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System Control for Sustainability: Application to Building Design

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/65875>

Abstract

In order to meet environmental, social and economic sustainability objectives, an immediate transformation needs to occur in housing design. We have been investigating a methodology for sustainable home design by applying control science because it can be applied to all of goal-oriented tasks. Our first study has shown the basic control system for sustainability. After that, regarding home as the complex of material and spatial elements, we have identified each element's variables and their desired values that lead to sustainability. Utilizing these schemes, we have composed the "control system for promoting sustainable home design" in which the "sustainable design guidelines" and "sustainability checklist" are incorporated. Following this control system, we have actually designed a home and constructed it. The results of this study indicate that if system users closely follow the methodology, they can design comprehensively sustainable and sufficiently energy-saving homes. Furthermore, the studies imply that this methodology is superior in user-friendliness as well as adaptable to regional differences and changes over time.

Keywords: control system, sustainable housing, climate change, adaptation, ageing population, material elements, spatial elements

1. Introduction

Buildings including homes have been causing various environmental problems such as climate change, environmental destruction, pollution, and depletion of natural resources. According to the IPCC, in 2010, buildings accounted for 32% of total global final energy use (24% for residential and 8% for commercial) and 19% of all global greenhouse gas emissions [1]. In the twenty-first century, continued emission of greenhouse gases will cause further warming, increasing the likelihood of severe, pervasive, and irreversible impacts on people and ecosystems [2].

Reducing climate change risks would require both “mitigation” and “adaptation” measures [2, 3], typically shown in **Table 1**. The chapter of “Climate-Resilient Pathways: Adaptation, Mitigation and Sustainable Development” in *Climate Change 2014* explains, “It takes sustainable development as the ultimate goal, and considers mitigation as a way to keep climate change moderate rather than extreme. Adaptation is considered a response strategy to anticipate and cope with impacts that cannot be (or are not) avoided under different scenarios of climate change” [4].

Mitigation measures	Adaptation measures
<ul style="list-style-type: none"> • Energy conservation • Harnessing renewable energy • Conserving timber resources • Carbon dioxide capture and storage 	<ul style="list-style-type: none"> • Measures against inland and coastal floods • Measures for dealing with water shortages • Heatstroke warning systems • Building resilient infrastructure

Table 1. Typical examples of mitigation and adaptation measures.

While growing human activities are aggravating climate change and seriously harming environmental sustainability, “ageing population” is becoming a fierce challenge to social and economic sustainability. According to the book titled *Agequake*, in the twenty-first century there will be more people older than younger ones. The “agequake” will turn the age pyramids upside down, first in Japan and Europe, but ultimately throughout the world [5]. Demographic pressures will continue to mount and add to concerns about fiscal sustainability [6, 7]. Ed Harding – International Longevity Centre UK clearly states, “Suitable housing is central to the challenge of population ageing. Appropriate housing offers the potential to reduce expenditure on public services and promote older people’s independence and wellbeing” [8].

It is obvious that an immediate transformation needs to occur in housing design, in order to meet sustainability objectives. Achieving sustainable development or sustainability is the ultimate goal-oriented task of humankind. It is a rational and reliable approach to apply control science to this challenge. Control science can be applied to all of goal-oriented tasks; it has already produced remarkable results in various fields, including engineering [9].

Based on the above recognition, we have been investigating a methodology for sustainable housing design by applying control science. Our first study has demonstrated the basic control system for sustainability. After that, we have systematically determined the relationships between the elements of home and sustainability. Utilizing these schemes, we have shown the control system for promoting sustainable home design and started putting it into practice. This paper reviews these studies and discusses the characteristics of the methodology and future prospects of our research.

2. Basic control system for sustainability

In the basic control system for sustainability (**Figure 1**), “controlled objects” are human activities which need to be controlled [10, 11]. “Disturbances” are harmful influences on controlled objects, which are caused by environmental, social, or economic problems. Examples of the disturbances are damaging influences caused by environmental pollution, floods or land-

slides resulting from environmental destruction, and various impacts caused by climate change. Moreover, “adaptation” has been added as the route from “disturbances” to “sustainability,” based on the recent IPCC’s recognition. “Controlled variables” are the variables that are related to the human activities and need to be controlled for basically solving or preventing the problems or adapting to disturbances.

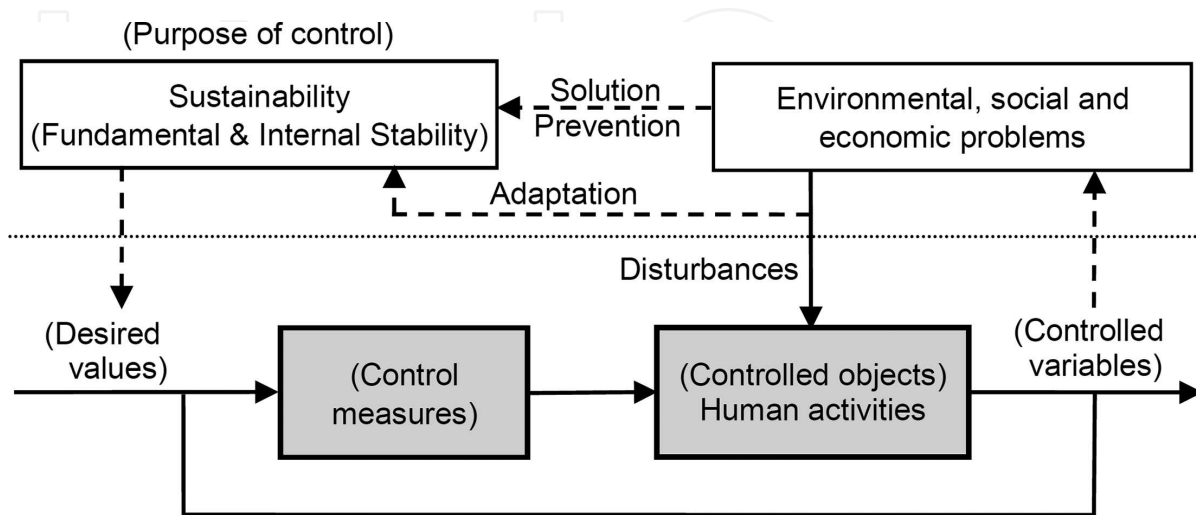


Figure 1. Basic control system for sustainability.

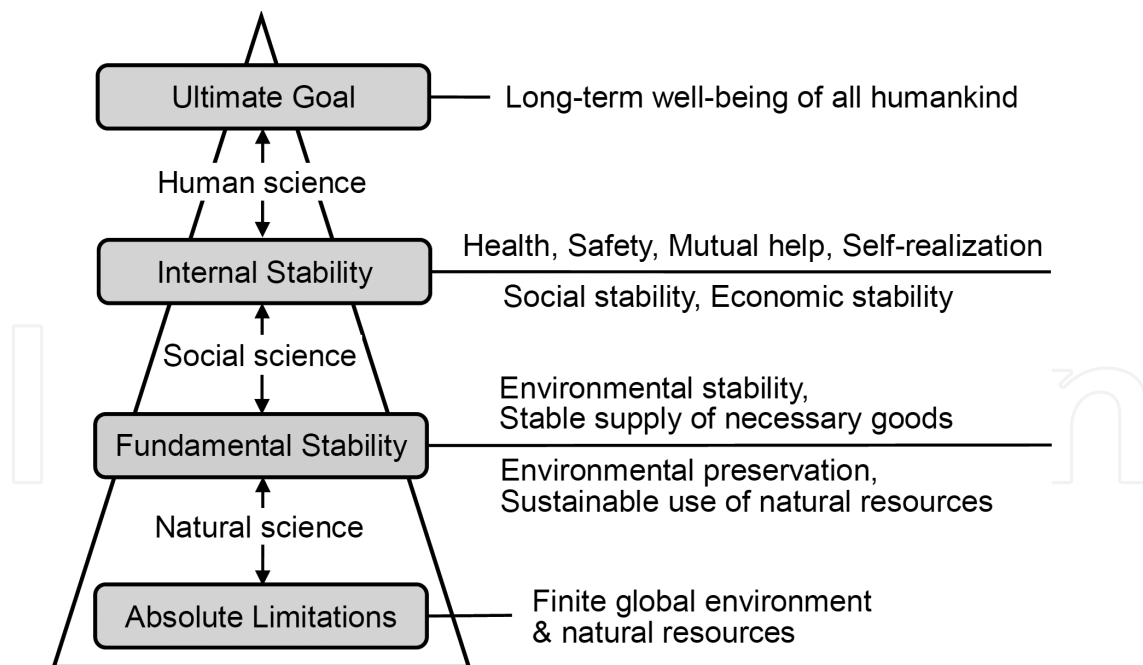


Figure 2. Model of sustainability.

“Desired values” are derived from the purpose of control, that is to say, sustainability. The model of sustainability (Figure 2) demonstrates that sustainability requires both “fundamental stability” and “internal stability,” in order to accomplish the long-term

well-being of humankind or ultimate goal, within the finite global environment and natural resources, or absolute limitations [10, 11]. Fundamental stability means environmental stability and a stable supply of necessary goods; the conditions for fundamental stability are environmental preservation and the sustainable use of natural resources. On the other hand, internal stability means social and economic stability; the conditions for internal stability are health, safety, mutual help, and self-realization, which are essential for well-being of humans.

The control objective is to adjust the controlled variables to their desired values. Furthermore, the control system requires designing and implementing “control measures,” or measures for achieving the control objective.

3. Methodology for sustainable housing design

3.1. Two-step preparatory work

Our previous study has provided the two-step preparatory work for sustainable home design. The two steps are (1) “determining the relationships between the standard home and sustainability” and (2) “sustainability checkup on a home as an object” [12, 13]. The following sections show the essence of these two steps.

3.1.1. Determining the relationships between the standard home and sustainability

In the first step, system designers select important elements of the standard home and determine the relationships between such elements and sustainability.

When selecting important elements, we have analyzed two main factors: “material” and “space” [12]. “Material” regards the home as the aggregate of material elements such as framework, exterior, interior, and piping; “space” considers it as the aggregate of spatial elements, such as rooms and areas. Based on these two factors, we have selected important elements, from which extracts are shown in the central column of **Table 2**. “Material elements” are from “framework” to “equipment for harnessing natural energy;” “spatial elements” are from “specified bedroom” to “garden area.”

After that, we have determined the relationships between these elements and sustainability. The left side of **Table 2** shows the relationships between the elements and fundamental stability; the right side demonstrates the relationships between the elements and internal stability. Considering the relationships between each element and the stability conditions, we have identified variables that indicate the degree of stability. Moreover, we have set the desired values of these variables that can meet relevant stability conditions.

Choosing only one element from **Table 2**, that is, “framework,” I concretely describe the relationships. Considering the relationship between “framework” and “sustainable use of natural resources,” a condition for fundamental stability, we have identified “durability” and “materials” as variables. The desired value of “durability” is set at “Grade 3” in the deterioration resistance grades (building frames, etc.) of JHPIS, that is, the Japan housing performance

Relationships with fundamental stability			Element	Relationships with internal stability		
Condition	Desired value	Variable		Variable	Desired value	Condition
Sustainable use of resources	JHPIS 3.1: Grade 3	Durability	Framework	Resistance to earthquakes	JHPIS 1.1: Grade 2 or over	Safety
Sustainable use of resources	CASBEE LR _H 2 1.1: Level 4 or over	Materials				
Sustainable use of resources	CASBEE LR _H 2 1.3: Level 4 or over	Durability	Exterior (outer wall, roof, etc.)	Fire resistance (outer wall)	JHPIS 2.6: Grade 3 or over	Safety
Sustainable use of resources	CASBEE Q _H 2 1.2 & 3: Level 4 or over	Materials		Shape & color	Consideration for the landscape	Health
Enviro-preserve Sustainable use of resources	JHPIS 5.1: Grade 4	Thermal insulation performance	Windows & doors	Sound insulation performance	JHPIS 8.4: Grade 2 or over	Health
Enviro-preserve Sustainable use of resources	CASBEE Q _H 1 1.1.2: Level 4 or over	Sunlight adjustment capability		Protection of glass against impacts	With shutters	Safety
Sustainable use of resources	CASBEE LR _H 2 1.4: Level 4 or over	Materials	Interior	Measures against formaldehyde	JHPIS 6.1: Grade 3	Health
Enviro-preserve Sustainable use of resources	LED	Type of light	Lighting fixtures			
Enviro-preserve Sustainable use of resources	CASBEE LR _H 1 3.2: Level 4 or over	Rainwater equipment	Equipment for rainwater use	Rainwater equipment	CASBEE LR _H 1 3.2: Level 4 or over	Health Safety (in crisis)
Enviro-preserve Sustainable use of resources	100% or more of the total energy usage	Harnessed natural energy	Equipment for harnessing natural energy	Harnessed natural energy	100% or more of the total energy usage	Health Safety (in crisis)
			Specified bedroom	Routes to toilet & bath area, dining room, kitchen, and entrance	Accessible without steps	Health safety
Enviro-preserve Sustainable use of resources	Placing them closer	Areas in the home	Areas relating to water use & hot water supply			
			Doorways	Differences in level	No differences	Health safety
				Width	75 cm or more	
Enviro-preserve	40% or more	Ratio to the exterior area	Garden area			

Note: (1) JHPIS means the Japan housing performance indication standards (for new homes).
 (2) CASBEE means CASBEE for detached houses (for new construction)—technical manual 2010 edition.

Table 2. Relationships between the standard home and sustainability [Essence].

Relationships with fundamental stability				Element	Relationships with internal stability			
Desired value	Assess.	Measured or estimated value	Variable		Variable	Measured or estimated value	Assess.	Desired value
JHPIS 3.1: Grade 3	No	JHPIS 3.1: Grade 1	Durability	Framework	Resistance to earthquakes	JHPIS 1.1 & 1.2: Grade 1	No	JHPIS 1.1: Grade 2 or over
CASBEE LR _H 2 1.1: Level 4 or over	OK	CASBEE LR _H 2 1.1: Level 4	Materials					
CASBEE Q _H 2 1.2 & 3: Level 4 or over	No	CASBEE Q _H 2 1.2 & 3: Level 2	Durability	Exterior (Outer wall, roof, etc.)	Fire resistance (Outer wall)	JHPIS 2.6: Grade 3	OK	JHPIS 2.6: Grade 3 or over
CASBEE LR _H 2 1.3: Level 4 or over	No	CASBEE LR _H 2 1.3: Level 3	Materials		Shape & color	Consideration for the landscape	OK	Consideration for the landscape
JHPIS 5.1: Grade 4	No	JHPIS 5.1: Grade 1	Thermal insulation performance	Windows & doors	Sound insulation performance	JHPIS 8.4: Grade 1	No	JHPIS 8.4: Grade 2 or over
CASBEE Q _H 1 1.1.2: Level 4 or over	No	CASBEE Q _H 1 1.1.2: Level 3	Sunlight adjustment capability		Protection of glass against impacts	With shutters	OK	With shutters
CASBEE LR _H 2 1.4: Level 4 or over	OK	CASBEE LR _H 2 1.4: Level 4	Materials	Interior	Measures against formaldehyde	JHPIS 6.1: Grade 3	OK	JHPIS 6.1: Grade 3
LED	No	Fluorescent	Type of light	Lighting fixtures				
CASBEE LR _H 1 3.2: Level 4 or over	No	No equipment	Rainwater equipment	Equipment for rainwater use	Rainwater equipment	No equipment	No	CASBEE LR _H 1 3.2: Level 4 or over
100% or more of the total energy	No	0 (zero)	Harnessed natural energy	Equipment harnessing natural energy	Harnessed natural energy	0 (zero)	No	100% or more of the total energy
				Specified bedroom	Routes to toilet & bath area, dining, kitchen, and entrance	With steps	No	Accessible without steps
Placing them closer	OK	Placing them closer	Areas in the home	Areas water use & hot-water supply				
				Doorways	Differences in level	With differences	No	No differences
					Width	60-70 cm	No	75 cm or more
40% or more	OK	45%	Ratio to the exterior area	Garden area				

Note: (1) JHPIS means the Japan housing performance indication standards (for new homes).

(2) CASBEE means CASBEE for detached houses (for new construction)—technical manual 2010 edition.

(3) When this checklist is used for the inspection or evaluation of existing homes, JHPIS (for existing homes) and CASBEE for detached houses (for existing building)—technical manual 2011 edition need to be referred to, instead of the “for new homes” version and “for new construction” version, respectively.

Table 3. An example of sustainability checkup on a home as an object [Essence].

indication standards (for new homes) [14]. Meanwhile, the desired value of “materials” is set at “Level 4 or over” in the assessment levels of the “use of materials effective for resource saving and waste prevention” of CASBEE, that is, CASBEE for detached houses (for new construction)—technical manual 2010 edition [15].

On the other hand, considering the relationship with “safety,” a condition for internal stability, we have selected “resistance to earthquakes” as a variable and set its desired value at “Grade 2 or over” in the “seismic resistance grades (prevention of collapse of building structures)” of JHPIS [14].

In addition, **Table 2** is the first updated version, which has been revised due to several reasons. First, we have revised the table so that following it leads to obtain long-life quality housing (*Choki Yuryo Jutaku*) certification. The long-life quality housing certification started in 2009 and has rapidly spread in Japan because of various incentives, such as tax reduction [16]. The second reason is the addition of adaptation measures against impacts caused by climate change. Other reasons are rapid spread of new technology, namely LED light, and minor changes in expressions and desired values.

3.1.2. Sustainability checkup on a home as an object

In the second step, “sustainability checkup on a home as an object” is conducted. To be concrete, first, the variables of a home as an object are measured or estimated. Next, the measured or estimated values are compared with the desired values and the comparison results are assessed. **Table 3** demonstrates the essence of “sustainability checkup,” which includes an example of the results.

In this case, the comparison results have simply been assessed, whether the variable reaches the desired value or not, that is, “OK” or “No.” The variables that have been assessed as “No” need to be identified as “controlled variables.”

3.2. Control system for promoting sustainable home design

Based on the basic control system and the two-step preparatory work, we have composed the control system for promoting sustainable home design.

First, as shown in **Figure 3**, we have derived two functions from the two-step preparatory work, that is, the “sustainable design guidelines” from step 1 and the “sustainability checklist” from step 2, respectively.

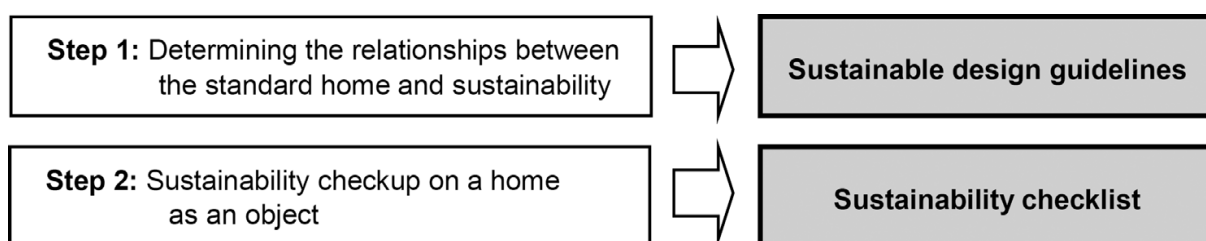


Figure 3. Two functions derived from the two-step preparatory work.

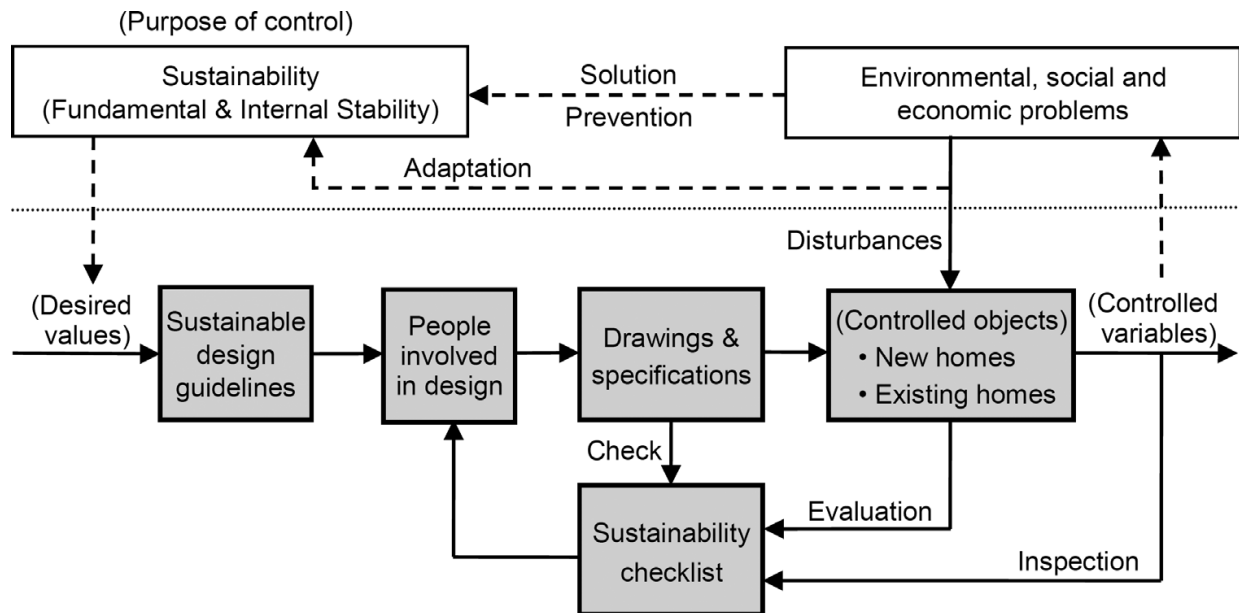


Figure 4. Control system for promoting sustainable home design.

Next, we have composed the control system for promoting sustainable home design in which these two functions are incorporated. **Figure 4** demonstrates the block diagram of the control system. In this control system, “controlled objects” include both “new homes” and “existing homes.” The following describes how to use the two functions in the process of sustainable home design, on the order of “new homes” and “existing homes.”

3.2.1. New homes

In the case of new homes, first, information on the desired values reaches “people involved in design” through the “sustainable design guidelines” [17]. “People involved in design” include homeowners, architects, designers, and homebuilders. Such people make a design so that the variables of home’s elements can attain their desired values as close as possible. At important steps in the design process, they check the drawings and specifications by referring to the “sustainability checklist.” After the construction is finished, the new home can be also evaluated against the “sustainability checklist.”

3.2.2. Existing homes

When existing homes are the objects, the design process starts with “inspection” on the home as an object. The “people involved in design” measure or estimate each element’s variables of that home by using the “sustainability checklist.” Next, they compare the measured or estimated variables with their desired values and assess the comparison results.

Table 3 in the last section is equivalent to an example of such inspection results. In addition, when inspecting an existing home and measuring or estimating variables by referring to the JHPIS or CASBEE for detached houses, “people involved” use the “for existing homes” version or “for existing building” version, instead of the “for new homes” version or “new construction” version, respectively. The “JHPIS (for existing homes)” and “CASBEE

for detached houses (for existing building)" are almost the same as their new home versions; however, these existing home versions include suitable assessment criteria for existing homes [14, 18].

After the inspection, the "people involved" usually make a design for improvement so that controlled variables meet their desired values as close as possible. When improvement is assumed to be technically difficult or costly, reconstruction can be chosen. Similar to the cases of new homes, they check the drawings and specifications for improvement or reconstruction against the "sustainability checklist." Moreover, sustainability of actually improved or reconstructed homes can be evaluated against the "checklist."

4. Case study

Following the above methodology, we designed a new home and constructed it. After this home began to be used, we objectively assessed its environmental performances.

4.1. Design process

In this case, the homeowner, who is the author of this paper, made the basic design by himself. After that, he made a contract with a housing manufacturer whose skills seemed sufficient to achieve the desired values as shown in **Table 2**.

In the basic design stage, the homeowner used the "sustainable design guidelines" and "sustainability checklist," in addition to following related laws and regulations. First, when making the site plan and floor plans, he considered spatial elements, such as "specified bedroom," "areas relating to water use and hot water supply," and "garden area." In addition, considering natural ventilation and day lighting, he planned "position and area of windows," which is omitted from the tables due to space limitations. Moreover, he examined how to install "equipment for harnessing natural energy" and "equipment for rainwater use" so as to satisfy the desired values of these material elements' variables.

At the beginning of the detailed design stage, the homeowner requested the architects of the housing manufacturer to refer to the "guidelines" and "checklist." They readily accepted them because the material and spatial elements are equivalent to real parts of the home. Next, we determined the site plan, floor plans, elevation, and fundamental specifications. After that, the architects designed the home's elements such as framework, exterior, windows and doors, interior, and lighting fixtures, so that as much as possible, the elements' variables meet their desired values.

After the design stage, we obtained long-life quality housing certification as well as building confirmation. Subsequently, the home, a wooden structure with two stories, was constructed in a residential area of suburban Tokyo.

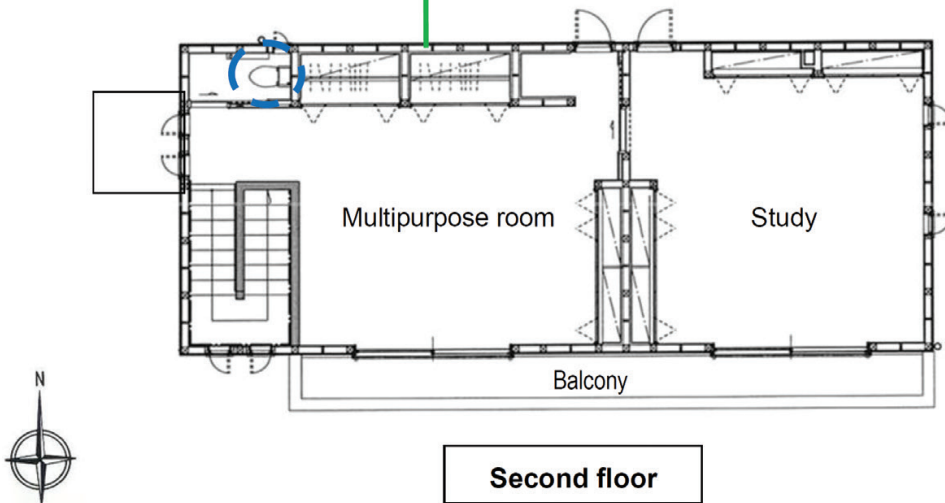
4.2. Results

This section shows the results of the design and construction, focusing on main elements' variables.

- First floor area: 61.48 m²
- Second floor area: 61.48 m²
- Total floor area: 122.96 m²

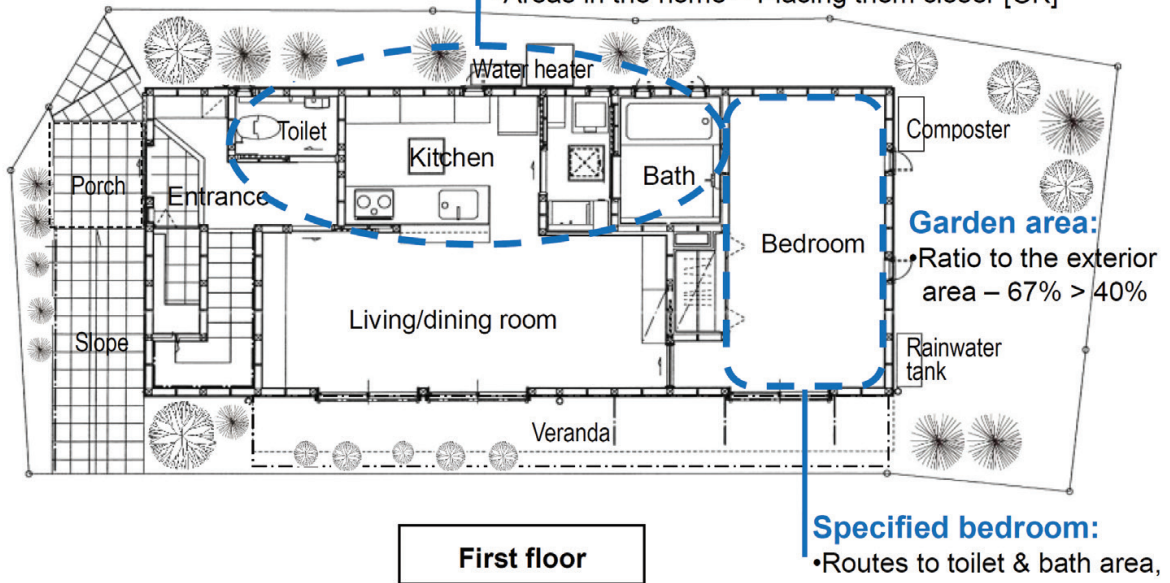
Framework:

- Resistance to earthquakes – JHPIS 1-1: Grade 3 > Grade 2
- Durability – JHPIS 3-1: Grade 3 [OK]
- Materials – CASBEE LR_{H2} 1.1 Level 5 > Level 4



Areas relating to water use and hot-water supply:

- Areas in the home – Placing them closer [OK]



Garden area:
•Ratio to the exterior area – 67% > 40%

Specified bedroom:
•Routes to toilet & bath area, dining room, kitchen, and entrance - Accessible without steps [OK]

Figure 5. Site and floor plans.

First, **Figure 5** demonstrates the site plan and floor plans in which three spatial elements and one material element are referred to:

- Specified bedroom

A “specified bedroom” is a bedroom which is used or expected to be used by elderly or wheelchair users. The owner couple was in their late fifties and not handicapped when they moved in. However, in order to prepare for their future, both their bedroom and other essential areas for their daily living, all have been placed on the same first floor. This arrangement enables them to have access to such areas without any steps.

- Areas relating to water use and hot water supply

“Areas relating to water use and hot water supply,” that is, kitchen, bath, washing room, toilet, and a place to put the water heater, have been placed closer. This planning reduces the total length of water piping and drainage piping. Moreover, this consideration helps to reduce heat loss from hot water piping.

- Garden area

A “garden area” is an area with plants such as trees, shrubs, herbs, grasses and vegetables. The ratio of this home’s garden area to the total exterior area is 67%, which surpasses its desired value, 40%. A larger garden area is favorable for environmental preservation, including mitigation of heat island phenomenon, and a higher level of biodiversity.

- Framework

This home has been designed so that the “resistance to earthquakes” of the framework meets “Grade 3” in the seismic resistance grades of JHPIS, which surpasses the required level, Grade 2.

The “durability” of the framework satisfies the desired value, or “Grade 3” in the deterioration resistance grades of JHPIS. Grade 3, the highest grade, requires measures to extend the period up to when large-scale renovation becomes necessary after three generations, or about 75–90 years, under normally assumed conditions and maintenance [14].

As for “materials,” more than half of the wood is domestically produced timber, legality and sustainability of which are authorized. This consideration has sufficiently satisfied the desired value.

Figure 6 shows external appearance, including a panoramic view, with the descriptions of four material elements: exterior, windows and doors, equipment for harnessing natural energy, and equipment for rainwater use.

- Exterior

The “fire resistance” capacity of the outer walls fulfills the desired value, namely “Grade 3” in the fire resistance grades of JHPIS [14]. Meanwhile, the “shape” is simple but accented by

Equipment for harnessing natural energy:

- Harnessed natural energy –
516% of the total energy usage > 100%

**Equipment for rainwater use:**

- Rainwater equipment –
CASBEE LR_H1 3.2: Level 4 [OK]



(Large windows with shutters)

Exterior (outer wall, roof, etc.):

- Fire resistance (outer wall) –
JHPIS 2-6: Grade 3 [OK]
- Shape & color – Consideration for
the landscape [OK]

Windows and doors:

- Thermal insulation performance – JHPIS 5-1: Grade 4 [OK]
- Sunlight adjustment capability –
CASBEE Q_H1 1.1.2: Level 5 > Level 4
- Protection of glass against impacts –
With shutters (large windows) [OK]

Figure 6. External appearance.

the balcony; the “color” of the outer walls, light beige, is coordinated with the colors of other parts, such as the windows and doors, entrance porch, and rainwater pipes. We are expecting that these considerations bring harmony and stability to the landscape.

- Windows and doors

Higher “thermal insulation performance” and “sunlight adjustment capability” of the openings contribute to reducing energy for heating and air conditioning as well as the occupants’ health and comfort [15, 19, 20]. However, both of these variables appear on only the left side of **Tables 2** and **3** as the space is limited. The “thermal insulation performance” of this house’s openings meets the desired value, or the highest grade of the relevant item of JHPIS. Meanwhile, the “sunlight adjustment capability” reaches “Level 5” in the assessment levels of the CASBEE’s relevant item. “Level 5” means that the sunlight penetration ratio of the subject windows can be reduced to 0.3 or less in the summer and 0.6 or over in the winter [15].

We have installed “shutters” on the large windows facing south, in order to “protect the glass against impacts” such as fire, hurricane, and flying objects. This installment is also expected to decrease the risk of being damaged by tornados or huge typhoons, which can be caused by serious climate change.

- Equipment for harnessing natural energy

The surface of the single-pitch roof is almost entirely covered with solar panels. The total generating capacity of the 49 solar panels amounts to 11.4 kW. In the first year, after moving-in, this solar system produced the electricity of 15,911 kWh. In the same period, the energy used in this home has been 3085 kWh. Accordingly, the energy self-sufficiency reached an amazing 516%. This value substantially exceeded the desired value, 100%.

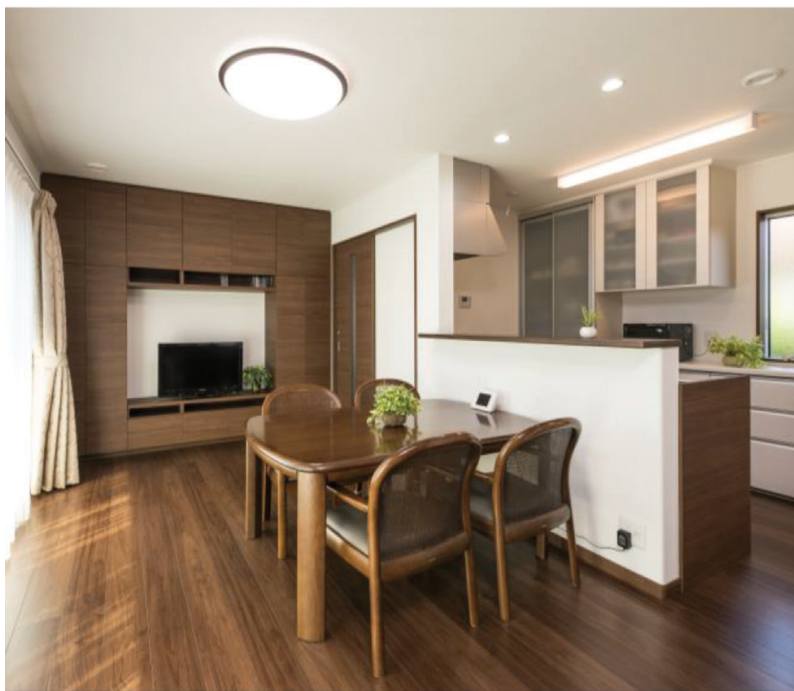
In addition, equipment for harnessing natural energy secures alternative energy sources and increases resilience or passive survivability in crisis. Therefore, it is recognized as an “adaptation” measure as well as “mitigation” [3, 21].

- Equipment for rainwater use

“Equipment for rainwater use,” in this case, a 200-l rainwater tank, meets the desired value. The rainwater in this tank is used for watering the garden, which can reduce the quantity of

Lighting fixtures:

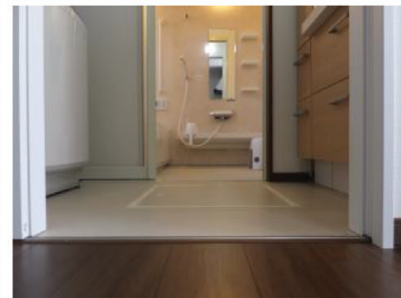
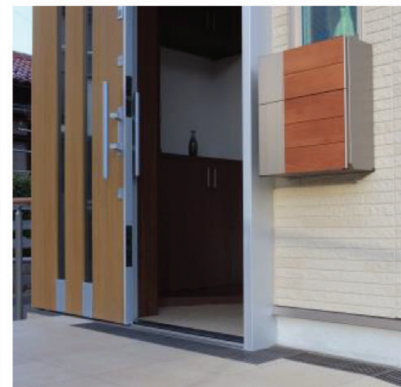
- Type of light – LED [OK]



Interior:

- Measures against formaldehyde – JHPIS 6.1: Grade 3 [OK]

(Entrance)



(Washing room and bath)

Doorways:

- Differences in level – No differences [OK]
- Width (except bath) – 75cm [OK]

Figure 7. Interior, lighting fixtures and doorways.

water supply. At the same time, storing rainwater is also considered one of “adaptation” measures because it leads to securing emergency water supply [3, 21].

Figure 7 illustrates two material elements, namely “interior” and “lighting fixtures,” and one spatial element, namely “doorways.”

- Interior

Interior, which includes floors, walls and ceilings, requires “measures against formaldehyde” as an important variable. Formaldehyde is a harmful pollutant; therefore, its desired value is set at the highest level of the countermeasures against formaldehyde in JHPIS. All of the interior finish and base materials used in this house are certified materials that meet the desired value.

- Lighting fixtures

All of the “lighting fixtures” of this house use “LED” lights, which meets the desired value.

- Doorways

We have taken barrier-free and universal design into maximum consideration. All of the “doorways” in this home have no “difference in level,” and “width” of the doorways on the first floor except for the bath is 75 cm.

4.3. Performance evaluation

4.3.1. Sustainability performance

After the home started to be used, we had its sustainability evaluated by the “CASBEE for detached houses (for new construction, 2010 edition).” The evaluation results show that the “environmental quality (Q)” and “environmental load (L)” have been “88” and “13” respectively. Consequently, as demonstrated in **Figure 8(A)**, the score of Building Environmental

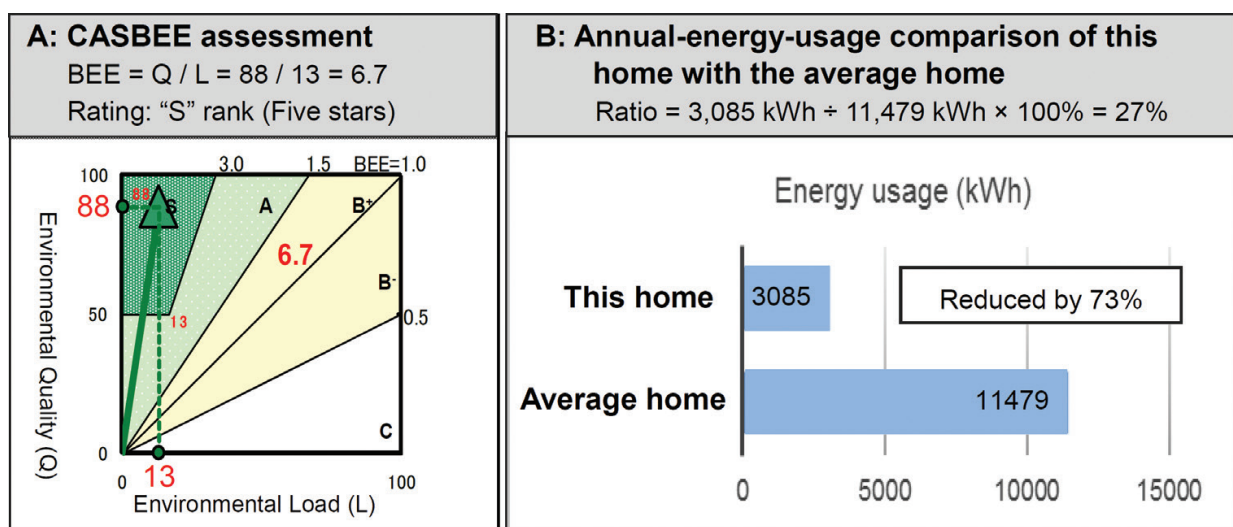


Figure 8. Sustainability performance and energy-saving performance of this home.

Efficiency (BEE) has reached 6.7, which has rated and certified the home with the highest “S,” or “five stars” [22].

4.3.2. Energy-saving performance.

We have analyzed the energy-saving performance of this home, by comparing its annual energy usage with that of the average home. The actual total energy usage in this home in a year was 3085 kWh. On the other hand, the average annual energy usage of the same two-person-household detached houses amounts to 41,325 MJ [23], which is equivalent to 11,479 kWh. The usage of 3085 kWh is equal to 27% of 11,479 kWh. Therefore, as shown in **Figure 8(B)**, this house has reduced energy consumption by over 70%, as compared to the average house under the same conditions.

5. Discussion

This chapter discusses the results of this study from the following perspectives: (1) effects of the methodology on achieving sustainable homes, (2) characteristics of the methodology, (3) future work, and (4) applicability of the methodology.

5.1. Effects of the methodology on achieving sustainable homes

As shown in the case study, we have designed a home, following the methodology. To be concrete, we have designed the home’s parts, or elements, so that as much as possible the elements’ variables meet their desired values. After the home started to be used, we have objectively assessed its environmental performances. First, CASBEE for detached houses, a comprehensive assessment system, has readily ranked the home in the highest “S,” with an extremely high score of BEE. Meanwhile, the energy-saving performance assessment has shown that the total energy usage of this home is equal to about 27% of the average home under the same conditions. These assessment results indicate that if system users closely follow the methodology, they can achieve comprehensively sustainable and sufficiently energy-saving homes.

5.2. Characteristics of the methodology

The characteristics of the methodology includes (1) visualization of the processes for promoting sustainable home design, (2) user-friendliness, (3) adaptability to regional differences and changes over time. In addition, the third point is beneficial for the system designers, whereas the second point is convenient for the system users.

5.2.1. Visualization of the processes

Figure 4 has demonstrated the control system in which the “sustainable design guidelines” and “sustainability checklist” are incorporated. It concisely shows processes for promoting sustainable design on both new and existing homes. Moreover, this schematic diagram contains “disturbances” caused by problems, such as climate change. Accordingly, we consider

that this diagram itself explains the whole picture of the sustainable design processes with the guidelines and checklist and helps people concerned to recognize them.

5.2.2. User-friendliness

The “sustainable design guidelines” and “sustainability checklist” are simple tables. The material and spatial elements in these functions are equivalent to real parts of homes. Therefore, the system users smoothly design, check, evaluate, and inspect the home, by easily comparing the drawings or real home with the guidelines or checklist. In fact, the design process in the case study has supported the user-friendliness of the functions; the designers of the home easily accepted them and efficiently made drawings.

5.2.3. Adaptability to regional differences and changes over time

This methodology originally has a mechanism of easily adapting to regional differences. As shown in Section 3.1., system designers determine the elements’ variables and their desired values, considering the relationships between the elements and sustainability conditions. This determination process has a mechanism of reflecting various regional features, such as natural, geographical, social, and cultural features. For example, a variable of the framework, “resistance to earthquakes,” reflects a geological feature of earthquake-prone Japan. This mechanism also enables the system designers to easily vary the guidelines according to the characteristics of the region. For instance, if the region is in a snowy area or strong wind area, they can adjust the guidelines to the region, by adding “resistance to snowfall” or “resistance to wind” as a variable of the framework.

This characteristic also leads to the flexibility of the functions toward changes over time. In fact, in order to adjust to ageing population, we could smoothly take basic barrier-free design in the guidelines and checklist. To be concrete, we have added necessary spatial elements, such as “specified bedroom” and “doorways.” Similarly, in order to adapt housing to climate change, we have taken adaptation measures in the functions. That is to say, we have added relevant variables including “protection of glass against impacts.”

5.3. Future work

5.3.1. Further case studies

The case study has successfully demonstrated the effects of the methodology on achieving sustainable homes. However, in order to confirm the effects, we need to conduct more case studies, applying it to both new and existing homes. We expect that an increase in the number of case studies will also strengthen the credibility of the methodology and help it to be widely used.

5.3.2. Update of the guidelines and checklist

It is necessary to update the “guidelines” and “checklist,” as the occasion arises. Probably, such revision will have to be made due to several reasons, for example, in response to the results of case studies, changes in the natural and social environment, developments in related sciences, and innovations in related technologies. Furthermore, through such processes, we are planning to examine how to revise them efficiently.

5.4. Applicability of the methodology

This section discusses the applicability of the methodology from two viewpoints: (1) application to other regions, (2) application possibility to other kinds of objects.

5.4.1. Application to other regions

As shown in Section 2, this methodology, specifically the “guidelines” and “checklist,” has a characteristic of being adaptable to regional differences. Therefore, it will probably be easy for system designers in another region to adapt the functions for that region. To be concrete, the system designers can compile its regional version, by examining the elements and adapting the elements’ variables and their desired values to the region’s features.

5.4.2. Application possibility to other kinds of objects

Theoretically, the methodology can be applied to various kinds of objects, or human activities. That is to say, in the control system of **Figure 4**, “homes” in the block of “controlled objects” can be replaced with other kinds of objects. Possibility of such replacement depends on if the table of relationships, or the “guidelines,” can be compiled or not.

It will not be difficult to apply it to other types of buildings besides the home, since the structure is similar to one another. It is also possible in theory to apply it to other sorts of infrastructure, such as roads and parks. Furthermore, we consider it possible to apply the methodology to more complex and large-scale objects, such as the city and town, for they are also regarded as the complex of material and spatial elements.

Acknowledgements

The author would like to thank Mr. Vance Carothers for his valuable advice and suggestions on the English expression of this paper.

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