

Entry

Japanese Prefabricated Housing Manufacturers

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Definition: Japanese prefabricated housing manufacturers have gained international recognition for their innovative approaches to the whole design process, ranging from initial design to innovative cutting-edge technologies, state-of-the-art automated production lines, meticulous workmanship, and mass customisation. In this entry, three manufacturers (Daiwa House, Sekisui House, and Misawa Homes) were selected as case studies for close examination. By studying these leading companies, researchers and industry professionals can gain valuable insights into best practices, challenges, and innovations within the Japanese prefabricated housing sector. The research methods involved a desktop study of available information on websites, articles, and reports, as well as undertaking two study tours on residential sustainable design in Japan in 2022 and 2023. These three manufacturers were discussed and compared with respect to their development trajectories, design customisation, research capabilities and technological advancements, sustainable initiatives and procurement, as well as their after-sale services. They have demonstrated their adaptability and flexibility in response to natural disasters and the transformation of the needs in society. They are all keen on reducing the environmental impacts of their work towards zero carbon emissions and a sustainable future.

Keywords: prefabrication; mass customisation; earthquake resistance; post-disaster recovery; sustainable procurement; post-sale service; corporate social responsibility; zero deforestation; zero emissions; carbon neutrality

1. Introduction

Japanese housing manufacturers are regarded as world leaders in prefabrication [1]. After the end of the Second World War, Japan opted for prefabricated construction for mass production to address the substantial housing deficits in society. Early examples include the prefabricated A-frame prototype house by Junzo Sakakura and the Prefabrication Maekawa Ono San-in Kōgyō (PREMOS) by Kunio Maekawa in the 1940s [2]. The mass production of housing led to shorter timeframes and lower construction costs but resulted in homogenous and identical products [3].

For facilitating the prefabrication and modernisation of the construction industry, the Japan Prefabricated Construction Suppliers and Manufacturers Association was set up in 1963 by the Ministry of International Trade and Industry and the Ministry of Construction [4]. The Japanese Government exhibited the “Home Core” House of Misawa Homes as a showcase of the quality of housing prefabrication to the public at the Japan World Exposition in Osaka in 1970 and launched the “House 55” nationwide competition in the 1970s to promote the improvement of the quality of work produced by the Japanese housing manufacturers [5].

Following the booming economy and the growing desires of the middle class for home ownership in Japan in the 1960s and 1970s, Japanese housing manufacturers shifted the focus from housing quantity to cope with the huge demand for post-war

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reconstruction to higher quality in design, production, and service to accommodate the individual needs of their customers. This signifies the transition from mass production to mass customisation.

The basic idea of mass customisation was first introduced by the American futurist Alvin Toffler as a technological capability in his best-selling book *Future Shock* in 1970 [6]. In 1987, Boston University Research Professor Stanley M. Davis further elaborated the notion of mass customisation:

... the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously they can be treated individually as in customized markets of pre-industrial economies. [7]

Influenced by Davis's book, Joseph Pine II refined mass customisation and developed strategies for mass customising products and services. Instead of focusing on volume sales of standardised products under mass production, it is important to have innovation in the whole process from design to delivery, with continual incremental improvements supported by research and development (R&D), to enhance customer satisfaction. Creating modular components is regarded as the most effective way to achieve mass customisation to minimise the cost and maximise the variations in end products to cater to individual customers [8].

Japanese housing manufacturers have applied mass customisation and developed a total coordination approach to the design, production, and marketing of prefabricated houses [9]. Prefabricated homes accounted for approximate 13.1% of the total residential construction started in Japan in 2022 [10]. Compared with traditional on-site construction practice, factory production of modular housing components has various benefits. Under optimal conditions and rigorous control in factories, enhanced quality of work is obtained, leading to better house quality in terms of air-tightness, energy consumption, and insulation [11,12]. With the use of automation and robot-equipped production lines, meticulous precision is achieved and construction waste is significantly minimised [13]. The mass production of modular components reduces the cost involved, while the combination of different components offers various options for customers in response to their respective demands. Customer-oriented approaches focusing on quality and value for money are adopted to prioritise customers' choices [14]. Customers are encouraged to engage throughout the whole design stage in customising their new houses according to their desires and expectations. Catalogues, interactive exhibitions, display homes, and computer-aided software facilitate customers making decisions and visualising the outcome for modification and optimisation. Based on the selected components, a cost estimate is provided for customers to consider whether to upgrade some of the standard items to optional features within their budget for better quality and cost-effective performance [15]. The selling price of Japanese prefabricated houses tends to be around 8% higher than site-built houses, yet their quality is higher through the cost-performance marketing and value-added production approach [3].

Large Japanese housing manufacturers have resources and funding to heavily invest in R&D with in-house research facilities to pursue continuous improvement and innovations [3]. Since Japan is prone to natural disasters, such as earthquakes, typhoons, and floods, well-established manufacturers have set up their own quality standards for enhanced performance with respect to earthquake resistance, structural integrity, and durability. Post-sale long-term warranty provides quality assurance to boost customer confidence. Apart from marketing strategies to deliver innovative and high-quality houses, some Japanese housing manufacturers are proactive in promoting sustainable development in the construction industry by setting sustainability targets and implementing sustainable procurement practices under effective environmental, social, and corporate governance.

This entry provides a review of the key innovative and sustainable approaches of Japanese prefabricated housing manufacturers and compares their different practices

through case studies. The materials and research methods of this entry are shown in the “Supplementary Material” section at the end of this entry.

2. Case Studies of Japanese Prefabricated Housing Manufacturers

The case studies of the three selected prefabricated housing manufacturers in Japan are discussed in detail in this section.

2.1. Daiwa House

2.1.1. Development Trajectories

In 1955, Daiwa House was founded and launched the prefabricated Pipe House series. Steel pipe columns and trusses with 22 to 27mm in diameter and standardised components of frames, roofs, walls, and floors were mass-produced in the factory, with guaranteed quality. These components could be easily and quickly assembled on site to tackle the huge housing demand under post-war reconstruction in Japan. The construction technology of the small-scale Pipe House was subsequently developed and applied for the large-scale structure of a sake brewery in Nishinomiya City, Hyogo Prefecture, in 1957. Following the intense cyclone strike of Typhoon Vera (also known as the Isewan Typhoon) in 1959, Pipe Houses were assembled as emergency shelters for providing temporary housing accommodations to those in need [16].

Daiwa House developed the Midget House within a 10m² floor area as an additional children’s room in 1959 and the Super Midget House with toilet and kitchen provisions in 1960 [17]. The Midget House series adopted the post-and-beam construction system using light-gauge steel. Since the Midget House was sold at an affordable price and could be erected within three hours, it was well-received by customers and was suitable for extension of houses and schools to cope with the post-war baby boom. Both the Pipe House and the Midget House were registered as important historical heritage under the category of “early prefabricated houses” by the National Museum of Nature and Science in Tokyo in 2011 (registration number: 00081) [18].

Following the Midget House, Daiwa House has developed different house series, including the panel-prefabricated Type A House using 1,260mm modules (1962), Type B House using 940mm modules (1967) [17], the computer-aided design of Type C House (1970), the energy-efficient Solar DH-1 house (1977), and the environmentally-friendly housing of Kankyo-Kobo (2000) [19]. The “xevo” brand of single-family houses was launched in 2006, with significant improvement in durability, earthquake resistance, insulation, and energy performance [20]. In 2014, the smart and eco-friendly community, SMA x ECO Town at Harumidai, Sakai City, in Osaka Prefecture, was completed, in which all 65 single-family houses and a community centre were equipped with photovoltaic power generation with lithium-ion storage batteries (POWER iE6) for achieving net-zero energy consumption [21]. The SMA x ECO Town at Harumidai generated 15% more energy than its consumption and reduced 95% carbon emissions from energy generation in the first three years after completion [22]. Besides single-family houses, Daiwa House offers both rental housing and condominiums. Daiwa House launched the net-zero energy rental housing TORISIA in 2022 and has adopted the net-zero energy specifications to the PREMIST-brand condominiums from 2024 onwards [23].

2.1.2. Design Customisation

To address customers’ various needs and requirements, Daiwa House has developed the useful-friendly online platform “LiveStyle Partner” [24]. Through a well-established database of numerous housing information, customers can input their preferences to the online platform to search for their ideal floor plans and favourite images of a living environment. Based on customers’ preferences, Daiwa House will deliver customised design to match those preferences accordingly. For better visualisation of the design outcome, Daiwa House has introduced the “3D Fast Plan” to enable customers to experience both

the exterior and interior of the house design in virtual reality. This shortens the time required for reaching a design agreement [25]. For catering to families with different budgets, Daiwa House offers single-family one- to two-storey house designs in both timber (xevo GranWood) and light-gauge steel frame (xevo Σ) as well as respective luxurious versions (Premium GranWood and xevo Σ Premium) [26–28]. A three-storey heavy-gauge steel-frame house design (Skye3) for single families is also available to cope with tight site areas [29].

2.1.3. Research Capabilities and Technological Advancements

Daiwa House first set up the Central Testing Laboratory in the Nara Factory in 1973 to conduct performance testing of components and full-size houses. The Central Testing Laboratory and the Research and Development Department were merged in 1980 to strengthen Daiwa House's research capabilities and technical advancements [30]. The Central Research Laboratory of Daiwa House was established in 1994 to conduct research in residential and commercial buildings as well as urban development and town planning. It also serves as an open laboratory to allow customers to experience the latest technology and provide feedback for continuous improvement [31]. The Mirai Kachi Kyoso Centre Kotokurie in Nara was completed in 2021 as an educational and training facility for staff and the general public to co-create value for the future [32] (Figure 1).

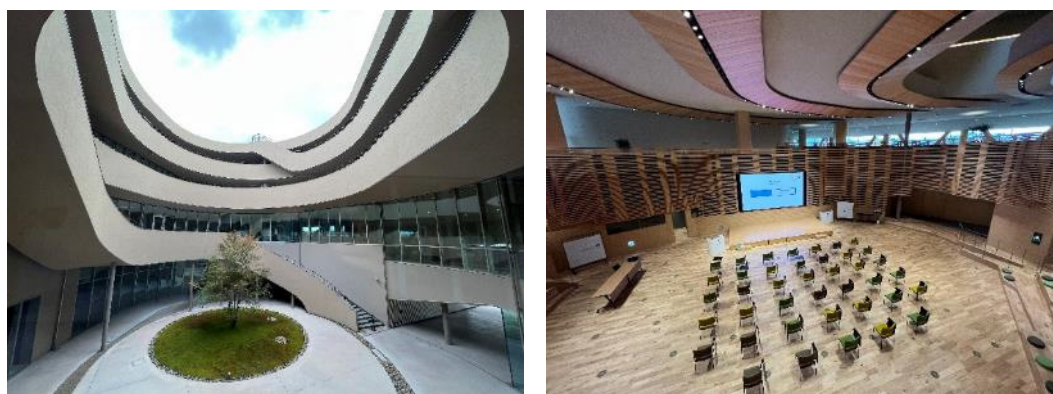


Figure 1. Kotokurie educational and training facility of Daiwa House.

Through research and development, Daiwa House has introduced various innovative construction technologies and enhanced its design capabilities using prefabricated timber and steel frames, together with modular unit prefabrication for condominiums [33]. The xevo Σ earthquake-resistant technology developed in 2014 is equipped with energy-absorbing load-bearing walls to absorb seismic energy to prevent catastrophic structural damage [34]. Since 2017, the GranWood construction technology has been applied to the highest grade custom-built timber residences using 100% high-quality local structural laminated timber with carefully designed hardware and joining accessories [35]. The xevo Σ Premium steel-frame houses were launched in 2018 with a high ceiling height of 2.72m, durable deep-engraved exterior ceramic wall materials, high air-tightness, and good earthquake resistance performance [28]. The Skye3 heavy-gauge steel-frame construction technology for three-storey residences was launched in 2020, with a wide span up to 6.37m, a double-height atrium, and large openings for spatial flexibility and vertical connectivity [29].

Daiwa House has been proactive in post-disaster recovery since the use of Pipe Houses as emergency shelters after the cyclone strike in 1959. Following the Great Hanshin Awaji Earthquake in 1995, more than 14,000 temporary house units were erected [19]. Additionally, 11,051 temporary homes were built for those affected by the Great East Japan Earthquake with immense tsunami waves in 2011 [36]. Compared with a standard house requiring nine to ten weeks to complete, it only took three to four weeks to erect a

provisional housing complex [37]. Facing the Kumamoto Earthquake in 2016, the planning time for preparing a site layout and overall plan for emergency housing was reduced to one hour by Daiwa House in collaboration with Kumamoto University [38]; this has greatly shortened the timeframe required and enables prompt response to cope with natural disasters. Daiwa House has also developed agri-cubes for hydroponic planting (Figure 2).



Figure 2. Daiwa House's research of agri-cubes for hydroponic planting.

2.1.4. Sustainable Initiatives and Procurement

The long-term target of “Challenge Zero 2055” was set in 2016 to signify the 100th anniversary of Daiwa House in 2055. Under this long-term vision, there are goals in four priority areas: climate change mitigation; harmony with nature; natural resource conservation; and chemical pollution prevention towards zero environmental impacts for the whole life cycle involving procurement, production, transportation, construction, habitation, renovation, and demolition [39]. Regarding procurement, Daiwa House established the Corporate Social Responsibility (CSR) Procurement Guidelines for suppliers in 2015, which have been substantially revised and renamed as the Supply Chain Sustainability Guidelines in 2023 to include a Business Partner Code of Conduct, Corporate Activity Guidelines, and Guidelines for Products (Chemical Substance Management Guidelines and Biodiversity Guidelines for Timber Procurement), covering comprehensive environmental and social responsibilities in terms of environmental protection, human rights, and occupational safety [40]. In 2022, the sustainable timber procurement rate of Daiwa House was 96.9%, in which suppliers of the remaining 3.1% C-ranked timber were required to submit plans for improvement towards the objective of the zero deforestation policy [41]. Through the promotion of new house products, such as the GranWood timber-frame house series, the xevoΣlight-gauge steel-frame house series, and the Skye3 heavy-gauge three-storey steel-frame house series, the rate of newly constructed net-zero-energy single-family houses in 2022 was 84%, which aims to achieve 100% by 2030 [25]. The rate of newly constructed net-zero-energy rental housing and condominiums in 2022 were 14.2% and 67.5%, respectively [23].

2.1.5. After-Sale Services

For ensuring that houses are properly maintained, Daiwa House provides a 30-year warranty for structural elements and waterproofing performance of newly built houses, with two 15-year extended warranty periods based on the maintenance plan and inspection program. After 60 years, a durability performance survey can be conducted as per customer request for further extension of the warranty period subject to necessary

maintenance work required. A 10-year warranty is also provided for equipment covering heaters and air-conditioners, intercoms, kitchen, vanities, and water closets [41]. Long-term warranty and comprehensive after-sale service foster greater confidence among customers.

2.2. Sekisui House

2.2.1. Development Trajectories

In the midst of a housing shortage in Japan, Sekisui House was established in 1960 by Sekisui Chemical Company for creating a new market for plastic products in panel-based prefabrication [42]. The light-gauge steel-frame Model A House was launched in 1960 and was recognised as a tangible cultural property (building) by Japan's Agency of Cultural Affairs in 2016 [43]. The Model B House was introduced in 1961 using 1,000mm modules, leading to more generously proportioned spaces than traditional three-shaku modules (1 shaku = 303mm) [41]. The Model B House was a forerunner in the Japanese housing industry of using one-metre modules [44], which are widely adopted in current house series [17].

Subsequent to the Model B House, Sekisui House has developed various house series using different materials. Timber-frame houses include Model W (1977), Shawood (1995), and Gravis Villa (20th anniversary edition of Shawood, 2015); light-gauge steel-frame houses include IS Flat (1984), Centrage Σ (1996), and IS Stage (30th anniversary edition of the IS series, 2014); and three-storey heavy-gauge steel-frame houses include Vantage 3 (1988) and Biena (1999) [43]. For providing an enabling living environment for persons with disabilities, Sekisui House built the first model house in Japan for people with disabilities in 1981 [45]. A universal design based on the lifetime housing concept has been implemented to all detached houses since 2002 [43]. Sekisui House also delivered the eco-friendly house series, Model PSH21 (passive solar house), in 1982, which was the first to be certified by the Minister of Construction to have the best energy-saving performance in 1985 [45]. Solar- Σ A House with a roof-integrated photovoltaic power generation system was introduced in 1997 [46]. Sekisui House also offers rental housing and condominiums apart from single-family houses. Sha Maison rental housing was launched in 2000, and zero-energy rental housing units have been offered since 2018. Sekisui House has launched zero-energy Grande Maison condominiums in Tokyo, Osaka, Nagoya, and Fukuoka since 2019 [41].

2.2.2. Design Customisation

Sekisui House set up the Home Amenities Experience Studio (Nattoku Kobe Studio) to enable customers to gain their first-hand experience of various house settings and component performance before making their personal decisions for design customisation [47]. Moreover, there are five Tomorrow's Life Museums across Japan (Kansai, Kanto, Tohoku, Shizuoka, and Yamaguchi) with experienced-based facilities and display homes for the general public to visit (Figures 3 and 4). "Everyone's House! Houses of the Future!" classes are organised to encourage students to learn how to design their own house of the future [48]. Sekisui House also organises Home Visit Days for customers to visit their completed houses and engage with homeowners to have a better understanding of the design customisation process from a user's perspective [41]. Similar to Daiwa House, Sekisui House offers single-family house design in timber (one to three-storey Shawood) [49], light-gauge steel frames with one to two storeys in height, and heavy-gauge steel-girder rigid frames with three to four storeys in height [50,51].



Figure 3. Exterior and interior of a display home of Sekisui House.



Figure 4. Tomorrow's Life Museum of Sekisui House.

2.2.3. Research Capabilities and Technological Advancements

In 1990, Sekisui House established the Comprehensive Housing R&D Institute in Kyoto to commemorate its 30th anniversary. At the R&D Institute, durability tests of building components and vibration tests of building structures are conducted for performance evaluation, whereas new technologies are developed for industry innovation [45]. In 2018, the Human Life R&D Institute was opened as the first institute specialised in research on living and lifestyles to foster happiness and wellbeing in Japan [41].

Sekisui House adopts both prefabricated timber and steel frames as construction systems similar to Daiwa House and has developed Dyne precast concrete wall panels for external finishes [41]. Through research and development, Sekisui House has developed innovative technologies for enhancing safety and comfort. The Sekisui House Earthquake Absorbing System (SHEQAS) was released in 2007 and has been accredited by the Japanese Government to convert seismic waves into heat energy and absorb building movement to reduce deformation by approximately 50% [52]. The Hybrid SHEQAS was introduced in 2013 to facilitate large windows and door openings for a higher degree of design flexibility while maintaining the required seismic control capability [44]. To have better performance in reducing heat loss in winter and resisting heat from entering indoors in summer, the Gururin Dannetsu thermal insulation system was developed in 2010 to achieve greater indoor thermal comfort and higher energy-saving efficiency [45]. In 2011, the Airkis indoor air system was launched to minimise the concentration of five types of indoor substances (formaldehyde, toluene, xylene, ethylbenzene, and styrene) to less than 50% of the standards specified by the Ministry of Health, Labour and Welfare guidelines to enable healthy living against sick building syndrome [47]. To have greater spatial design freedom and more flexible window positioning, the Flexible β System has been

implemented since 2017, involving the use of heavy-gauge steel-frame technology for three- and four-storey housing construction [53].

Facing the ageing population in Japan with longer life expectancies, Sekisui House launched the Platform House Concept at the Consumer Electronics Show (CES) at Las Vegas in the US in 2019 [53]. Through the use of non-contact sensors and the In-Home Early Detection Network (HED-Net), the house environment data and residents' biodata are constantly collected for health monitoring; preventive care; and early detection of emergency issues, such as stroke, acute myocardial infarction, accidental fall, and drowning in a bathtub [54]. Once an abnormality is detected, the emergency call centre will be notified; the operator will then confirm the residents' health status and arrange ambulance services whenever necessary. The smartphone app Platform House touch was further introduced in 2021 to enable home owners to have remote control of the house and monitor the living environment for home security and safety [48].

2.2.4. Sustainable Initiatives and Procurement

In line with the 1997 Kyoto Protocol, which has been implemented since 2005, Sekisui House announced the Environmental Future Plan in 1999, followed by the Declaration of Sustainability in 2005 to demonstrate their commitment to making concerted efforts for sustainable development, with the four key values of the environment, society, economy, and residential homeowners' needs [45]. For the 34th G8 Summit at Tokyo in Hokkaido in 2008, the Zero Emission House was built to showcase the technologies for achieving a zero-emission living environment. Sekisui House was the first among other Japanese organisations in the housing industry to be the Eco-First Company certified by the Ministry of the Environment in 2008 [46]. The Green First Model was introduced in 2009 to enable house owners and residents to have a comfortable, economical, and eco-friendly living by reducing energy consumption through thermal insulation and energy-saving technology, rather than generating electricity through the use of photovoltaic systems or Ene-Farm household fuel cell systems [41]. In response to the rolling blackouts caused by the Great East Japan Earthquake in 2011, the Green First Hybrid Model was launched in 2011 to equip houses with three different types of cells (photovoltaic, fuel, and storage) to ensure self-sustained living during a disaster-induced blackout and enable optimal energy consumption [47]. Based on the previous Green First initiatives, the Green First Zero Model was released in 2013 for residents to enjoy quality living while achieving energy self-sufficiency. Through high-performance thermal insulation and high-efficiency equipment, household energy use can be reduced to 50% of conventional levels, and the remaining 50% electricity is produced by home generation (photovoltaic, fuel, and storage cells) for reducing primary energy consumption to zero on a net basis [44].

Sekisui House is a pioneer in recycling 100% of building waste at 23 Resources Recycling Centres across Japan, including the Resource Wellspring Resource Recycling Centre in the Eco First Park [41] (Figure 5). Waste measurement systems are used at new construction sites for accurate tracking of the amount of waste generated with IC tags for traceability before sorting it into 27 categories. The waste collected from construction sites is further separated into 80 sub-categories at the Resources Recycling Centres for recycling either in-house or by contractors [55]. Through waste recycling, Sekisui House has developed its own recycled products, such as Platama Powder, an athletic field marking chalk [48].



Figure 5. Eco First Park of Sekisui House with recycling facilities.

In 2016, Sekisui House formulated the Sustainability Vision 2050, which was elaborated in the Sustainability Report 2017 [56]. This long-term vision leads the way to (1) a decarbonised society by eliminating carbon dioxide emissions from the entire housing lifecycle; (2) a resource-recycling society by promoting a circular economy; (3) a society with co-existence between humans and nature by committing to the procurement of FairWood products for zero deforestation; (4) a healthy and longevity society by providing age-friendly, safe, and secure housing solutions; as well as (5) a diverse society by addressing each individual's needs [48]. Regarding procurement, Sekisui House promoted eight procurement policies since 2007, focusing on social responsibilities, eco-friendliness, supply optimisation, highest quality, optimal pricing, trusting relationship, and creation of customer value, together with fairness and impartiality [57]. In 2018, the Corporate Social Responsibility (CSR) Procurement Guidelines were established, with nine standards on corporate governance, human rights, labour, environment, fair business practices, information security, supply chain, harmonious coexistence with local communities, as well as quality and safety [48]. The Timber Procurement Guidelines were released in 2007 for promoting FairWood procurement. In 2022, the sustainable timber procurement rate was 97.1%, and the rate of newly constructed net-zero-energy single-family houses was 93%. The rate of newly constructed net-zero-energy rental housing and condominiums in 2022 were 65% and 88.8%, respectively [41].

2.2.5. After-Sale Services

Regarding after-sales service, Sekisui House provides 20 years of warranty on top of the 10-year defect liability period, as stipulated by the Housing Quality Assurance Act. The U-Trus System further extends warranties by additional 10-year intervals as long as the required fee-based inspections and maintenance works are carried out. The le-Log database has also been developed to maintain updated information about each house, ranging from basic building information and inspection results to repair records [41].

2.3. Misawa Homes

2.3.1. Development Trajectories

Founded in 1967, Misawa Homes developed a proprietary timber panel adhesion construction system for prefabricated houses. Misawa Homes debuted the Home Core House design concept in Abu Dhabi, UAE, in 1968 and showcased the Home Core House at the Japan World Exposition in Osaka in 1970 [58]. Since 1968, Misawa Homes has been involved in the design and construction of facilities at the Showa Base, with exceptional performance in thermal insulation, air-tightness, and wind resistance for the Japanese Antarctic expedition team against the extreme weather in Antarctica [59].

Misawa Homes has launched various eco-friendly house series and has initiated the investigation of the performance of built-in photovoltaic systems since 1977. The Type SIII House equipped with an energy-efficient photovoltaic system was introduced in 1980 [60].

The concept model of a zero-energy house (ZEH) was showcased at the International Garden and Greenery Exposition in Osaka in 1990 [61], followed by the launch of Japan's first ZEH, Hybrid-Z in 1998 with an integrated photovoltaic system on the roof [62]. Life Cycle Carbon Minus (LCCM) prototype houses were further developed for a cold region in Hokkaido and a hot humid region in Mie Prefecture in 2008 and 2009, respectively, to achieve an overall negative carbon dioxide emission balance throughout the whole lifecycle of the house, from construction and occupancy to demolition [60]. The installation of a photovoltaic power-generating system has become a standard feature of the Smart Style House series since 2015 [63]. In 2022, the Century with Storage ZEH Advance House was debuted as the fulfilment of both ZEH and LCCM standards [64]. Compared with Daiwa House and Sekisui House, the core business of Misawa Homes in the domestic market is single-family houses and rental housing. Misawa Homes debuted Belle Lead SkipHigh rental housing in 2019 in compliance with the net-zero energy house (ZEH) design specifications [65].

2.3.2. Design Customisation

During the design process, customers are encouraged to visit display homes and choose from basic available house floor plans first before selecting numerous options to personalise their homes (Figure 6). This reduces the time and effort to design the house from scratch and to have better control of the budget [66]. Although Misawa Homes only offers prefabricated timber houses, various house designs are available for customers to select, ranging from affordable MJ Wood series with post-and-beam construction [62,67] to prefabricated timber panel constructions of the Genius house series with 2.6m high ceilings [68] and the Century house series [69], in which the recent model of Century with Storage ZEH Advance House has up to a 3.3m high ceiling [70]. Prefabricated single-family houses are offered in single-storey, double-storey, and three-storey versions depending on the customers' budget and requirements.



Figure 6. Exterior and interior of a display home of Misawa Homes.

2.3.3. Research Capabilities and Technological Advancements

The Misawa Homes Institute of Research and Development (MHIRD) was established in 1973, which was one of the first think tanks in the Japanese housing industry for pursuing innovations and advancing future lifestyles through technical development [71] (Figure 7). The MHIRD has been actively engaging with higher education organisations for research collaborations. For example, the MHIRD engaged with the Okinawa Institute of Science and Technology Graduate University (OIST) in 2016 for setting up an experimental eco-friendly house in Okinawa for promoting sustainable living and improving the quality of life in hot and humid areas [72].



Figure 7. Misawa Homes Institute of Research and Development in Tokyo.

Misawa Homes® expertise is the proprietary timber panel adhesion system for prefabricated construction. The Misawa Governance System for Earthquake Oscillation Control (MGEO) vibration damping device was released in 2004 to reduce the earthquake damage to houses [73]. The earthquake damage evaluation system Gainet was launched in 2015 for measuring the degree of earthquake damage to a house in real time, uploading the data to a cloud server instantaneously for analysis, and informing the homeowners of the status of the damage via smartphones or other digital devices [63]. The ECO Micro Climate Design was firstly introduced in the Century VikiCourt House in 2006 to maximise the comfort of the house during hot summers and cold winters [73]. The M-Wood2 product was developed by Misawa Homes in 1998 as a 100% recycled material by reusing waste timber and plastic. Having similar colour and texture to timber itself, M-Wood2 has better weather resistance performance and can be repeatedly recycled and reprocessed [64]. In 2017, the Century Monocoque prefabricated timber construction technique was developed using 120mm thick timber panels to achieve higher thermal insulation performance [74]. The LinkGates system using Internet of Things (IoT) was released in 2018 to keep household energy use at optimum levels and provide crime prevention and security monitoring services [75].

2.3.4. Sustainable Initiatives and Procurement

In line with the Japanese Government's policy for reaching net-zero greenhouse gas emissions by 2050, Misawa Homes has set the goal to achieve carbon neutrality by 2050. A total of 24 key sustainability challenges were selected for progress monitoring over time, which include (a) creating carbon-neutral, recycling-oriented communities through the delivery of ZEH and LCCM houses, and the use of low-environmental impact materials; (b) building safe and secure communities through the delivery of durable, disaster-resistant houses with good indoor air quality; and (c) taking actions on biodiversity conservation through the use of sustainable forest resources and other environmentally-friendly initiatives. Misawa Homes has also formulated Timber Procurement Guidelines. In 2022, the sustainable timber procurement rate was 84.4%, whereas the rate of newly constructed net-zero energy single-family houses was 77% [64]. There is no available information about the ZEH built rate of rental housing and condominiums for Misawa Homes. Instead, in 2020, Misawa Homes set the 2030 intermediate goal of achieving a 50% ZEH built rate of new apartments [76].

2.3.5. After-Sale Services

Under the motto "Lifelong Commitment to Customers through Housing", Misawa Homes played a leading role among prefabrication companies in Japan to introduce a home guarantee system in 1962 and an after-sale service system in 1972 [77]. Nowadays, Misawa Homes provide 30 years of warranty for structural elements; 15 years basic water-leakage warranty; and 5 years of warranty for equipment and electrical, plumbing, and

drainage systems. The warranty for structural elements and the water-leakage warranty can be further extended for another 10 years and 15 years, respectively, subject to a durability check and the required maintenance work [78].

3. Discussion

All three selected Japanese housing manufacturers were established in the 1950s–1960s during the post-war reconstruction era. Among them, Daiwa House has the longest history, followed by Sekisui House and Misawa Homes. All three manufacturers have been in continuous pursuit of innovations and advancements with respect to design, production, marketing, and sustainable procurement. Through in-house R&D institutes and testing facilities, the manufacturers have maintained rigorous quality control and thorough performance evaluation. Both Daiwa House and Misawa Homes set up the Central Testing Laboratory and the Institute of Research and Development in the same year of 1973, whereas the Comprehensive Housing R&D Institute of Sekisui House was founded in 1990. Various house design series have been launched, including environmentally friendly design initiatives, such as the Solar DH-1 House (1977) of Daiwa House, the PSH21 passive solar house (1982) of Sekisui House, and the ZEH concept model (1990) of Misawa Homes. Misawa Homes has even introduced the Life Cycle Carbon Minus (LCCM) prototype house since 2008.

Considering that Japan is vulnerable to natural disasters, Japanese housing manufacturers have put a lot of effort into developing technologies that deliver structurally durable, safe, and comfortable housing environments. Examples include the Misawa Governance System for Earthquake Oscillation Control (MGEO) vibration damping system (2004), the Sekisui House Earthquake Absorbing System (SHEQAS, 2007), and the xevo Σ earthquake-resistant technology (2014) of Daiwa House. There are other salient innovative technologies developed by these three Japanese housing manufacturers; for instance, the M-Wood2 system using 100% recycled material (1998) of Misawa Homes, the Gururin Dannetsu high-efficiency thermal insulation system (2010) and Airkis indoor air system (2011) of Sekisui House, and the Skye3 heavy-gauge steel-rigid-frame technology (2020) of Daiwa House. These innovative technologies are demonstrated in display homes and interactive exhibitions, such as the Home Amenities Experience Studio and Tomorrow's Life Museum of Sekisui House. All three manufacturers share similar approaches for inviting their customers to be actively involved in the design process, with various options and components for them to select based on their budget and outcomes. In line with mass customisation and their state-of-the-art automated production lines, these Japanese companies can manufacture customised products on a mass basis to maintain the high quality of work and to fulfil the demands for personalised design.

All three Japanese manufacturers are conscious of their corporate social responsibility (CSR), with commitments to minimise the environmental impacts of their work. They have set long-term targets towards carbon neutrality, such as the Sustainability Vision 2050 of Sekisui House and the Challenge Zero 2055 of Daiwa House. Among them, Sekisui House was the earliest in reaching zero emissions of all factories in 2002, followed by Daiwa House in 2003 and Misawa Homes in 2007. Sekisui House achieved the highest percentage of a net-zero energy-house (ZEH) built rate of 93% in 2022, compared with 84% of Daiwa House and 77% of Misawa Homes in the same year. Similarly, in 2022, Sekisui House achieved a higher ZEH built rate of rental housing (65%) and condominiums (88.8%) compared with 14.2% in rental housing and 67.5% in condominiums by Daiwa House. Misawa House set the 2030 intermediate goal of ZEH built rate of new apartments of 50% in 2020, but they did not provide actual figures for comparison. All three manufacturers have implemented relevant sustainable procurement policies to mitigate climate change, to protect biodiversity, and to heighten their suppliers' awareness of these responsibilities, including the Timber Procurement Guidelines of Misawa Homes and Sekisui House, as well as the CSR Procurement Guidelines of Sekisui House and Daiwa House. In 2022, Sekisui House has achieved the highest sustainable timber

procurement rate of 97.1%, above the 96.9% of Daiwa House and 84.4% of Misawa Homes. For fostering a circular economy, Sekisui House has exceptional performance by implementing a 100% recycling arrangement for the building waste generated.

Comprehensive after-sale service and long-term warranty are provided by these three manufacturers to increase customer confidence and to ensure their housing products are properly maintained. They offer the same 30-year warranty for structural elements but provide different warranty periods for other aspects, which can be further extended subject to inspections and maintenance work required at the customers' expense. Table 1 below provides a comparison matrix of these three manufacturers.

Table 1. Comparison matrix of the three Japanese prefabricated housing manufacturers.

	Daiwa House	Sekisui House	Misawa Homes
Established	1955	1960	1967
Research/development capabilities	Central Testing Laboratory in the Nara Factory (1973) Industry's Central Research Laboratory (1994) Kotokurie educational & training facility (2021)	Comprehensive Housing R&D Institute & Home Amenities Experience Studio (1990) Human Life R&D Institute (2018) Tomorrow's Life Museum (2021)	Misawa Homes Institute of Research and Development (1973)
House design	Pipe House (1955) Midget House (1959) Type A House (1962) Type B House (1967) Type C House (1970) Solar DH-1 House (1977) Kankyo-Kobo House (2000) xevo single-family house (2006) xevo GranWood (2013) SMAxECO Town Harumidai (2014) xevo Σ single-family house (2014) Premium GranWood (2017) xevo Σ Premium (2018) skye3 steel-frame house (2020) Torisia net-zero energy house (2022)	Model A House (1960) Model B House (1961) Model W House (1977) PSH21 passive solar house (1982) IS Flat (1984) Vantage 3 (1988) Shawood House (1995) Centrage Σ House (1996) Solar-ΣA House (1997) Biena House (1999) Zero Emission House (2008) Green First Models (2009) IS Stage (2014) Gravis Villa House (2015) Platform House (2019)	Home Core (1968) House 55 (1976) Type SIII House (1980) ZEH concept model (1990) Hybrid-Z House (1998) Century VikiCourt (2006) LCCM House (2008) Genius LCCO2 (2011) Genius Gate (2013) Smart Style House (2015) Century Primore3 & Belle Lead SkipHigh (2019) Century Stylepro (2020) Century with Storage ZEH Advance House (2022)
Design customisation	Online Live Style Partner to visualise own ideal house design + 3D Fast Plan to experience the house design in virtual reality	Home Amenities Experience Studio for exploring various Options to cater for own lifestyle and needs + Home Visit Days	Selection from basic plans and various design options for personalisation and cost control
Type of housing provided	Single-family houses, rental housing, condominiums	Single-family houses, rental housing, condominiums	Single-family houses, rental housing
Prefabricated construction systems	Timber/steel frames + modular unit prefabrication for condominiums	Timber/steel frames + concrete wall panels for condominiums	Timber panel adhesion system
Technological advancements	Steel pipe frame system (1955) xevo Σ (seismic resistance) (2014) Granwood timber construction (2017) Xevo Σ Premium houses (2018) Skye3 steel rigid frame technology (2020)	Light-gauge steel-frame (1960) SHEQAS system (2007) Gururin Dannetsu high-efficiency thermal insulation system (2010) Airkis (indoor air system) (2011) Hybrid SHEQAS (2013) Flexible β System for flexible floor plans with column elimination (2017)	Timber panel adhesion system (1967) M-Wood2 (1998) MGEO system (2004) ECO microclimate (2006) Gainet system (2015) Century Monocoque (2017) LinkGates system (2018)
Sales and marketing strategies	<ul style="list-style-type: none"> Mass customisation with total coordination among design, production, sales, and marketing Use of catalogues, websites, interactive exhibitions, and display homes 		

	<ul style="list-style-type: none"> Customer service and consultation with digital visualisation, cost estimate, and quality assurance 		
Sustainable procurement	CSR Procurement Guidelines (2015) Supply Chain Sustainability Guidelines (2023)	Timber Procurement Guidelines (2007) CSR Procurement Guidelines (2018) 100% recycling of building waste	24 key sustainability Challenges Timber Procurement Guidelines 100% recycled M-Wood2 (1998)
Sustainability targets	Challenge Zero 2055	Sustainability Vision 2050	Committed to carbon neutrality by 2050
Sustainable timber procurement rate	96.9% (2022)	97.1% (2022)	84.4% (2022)
Production/construction	State-of-the-art production facilities for mass customisation, prefabrication, and supply of high-precision, high-quality, and high-performance building components		
Zero emissions by all factories	2003	2002	2007
ZEH built rate of single-family houses	84% (2022)	93% (2022)	77% (2022)
ZEH built rate of rental housing	14.2% (2022)	65% (2022)	**
ZEH built rate of condominiums	67.5% (2022)	88.8% (2022)	**
After-sale services	30-year warranty for structure and waterproofing, with 2 extended periods (15 years each) 10-year warranty for equipment	30-year warranty for structure and waterproofing, with 10-year extension	30-year warranty for structure (10-year extension), 15-year warranty for water leakage (15-year extension), and 5-year warranty for equipment

** There is no available information about the zero-energy house (ZEH) built rate of rental housing and condominiums of Misawa Homes. Instead, Misawa Homes set the 2030 intermediate goal of a ZEH built rate of new apartments of 50% in 2020.

4. Conclusions

In this entry, three Japanese prefabricated housing manufacturers (Daiwa House, Sekisui House, and Misawa Homes) were selected as case studies for close examination. Through case studies and comparison, all three housing manufacturers have set high benchmarks in the prefabricated housing industry. They strive for innovations and continuous improvement in housing design, production, marketing, and after-sale services. They have developed leading-edge technologies in earthquake resistance, thermal insulation, and automated production lines for mass customisation. They are all keen on setting long-term sustainability targets and adopting sustainable procurement to reduce the associated environmental impacts towards zero carbon emissions.

The Japanese population is ageing and shrinking, with a declining birth rate leading to a reduced demand for new housing construction and a growing number of vacant houses. The issue of vacant and poorly maintained houses has become a blemish and a safety hazard in the community. To tackle this issue, Misawa Homes has launched the Smile-Ring System to extend their business to the purchase, renovate, and resale of pre-owned houses to extend their lifespan beyond their original owners. Facing the shrinking domestic market, both Daiwa House and Sekisui House have set up overseas operations. Daiwa House has established locally rooted businesses in 25 countries in Asia, Europe, Australasia, and the Americas [79], whereas Sekisui House has branches into five countries: China, Singapore, Australia, the United Kingdom, and the United States [80]. For future research, the overseas development of these housing manufacturers and their participation in non-residential markets are worthy of further investigation.

These three Japanese housing manufacturers have demonstrated their adaptability and flexibility in response to natural disasters and the transformation of environmental and social needs. Although only three Japanese housing manufacturers were selected for examination, which is the limitation of this entry, these three reputable and well-established manufacturers serve as good exemplars for other prefabricated housing manufacturers, not just from Japan but from throughout the world, to learn from their resilience and their pursuit of innovations and advancements towards a sustainable future.

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