, 3–12. [CrossRef]
48. Lee, W.-H.; Kim, K.-W.; Lim, S.-H. Improvement of floor impact sound on modular housing for sustainable building. *Renew. Sustain. Energy Rev.* **2014**, *29*, 263–275. [CrossRef]
49. Newton, C. *Prefabrication Perspectives from Australia*; Presentation Material: Seoul, Korea, 2014.
50. Inside One9: The Six Star, Prefab Apartments in Moonee Ponds. Available online: http://www.theurbandeveloper.com/inside-one9-the-six-star-prefab-apartments-in-moonee-ponds/ (accessed on 21 December 2015).
51. Meng, X.; Wang, C.; Liang, W.; Wang, S.; Li, P.; Long, E. Thermal performance improvement of prefab houses by covering retro-reflective materials. *Proced. Eng.* **2015**, *121*, 1001–1007. [CrossRef]
52. Chen, H.; Long, E.; Huang, L.; Wang, T. Discussion of the indoor thermal environment of prefab house in winter of Chengdu. *Refrig. Air Cond.* **2011**, *121*, 1628–1634.
53. Synnefa, A.; Santamouris, M.; Livada, I. A study of the thermal performance of reflective coatings for the urban environment. *Solar Energy* **2006**, *80*, 968–981. [CrossRef]
54. Soares, N.; Costa, J.J.; Gasper, A.R.; Santos, P. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. *Energy Build.* **2013**, *59*, 82–103. [CrossRef]
55. Li, Y.; Wang, Y.; Meng, X.; Wang, M.; Long, E. Research on indoor thermal environment improvement of lightweight building integrated with phase change material under different climate conditions. *Proced. Eng.* **2015**, *121*, 1628–1634. [CrossRef]
56. Annan, C.; Youssef, M.; el Naggar, M. Seismic overstrength in braced frames of modular steel buildings. *J. Earthq. Eng.* **2008**, *13*, 1–21. [CrossRef]
57. Annan, C.; Youssef, M.; el Naggar, M. Analytical investigation of semi-rigid floor beams connection in modular steel structures. In Proceedings of the 33rd Annual General Conference of the Canadian Society for Civil Engineering, Toronto, ON, Canada, 2–4 June 2005.
58. Annan, C.; Youssef, M.; el Naggar, M. Seismic performance of modular steel braced frames. In Proceedings of the Ninth Canadian Conference on Earthquake Engineering, Ottawa, ON, Canada, 26–29 June 2007.
59. Annan, C.; Youssef, M.; el Naggar, M. Experimental evaluation of the seismic performance of modular steel-braced frames. *Eng. Struct.* **2009**, *31*, 1435–1446. [CrossRef]
60. Fokaides, P.A.; Papadopoulos, A.M. Cost-optimal insulation thickness in dry and mesothermal climates: Existing models and their improvement. *Energy Build.* **2014**, *68*, 203–212. [CrossRef]
61. Zhang, Y.; He, C.-Q.; Tang, B.-J. China's energy consumption in the building sector: A life cycle approach. *Energy Build.* **2015**, *94*, 240–251. [CrossRef]
62. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), Official Journal of the European Union, 153 (2010) 13–35. Available online: http://www.eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF (accessed on 20 April 2016).
63. Institute, M.B. Modular Advantage. Available online: http://www.modular.org/HtmlPage.aspx?name=Modular_Passive_House_Dorm_MA (accessed on 31 May 2016).
64. Adalberth, K. Energy use during the life cycle of single-unit dwellings: Examples. *Build. Environ.* **1997**, *32*, 321–329. [CrossRef]
65. Scheuer, C.; Keoleian, G.A.; Reppe, P. Life cycle energy and environmental performance of a new university building: Modeling challenges and design implications. *Energy Build.* **2003**, *35*, 1049–1064. [CrossRef]
66. Keoleian, G.A.; Blanchard, S.; Reppe, P. Life-cycle energy, costs, and strategies for improving a single-family house. *J. Ind. Ecol.* **2000**, *4*, 135–156. [CrossRef]

67. Cole, R.J.; Kernan, P.C. Life-cycle energy use in office buildings. *Build. Environ.* **1996**, *31*, 307–317. [CrossRef]
68. Cole, R.J. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. *Build. Environ.* **1998**, *34*, 335–348. [CrossRef]
69. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr. Build. Mater.* **2009**, *23*, 28–39. [CrossRef]
70. Itard, L.; Klunder, G. Comparing environmental impacts of renovated housing stock with new construction. *Build. Res. Inf.* **2007**, *35*, 252–267. [CrossRef]
71. Kim, D. *Preliminary Life Cycle Analysis of Modular and Conventioinal Housing in Benton Harbor, Michigan*; University of Michigan: Ann Arbor, MI, USA, 2008.
72. Ramaji, I.J.; Memari, A.M. Product architecture model for multistory modular buildings. *J. Constr. Eng. Manag.* **2016**. [CrossRef]
73. Kamar, A.M.; Hamid, Z.A.; Azman, N.A. Industrialized Building System (IBS): Revisiting issues of definition and classification. *Int. J. Emerg. Sci.* **2011**, *1*, 120–132.
74. Zavala, G.R.; Nebro, A.J.; Luna, F.; Coello, C.A. A survey of multi-objective metaheuristics applied to structural optimization. *Struct. Multidiscip. Opt.* **2014**, *49*, 537–558. [CrossRef]
75. Dodier, R.H.; Henze, G.P. Statistical analysis of neural networks as applied to building energy prediction. mboxemphJ. Solar Energy Eng. **2004**, *126*, 592–600. [CrossRef]