Chapter

Sustainable Housing Design: System Control Strategy

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Abstract

Current housing design faces various environmental, social, and economic issues, such as climate change, aging population, and workplace needs. Dealing with such issues and pursuing sustainability is a target-oriented challenge. The science of system control can be utilized for all target-oriented tasks. Therefore, applying system control, we have been developing methods for sustainable design. Based on our finished research and practice results, this chapter shows how to design sustainable homes. Section 2 briefly illustrates the methods with two figures: (1) the control system for promoting sustainable housing design, (2) the process of producing and revising sustainable housing design guidelines. Section 3 demonstrates a concrete process of creating sustainable design guidelines. First, it identifies global and general problems related to current homes and specifies requirements for sustainable housing design. Next, it converts these requirements into a tabular form of "housing elements, variables, and their desired values." The completed table has turned out compact "sustainable housing design guidelines" for general use. The methods have four significant features: (1) total visualization for promoting sustainable design, (2) user-friendliness, (3) comprehensiveness, (4) flexibility toward optimization.

Keywords: system control, sustainable design guidelines, climate change, aging population, workplace needs

1. Introduction

Present housing design faces various environmental issues, including climate change. In 2014, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) said, "without additional efforts to reduce greenhouse gas emissions beyond those in place today, global warming in 2100 ranges from 3.7°C to 4.8°C above the average for 1850-1900" [1]. The Paris Agreement of 2015 has aimed to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels [2]. In order to curb global warming, the building sector must reduce CO_2 emissions drastically [3]. Meanwhile, no matter whether the Paris Agreement is fulfilled or not, the global mean temperature will inevitably rise from the present level. Accordingly, today's housing also needs to prepare for more severe extreme weather events caused by climate change [1].

On the other hand, changing social and economic situations also urge housing design to be altered. For example, aging population, which is remarkably progressing in this century [4], increases the proportion of people with disabilities in the population and households [5]. Thus, houses should adopt fundamental accessible and universal design features [5, 6]. Meanwhile, along with the development of information technology and network, the number of people who work at home or from home has been increasing [7, 8]. Currently, homes need to be recognized as significant places for working and economic activities [9].

Dealing with environmental, social, and economic issues and pursuing sustainability is a target-oriented challenge. The science of system control can be used for all target-oriented tasks [10]. Besides, that science has brought fruitful results in many fields, including engineering [10]. Therefore, applying system control, we have been progressing in research on sustainable design.

Our finished study results include the "control system for promoting sustainable housing design" and the "process of producing and revising the sustainable design guidelines." Utilizing these methods, we have already developed and revised sustainable housing design guidelines, mainly for use in Japan. Based on these accomplished results, this chapter shows how to design sustainable homes. First, the next section briefly illustrates the methods. After that, the main section demonstrates a concrete process of creating sustainable housing design guidelines.

2. Methods

2.1 Control system for promoting sustainable housing design

The control system for promoting sustainable housing design is shown in **Figure 1**. The upper and lower sections separated by the dotted line are the "theoretical world" and the "practical world."

In **Figure 1**, "controlled objects" are homes, which include both new and existing homes. "Disturbances" mean adverse effects on controlled objects originating from environmental, social, or economic issues. Instances of the disturbances are impacts of pollution and extreme weather events caused by climate change. The route from "disturbances" to "sustainability" is "adaptation." Recently, the

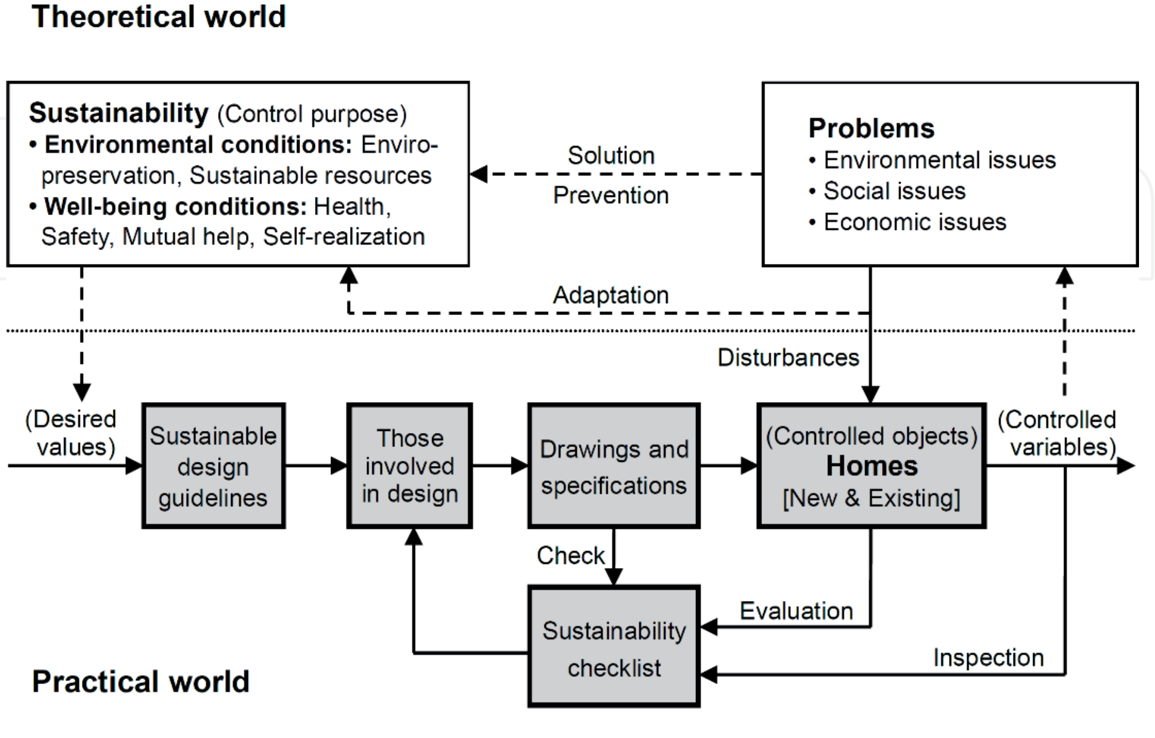

Figure 1.
Control system for promoting sustainable housing design.

necessity of adaptation to disturbances has become widely recognized, along with the progress of climate change [1]. The IPCC has stated that achieving sustainability also requires adapting to climate-related impacts, in addition to mitigating climate change [11].

The control purpose is the accomplishment of "sustainability." The upper-left box in **Figure 1** shows that achieving sustainability requires fulfilling both environmental and well-being conditions. Environmental conditions are "environmental preservation" and "sustainable use of natural resources." Meanwhile, well-being conditions are "health," "safety," "mutual help," and "self-realization," which are significant factors for people's well-being [12].

"Controlled variables" are the variables that are related to controlled objects and should be controlled for mostly solving or preventing the issues or adapting to disturbances. On the other side, "desired values" are derived from the control purpose, namely sustainability. The control objective of this control system is to adjust the controlled variables to their desired values [13, 14].

In the practical world, the subjects of control are "those involved in design," including homeowners, designers, architects, and homebuilders. In order to adjust the controlled variables to their desired values, those involved in design utilize the "sustainable design guidelines" and "sustainability checklist." Both of the design guidelines and checklist have almost the same expressions, that is, elements, variables, and desired values. However, the checklist is formed to smoothly compare measured or estimated values of the variables with the desired values and search for controlled variables [13, 14].

When objects are new homes, information about the desired values reaches "those involved in design" through the "sustainable design guidelines." Those involved prepare "drawings and specifications" so that the variables of the home's elements can satisfy their desired values to full potential. At significant phases in the design work, those involved in design check the drawings and specifications by seeing the "sustainability checklist" [13, 14].

When objects are existing homes, the design work starts with "inspection" on the home as an object. Using the sustainability checklist, "those involved in design" measure or estimate each element's variables of that home. Next, they compare the variables' measured/estimated values with the desired values. As a result, the variables whose measured or estimated values fall below the desired values should be "controlled variables." After the inspection, those involved in design usually prepare "drawings and specifications" for improvement so that the controlled variables meet their desired values to the maximum [13, 14].

2.2 Production and revision process of sustainable design guidelines

Figure 2 demonstrates the process of producing and revising the sustainable housing design guidelines and sustainability checklist. The upper section of the diagram is the "theoretical world," and the lower section is the "practical world."

The four blocks on the left side are the items that system designers refer to when producing or revising the sustainable housing design guidelines. The central part shows the flow of planning and using the sustainable design guidelines and checklist. First, the system designers produce or revise the design guidelines through the three-stage process. Subsequently, system users employ the design guidelines and checklist. Finally, the residents use the completed homes that have been designed with the design guidelines and checklist. Meanwhile, the two items on the lower right show the feedback loops from the system users and home residents.

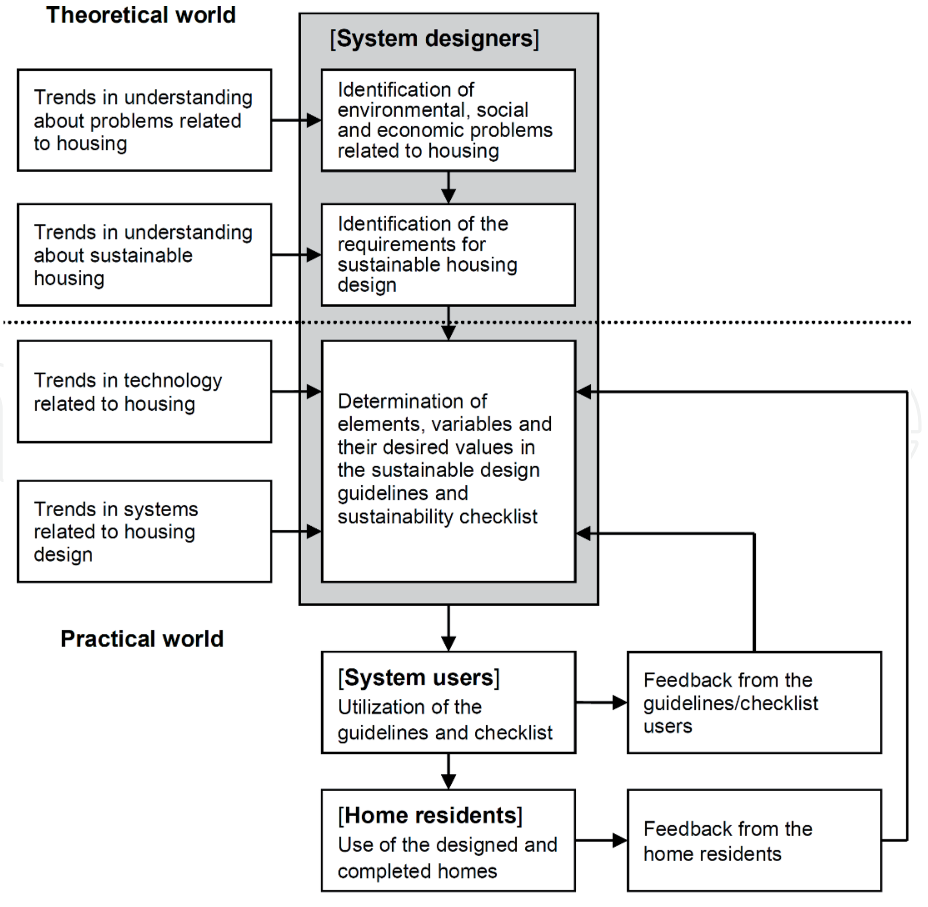

Figure 2.
Process of producing and revising the sustainable housing design guidelines and sustainability checklist [9].

2.2.1 Production process of the sustainable design guidelines

The production process of the sustainable housing design guidelines is made up of three stages: (1) identification of environmental, social, and economic problems related to housing, (2) identification of the requirements for sustainable housing design, (3) determination of elements, variables, and their desired values in the sustainable design guidelines [9].

In the first stage, system designers identify environmental, social, and economic issues related to housing, while checking trends in understanding about such issues. The basis for the identification is that the issues affect the well-being and environmental conditions shown in **Figure 1**, such as health, safety, and environmental preservation. System designers can specify local/particular issues in their country or region, in addition to global/general issues [9].

Next, based on the specified housing-related issues, the system designers identify the requirements for sustainable housing design. When identifying such requirements, it is useful to observe trends in understanding about sustainable housing [9].

In the third stage, the requirements for sustainable housing design are converted into a table of "element-variable-desired value," which can be found in the design guidelines. First, the system designers select "elements" so as to cover significant and necessary parts of homes. When selecting elements, it is helpful to base two factors on: "material" and "space." "Material" considers homes as the complexity of material elements, including framework, exterior, interior, windows and doors, and plumbing. "Space" regards homes as the complexity of spatial elements, such as rooms and areas [13, 14]. After identifying elements, system designers specify the elements' "variables" that can show the directions of the requirements for sustainable design. Subsequently, they determine the variables' "desired values" to meet the requirements.

The most significant advantage of converting the requirements into the "element-variable-desired value" table is practical convenience to system users. "Elements" in the table correspond to actual parts of homes. "Variables" and their "desired values" show the design points and their targets, respectively. Therefore, the system users can easily understand what should be designed and design steps [9].

2.2.2 Revision process of the sustainable design guidelines

The sustainable design guidelines are necessary to be revised, for adjustment to changing situations and improvement toward higher validity and user-friendliness. We have created the revision process by integrating three factors: (1) changes in the theoretical world, (2) changes in the practical world, (3) user feedback [9]. After making preparations from these three spheres, system designers amend the "element-variable-desired value" expressions.

As demonstrated in the upper left of **Figure 2**, changes over time in the theoretical world are reflected into the design guidelines [9]. First, observing the latest trends in understanding about housing-related problems, system designers amend the problem list. After that, they also modify the list of the requirements for sustainable housing design. When modifying the requirement list, it is also necessary to search for changes in understanding about sustainable housing.

Changes over time in the practical world also need to be taken in the design guidelines. In order to reflect such changes, the system designers observe current trends in housing-related technology and systems related to housing design [9]. In addition, systems related to housing design include compulsory systems, such as building codes, and voluntary systems relating to sustainable housing (assessment and rating systems, standards, guidelines, etc.) [15].

Meanwhile, "user feedback" is significant for the improvement of the design guidelines and checklist. In this case, there are two feedback loops: from system users and home residents. The feedback from the system users is information about reactions to the guidelines and checklist, such as comments on their adequacy and user-friendliness. On the other hand, the feedback from the home residents includes responses to the completed homes, such as remarks about the homes' amenities and sustainability performance [9].

3. Sustainable housing design guidelines for general use

Using the methods illustrated in the previous section, we have already produced and revised sustainable housing design guidelines, chiefly for use in Japan. Based on these studies and practical results, this section anew demonstrates how to produce sustainable housing design guidelines for general use. In line with the process of producing guidelines, this section consists of two subsections: (1) housing-related problems and requirements for sustainable design, (2) conversion into housing elements, variables, and desired values.

3.1 Housing-related problems and requirements for sustainable design

Housing-related problems and requirements for sustainable housing design have been demonstrated in **Table 1**. We have first selected main global and general issues, considering the conditions for sustainability. The first two items, "global

Housing-related problems (Main global/general issues)	Requirements for sustainable housing design	Conditions for sustainability
• Global warming and climate change	• Energy saving • Use of renewable energy • Increase of green spaces	• Enviro-preservation
• Environmental issues related to building materials (environmental destruction, biodiversity loss, environmental pollution, climate change, resource depletion, waste)	• Material saving • Extension of housing lifespan • Use of low-environmental-load materials	• Enviro-preservation • Sustainable resources
• Harmful effects on housing caused by climate change (more-severe heat waves, heavy precipitation events, cyclonic storms, floods, drought, wildfires, etc.)	• Adaptation measures (measures against increasing temperatures, more impact-resistant exterior, securing emergency water and energy, etc.)	• Health • Safety
• Urban heat island • Urban flooding due to rainwater runoff	• Increase of green spaces • Reduction of impervious surface areas	• Enviro-preservation • Health • Safety
• Blackout risks due to increasing solar and wind power generation	• Storage of electricity	• Health • Safety
• Water shortage risks	• Water saving • Use of rainwater	• Health • Safety
• Issues resulting from aging population (Increase of medical and nursing care expenses, etc.)	• Accessible and universal design	• Health • Safety
• Poor indoor thermal performance	• Healthy indoor thermal performance	• Health
• Indoor air pollution caused by toxic substances (volatile organic compounds, etc.)	• Use of non-toxic substances for the occupants	• Health
• Insufficient considerations for working at/from home and learning	• Spaces and equipment for working and learning	• Self-realization
• Issues resulting from insufficient communication	• Planning suitable for communication	• Mutual help • Self-realization
• Neglected landscape	• Consideration for the landscape	• Health
• Crimes (burglaries, etc.)	• Security measures	• Safety

Notes: (1) Housing-related problems listed in this table are only main global and general issues. If intending to create design guidelines for a region or country, system designers need to add local and particular issues of that region or country to the problem list [9]. (2) This housing design study deals with issues that can occur after housing sites are determined. Therefore, matters concerning housing land development or site selection are excluded from this table. Instead, such issues are handled in the study on urban design [16].

Table 1.
Housing-related problems and requirements for sustainable design.

warming and climate change" and "environmental issues related to building materials," are significant problems linked to environmental conditions. The other issues are chiefly related to well-being conditions, such as health and safety. Choosing five items from the table, this section briefly explains the outlines of the problems and the requirements for sustainable design.

3.1.1 Global warming and climate change

The IPCC's Fifth Assessment Report has concluded that cumulative emissions of CO_2 largely determine global mean surface warming [1]. The amount of CO_2 in the atmosphere has been obviously increasing due to human emissions [1, 17]. In order to cut CO_2 emissions, the housing sector must reduce energy originating from fossil fuels. Therefore, two mitigation measures, namely saving energy and using renewable energy, are significant as the requirements for sustainable design [1]. Moreover, the necessity of enhancing the sinks of CO_2 requires increasing green spaces [1].

3.1.2 Environmental issues related to building materials

Building materials over their life cycles, from resource acquisition, throughout construction, demolition, and disposal or recycling, are related to various environmental problems. Such issues include environmental destruction, biodiversity loss, environmental pollution, climate change, resource depletion, and waste.

The strategy of reducing environmental impacts related to housing materials can be divided into three: (1) material saving, (2) extension of housing lifespan, (3) use of low-environmental-load materials [18]. "Material saving" aims to reduce the amount of material in a housing structure. The "extension of housing lifespan" requires tactics for long-life homes, such as selecting durable materials, adopting deterioration prevention measures, and considerations for adapting to future layout changes. Meanwhile, the "use of low-environmental-load materials" includes various options, such as using locally produced materials, utilizing recyclable or recycled materials, and sustainable use of renewable materials [18].

3.1.3 Harmful effects on housing caused by climate change

Along with increasing atmospheric CO_2 concentrations, climate-related impacts on the built environment are also becoming more severe [1]. Such impacts include heat waves, heavy precipitation events, cyclonic storms, floods, drought, and wildfires [1]. Accordingly, the necessity to adapt housing design to climate change is also increasing. Adaptation measures in the building sector include measures against rising temperatures (insulation, external shading, cross ventilation, etc.), more impact-resistant exterior, and securing emergency water and energy [19, 20].

In addition, measures to reduce climate-related risks differ across regions [1]. Thus, those engaged in sustainable design in each region should adequately predict future risks and plan effective measures.

3.1.4 Issues resulting from aging population

Aging population is becoming a crucial challenge to economic and social sustainability. An increasing number of the elderly inflates public expenditures on pensions, and medical and nursing care [21]. Meanwhile, since disability rates increase with age, the aging population raises the percentage of people with disabilities in the population and households [5].

Current demographic changes require housing to adopt accessible and universal design [5, 6, 22]. Incorporating universal design features into homes improves safety, helping to prevent accidents caused by falls and slips [6, 22, 23]. In addition, universal design helps everyone with assistance needs, such as people with disabilities, the elderly, small children, pregnant women, and people with a temporary injury or illness [24, 25]. Furthermore, including universal design principles in advance leads to a drastic reduction of future renovation costs. According to the Victorian Government of Australia, the cost of incorporating fundamental universal design features into a new home is more than 20 times cheaper than retrofitting such features into an existing home [26, 27].

3.1.5 Insufficient considerations for working at/from home and learning

Recently homes have been becoming more significant as working places [9]. The development of information technology and networks has been promoting home-based businesses [7]. Besides, an increasing number of firms are adopting working from home [7, 8]. Meanwhile, life longevity is increasing the necessity of lifelong learning [28]. As a result, housing is also gaining importance as a place of learning for adults as well as children.

Previously, houses were not recognized as significant places of working and lifelong learning. Accordingly, if attempting to start working or learning at home, people often encounter difficulties due to a lack of space and facilities. In fact, unexpected demands for working from home forced by the COVID-19 pandemic revealed such difficulties. For example, in April of 2020, a housing-related firm in Japan, Recruit Sumai Company Ltd., conducted a questionnaire to office workers living in the Greater Tokyo Metropolitan area and gained 1390 valid responses. As a result, many workers from home answered that there were various insufficiencies in their houses, such as a lack of space or room for working and equipment shortages [29].

3.2 Conversion into housing elements, variables, and desired values

We have converted the requirements for sustainable design into the structure of housing elements, variables, and desired values. First, based on the above-mentioned two factors, namely “material” and “space,” we have selected a total of 23 housing elements. After specifying the elements, we have determined variables and their desired values, as shown in **Table 2**.

3.2.1 Material element design

In **Table 2**, material elements are from “entire building” to “outdoor facilities.” Choosing four from these 14 items, this section illustrates material element design for sustainable housing.

3.2.1.1 Entire building

The shape of the entire building closely relates to the “energy saving” and “material saving” shown in **Table 1**. Preferring compact forms to sprawling ones reduces the building envelope surface area and decreases thermal transfer through the surface [18, 30]. Moreover, pursuing compact shapes also leads to lower embodied energy and environmental impacts related to materials for constructing the envelope itself [30]. Therefore, we have identified the entire building’s key variable and its desired value as “shape: compactness” and “compact,” respectively.

The most common quantitative indicator of compactness is the ratio of the envelope surface area (S) to the enclosed volume (V) [30]. Accordingly, we have adopted the “surface-to-volume ratio (S/V)” as the index of the variable and determined its desired value as a “smaller S/V ratio.” For example, the S/V ratio of the house shown in **Figure 3** is 0.888, which is a considerably small figure among S/V ratios of shapes with the same enclosed volume as this house. When planning this home, the owner and designers pursued a more compact form in the restriction of the shown narrow land.

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Element	Variable	Desired value
Entire building	Shape: Compactness (Index: Surface-to-volume ratio [S/V])	Compact (Not sprawling) (Index: Smaller S/V ratio)
	External appearance	Consideration for the landscape
Framework	Durability	Long service life (Superior deterioration resistance against decay or corrosion)
	Materials	Low-environmental-load materials (Priority of wood over steel and concrete)
Exterior (roof, wall, etc.)	Resistance against impacts (fires, storms, etc.)	Sufficient resistance against anticipated impacts
	Durability	Long service life (Longer expected lifespan, easier replacement of the features)
	Materials	Low-environmental-load materials
Thermal insulation	Thermal insulation performance	Sufficient thermal insulation performance for occupants' health
Windows and doors	Thermal insulation performance	Sufficient thermal insulation performance for occupants' health
	Sunlight adjustment capability	Sufficient capability of taking the sunlight in winter and reducing it in summer (Primary related factors: Types of window glass, solar shading materials such as blinds, and eaves)
	Protection of glass against impacts	Shutters
	Security measures	Sufficient intrusion prevention measures
Interior (floor, wall, ceiling, etc.)	Toxicity	Non-toxic for occupants' health
	Materials	Low-environmental-load materials
Lighting fixtures	Type of light	LED (Lighting fixtures in living spaces are fitted with lighting controls)
Energy-using equipment (heating, air-conditioning, hot-water supply, ventilation, etc.)	Energy efficiency	High energy efficiency
Plumbing (water pipes, drainage pipes, gas pipes, etc.)	Durability	Long service life (Longer expected lifespan, easier replacement of the piping)
Equipment for harnessing renewable energy	Harnessed renewable energy	100% or more of the total energy usage
Storage battery	Type	Household battery or Electric vehicle battery
	Linkage	Interconnection with the home electrical system
Equipment for rainwater use	Rainwater-using equipment	Rainwater tank
Water-using equipment (toilet bowls, faucets, shower heads, etc.)	Water saving performance	High water saving performance
Outdoor facilities (fence, etc.)	Form	Secure unhindered sightlines
	Appearance	Consideration for the landscape
	Materials	Low-environmental-load materials

Element	Variable	Desired value
Areas relating to water use and hot-water supply	Areas in the home	Placing them closer
Living/dining room and kitchen area	Place in the home	Between the entrance and private room area
	Type of kitchen	Open or semi-open
Areas for working and learning	Places in the home	In or near the living/dining room and kitchen area
	Equipment	Table/desk and shelf (fixed or movable) and Internet connection
Bedroom for the disabled or elderly	Floor space	10 m^2 or more, with one wall a minimum length of 3 m
Accessible route	Areas connected with the accessible route	Bedroom for the disabled or elderly, toilet and bath area, living/dining room, kitchen, area for working and learning, entrance, street, (parking)
	Passages' surface on the route	Flat or gently sloping (Gently sloping: 1/12 gradient max.)
	Doorways' thresholds on the route	No level differences
	Passages' width on the route	90 cm or more
	Doorways' width on the route	75 cm or more
Toilet and bathroom	Wheelchair maneuverability space	Sufficient clear space from the rim of the toilet bowl and the bathtub
	Handrails help toilet users sit and stand	Installed
	Handrails help bath users go in and out of the bathtub	Installed
Stairs	Gradient of steepness	40 degrees or less
	Handrails	Installed
Position and area of windows	Positions of windows in each living space (Natural ventilation)	Two or more places on walls in each living space (Cross ventilation)
	Ratio of total window area to floor area in each living space (Daylighting)	20% or more
Green space	Ratio of the green space in the outside area	High ratio of the green space

Notes: Material elements are from "entire building" to "outdoor facilities" and spatial elements are from "areas relating to water use and hot-water supply" to "green space".

Table 2.
Sustainable housing design guidelines for general use.

3.2.1.2 Equipment for harnessing renewable energy

Responding to "use of renewable energy," a requirement for sustainable housing design, we have identified "equipment for harnessing renewable energy" as a material element. After that, we have determined the key variable and its

Figure 3.
An example of material element design for sustainable housing [31].

desired value to be "harnessed renewable energy" and "100% or more of the total energy usage," respectively. This desired value means aiming at net-zero-energy or surplus-energy housing. Achieving the desired value usually needs both energy saving and a considerable equipment capacity to harness renewable energy.

The most common equipment for harnessing renewable energy on housing sites is solar power generation systems. For example, the house demonstrated in **Figure 3** is equipped with 49 solar panels on the single-pitch roof. The combination of this larger-scale photovoltaic generation system and various energy-saving schemes has enabled this home to reach an amazing 500% of self-sufficiency in energy [31].

3.2.1.3 Windows and doors

Openings, especially windows, are related to many requirements for sustainable housing design, including healthy indoor thermal performance. Improving indoor thermal performance requires windows to secure sufficient "thermal insulation performance" and "sunlight adjustment capability," both of which contribute to energy saving by decreasing the demand for heating and air-conditioning [32]. Besides, such tactics also become adaptation measures because they can reduce temperature-related impacts, including overheating during heat waves [19, 33]. Therefore, we have identified the desired value of thermal insulation performance as “sufficient thermal insulation performance for occupants’ health.” Meanwhile, the desired value of sunlight adjustment capability has been determined to be “sufficient capability of taking the sunlight in winter and reducing it in summer.” Primary factors influencing the sunlight penetration ratio are types of window glass, solar shading materials such as blinds, and eaves. Concerning the windows on the southern façade of the home in **Figure 3**, the window glass, lace curtains, the balcony, the roof with the pendent eave, and the deciduous tree cooperate to control the sunlight.

Moreover, considering an adaptation measure, that is, more impact-resistant exterior, we have specified “protection of glass against impacts” as another variable of windows. Subsequently, we have determined its desired value to be “shutters.” Protecting the most vulnerable part of housing external surfaces, namely windowpanes, helps prevent damage caused by climate-related extreme events. As shown in the lower right of **Figure 3**, shutters cover the windows and protect the glass against impacts, such as fire, hurricanes, and flying objects. In addition, covering windows with shutters also helps upgrade intrusion prevention measures.

3.2.1.4 Lighting fixtures

Regarding “lighting fixtures,” we have specified the key variable and its desired value as “type of light” and “LED,” respectively. LED lamps are significantly more energy-efficient than others, including fluorescent lamps and incandescent lightbulbs; therefore, using LEDs can satisfy energy saving, one of the requirements in **Table 1**. Besides, LEDs are much more durable than other light sources. Furthermore, LEDs do not contain toxic materials, such as mercury [34]. Accordingly, using LED also contributes to reducing environmental impacts related to building materials.

Meanwhile, we have added notes to “LED,” saying “lighting fixtures in living spaces are fitted with lighting controls” (**Figure 3**, lower left) [9]. Dimmers and other controls can reduce brightness and help consume only the amount of electricity needed. Thus, LED with lighting controls is highly energy-efficient. Moreover, brightness and color adjustment functions are beneficial for occupants’ health and well-being. For example, avoiding bright lights and blue light before bedtime contributes to preventing sleep-quality-related diseases [35, 36].

3.2.2 Spatial element design

The items shown in the latter part of **Table 2**, namely from “areas relating to water use and hot-water supply” to “green space,” are spatial elements. Selecting five from these nine items, this section illustrates spatial element design for sustainable housing.

3.2.2.1 Areas relating to water use and hot-water supply

“Areas relating to water use and hot-water supply” include a kitchen and hygiene-related area, such as a bathroom and laundry, as well as a place for a water heater (**Figure 4**). These areas should be placed closer, in order to reduce plumbing-related materials and energy. This spatial planning leads to reduction of the total length of water and hot-water plumbing and waste pipes. This consideration also contributes to cutting down the heat loss from hot-water supply pipes. In addition, this arrangement leads to comfort in occupants’ daily life. As the distance from the water heater to the faucet decreases, the time until hot water comes out shortens [31].

3.2.2.2 Areas for working and learning

As described in Section 3.1, housing has been gaining importance as a place of working and learning. Considering such recent situations, we have selected "areas for working and learning" as a spatial element. After that, we have determined the key variable and its desired value as "places in the home" and "in or near the living/ dining room and kitchen area," respectively. In addition, the above-mentioned survey conducted under the COVID-19 pandemic has also supported the appropriateness of this space planning. The answers to the questionnaire have included two types of needs: (1) want to work in a larger living room, (2) want to work in a space or room for exclusive use [29]. Accordingly, in **Figure 4**, we have partially overlapped the "areas for working and learning" with the "living/dining room and kitchen area."

3.2.2.3 Bedroom for the disabled or elderly

A "bedroom for the disabled or elderly" means a private area used or expected to be used by the residents limited in their movements, such as wheelchair users and the elderly. As shown in **Figure 4**, this room needs to be connected with the accessible route. Therefore, the room is usually placed on the entrance-level floor, unless the home is equipped with an elevator.

The "bedroom for the disabled or elderly" is capable of responding to various needs. If there are no occupants with disabilities at first, it can be utilized as an ordinary bedroom. Meanwhile, this room can also be used for working or learning. Thus, in **Figure 4**, the area of this room has been outlined by the broken green line,

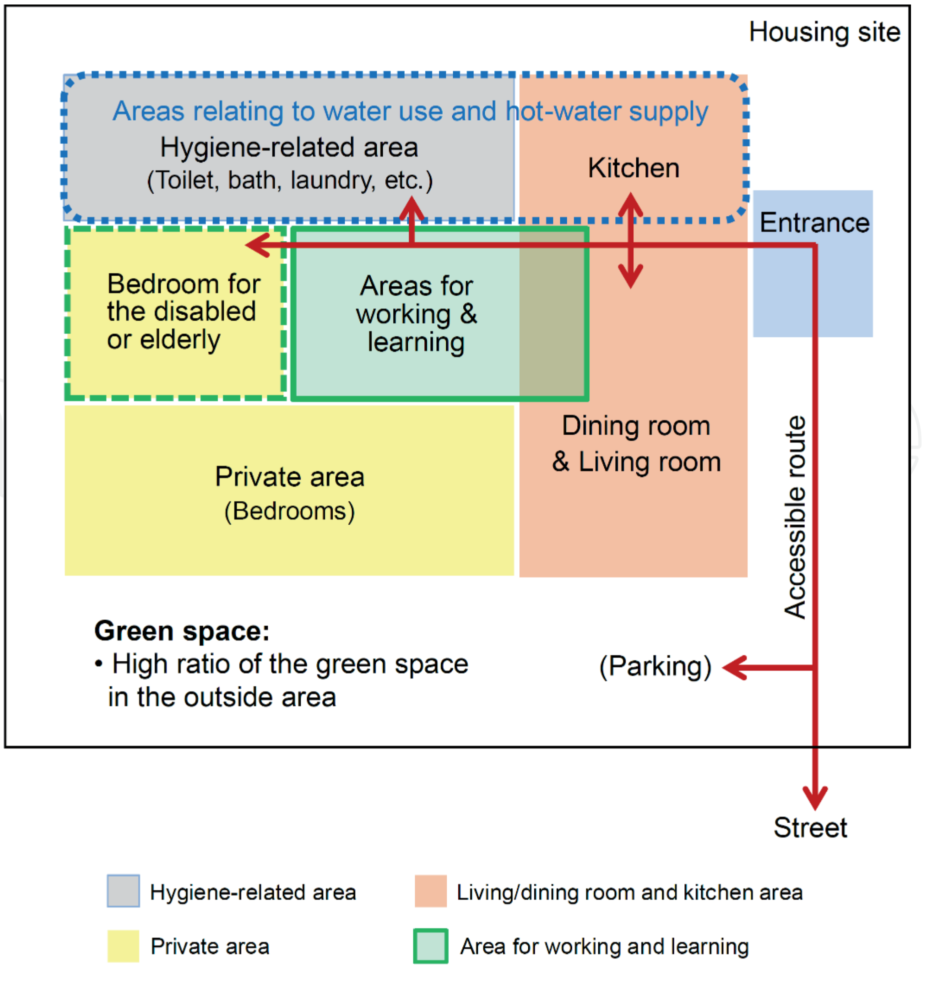

Figure 4.
Concept of spatial planning for sustainable housing.

as well as colored with yellow. While homes are used, occupants' number, age, and health conditions change inevitably. Therefore, housing should have the flexibility to manage such changing situations. Adaptability to possible future layout changes contributes to extending housing lifespan and reducing the environmental burden.

3.2.2.4 Accessible route

An "accessible route" means a course on which disabled people and the elderly can move around easily. As demonstrated in **Figure 4**, the accessible route should be connected to a bedroom for the disabled or elderly, a toilet and bath area, an area for working and learning, a living/dining room, a kitchen, an entrance, and the street. Moreover, if there is parking in the housing site, it should also be linked with the accessible route. The surface of the passages on the route must be flat or gently sloping. Similarly, the doorways on the route should have no level differences. Moreover, the passages and doorways on the accessible route must be wide enough for a wheelchair to pass.

3.2.2.5 Green space

A "green space" is an area with plants, such as trees, shrubs, herbs, and grasses. Increasing green spaces contributes to environmental preservation, health, and safety in various ways. First, it mitigates global warming and climate change, enhancing the sinks of CO_2. Moreover, increasing green spaces also mitigate both urban heat island and urban flooding risks. As implied in **Figure 4**, extending green spaces in the outside area of the housing site leads to reducing impervious surface spaces, typically areas covered with concrete and asphalt. These two factors reduce urban heat island effects through increasing evapotranspiration and decreasing heat absorption. Meanwhile, the increase of pervious surface spaces can decrease urban flooding risks by reducing rainwater runoff.

4. Conclusion

This study showed how to design sustainable housing by employing the system-control-based methods. Section 2 illustrated the methods with the two diagrams: (1) the control system for promoting sustainable housing design, (2) the process of producing and revising sustainable housing design guidelines. Using these methods, Section 3 demonstrated a concrete process of creating sustainable housing design guidelines. After identifying global and general problems related to homes, it specified requirements for sustainable housing design. Subsequently, these requirements were converted into a tabular form of "housing elements, variables, and their desired values." The completed table has turned out compact "sustainable housing design guidelines" for general use.

The proposed methods include four significant features: (1) totally visualized for promoting sustainable housing design, (2) user-friendly, (3) comprehensive, (4) flexible toward optimization. The first feature originates from the two diagrams shown in Section 2, namely **Figures 1** and **2**. These schematizations help understand the whole picture for promoting sustainable housing design.

The second characteristic, "user-friendly," results from the tabular form of "element-variable-desired value." Elements in the table are equivalent to actual parts of homes. Accordingly, system users can easily compare the design guidelines with actual homes or drawings. Meanwhile, the third characteristic, "comprehensive," originates in the understanding about sustainability and housing elements. As shown in **Figure 1**, we inclusively examined the sustainability conditions from two aspects: environment and well-being. Moreover, when selecting housing elements, we analyzed homes based on two fundamental factors: material and space. Consequently, the completed design guidelines could deal with various environmental, social, and economic issues, such as climate change, aging population, and workplace needs.

The fourth feature, "flexible toward optimization," results from the process of revising the design guidelines. As shown in **Figure 2**, the revision process has been created by combining the two aspects: (1) updates of related knowledge and information, (2) feedback from users. Through the updates of related knowledge and information, the system designers can adapt the design guidelines to deal with the changing necessities of the situation. On the other hand, the feedback loops help make the design guidelines more accurate and user-friendly. Therefore, repeatedly using that revision process enables the system designers to optimize the design guidelines to pursue sustainability.

Our future work includes further research and practice on sustainable housing design. First, following the revision process demonstrated in **Figure 2**, we are planning to revise the sustainable housing design guidelines for general use as well as those for use in Japan. Moreover, we must secure the coordination between the guidelines for housing design and urban design. Through such future work, we are aiming to refine the system-control-based methodology for sustainable design.

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