Chapter

How to Design Sustainable Structures

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Abstract

Achieving sustainability is the ultimate goal-oriented challenge. Control science can be applied to all goal-oriented tasks. Accordingly, utilizing control science, we have been progressing in research on sustainability and sustainable design. Here this chapter illustrates the methodology for designing sustainable structures with two examples. In this context, "structures" include various city components, such as buildings, roads, and parks, as well as the whole city. First, this chapter illustrates the control system for promoting sustainable structure design. Next, it shows the process of producing and revising sustainable structure design guidelines. Based on this process, Section 4 demonstrates how to produce and revise sustainable housing design guidelines, with the completed guidelines' extracts. Moreover, Section 5 outlines a way of producing sustainable urban design guidelines. Designing the whole city needs extensive spatial planning; therefore, the guidelines consist of three parts: (1) development allowable areas, (2) spatial relationships among city components, (3) principles of designing city components. This methodology's characteristics include visualization of the whole picture for promoting sustainable design, user-friendliness, comprehensiveness, and adaptability to different and changing situations.

Keywords: sustainable structure, system control, design guidelines, housing design, urban design, sustainable design, climate change

1. Introduction

Cities are becoming increasingly related to environmental change and sustainability. Since 2007, more than half of the world's population has been living in urban areas; that share is projected to rise 60% by 2030 [1]. A vast number of buildings, transport systems, and other facilities occupy cities, where intense socio-economic activities are performed. On the other hand, there have been various urban problems, including sprawl, traffic congestion, environmental pollution, waste, unemployment, and crimes. World cities are responsible for up to 70% of harmful greenhouse gases [2]. Furthermore, cities lie near waters, such as seas and rivers; therefore, urban areas are at increased risk from flooding and sea-level rise caused by climate change.

Cities, as well as various city components, need to be designed and implemented toward sustainability. The Sustainable Development Goals (SDGs) set by the United Nations in 2015 also refer to cities, housing, and infrastructure. Typically, Goal 11 demands to make cities and human settlements inclusive, safe, resilient, and sustainable. Meanwhile, Goal 9 requires people to build resilient infrastructure [3].

As the term "goal" indicates, achieving sustainability is the ultimate goal-oriented challenge. The science of control can be applied to all goal-oriented tasks

[4]. Besides, control science has produced remarkable results in many fields, particularly engineering [4]. Accordingly, utilizing control science, we have been progressing in research on sustainability and sustainable design.

Based on our accomplished research results, this chapter illustrates the methodology for designing sustainable structures with two examples. First, it shows the "control system for promoting sustainable structure design" and "process of producing and revising sustainable structure design guidelines." Following these basic schemes, Section 4 demonstrates a way of producing and revising sustainable housing design guidelines. Furthermore, Section 5 outlines how to produce sustainable urban design guidelines.

2. Control system for promoting sustainable structure design

The "control system for promoting sustainable structure design" is demonstrated in **Figure 1**. The upper and lower areas divided by the dotted line represent the "theoretical world" and the "practical world," respectively.

In this control system, "controlled objects" are structures, which include both new and existing structures. In this context, "structures" include various city components, such as houses, other buildings, roads, and parks, as well as the whole city.

"Disturbances" mean harmful influences on controlled objects resulting from environmental, social, or economic problems. Instances of the disturbances are adverse effects due to environmental pollution and a variety of impacts caused by climate change. The course from "disturbances" to "sustainability" means "adaptation." This course has been added, on the basis of the current scientific understanding that achieving sustainability also needs adaptation measures to climate change impacts [5–8].

The purpose of control is the accomplishment of "sustainability." The model of sustainability (**Figure 2**) demonstrates that sustainability requires both fundamental stability and internal stability, to achieve the long-term well-being of all humankind, within the finite global environment and natural resources [9]. Fundamental stability means environmental stability and a stable supply of necessary goods; the conditions for fundamental stability are "environmental preservation" and "sustainable use of natural resources" [9]. Meanwhile, internal stability is social and economic stability; the

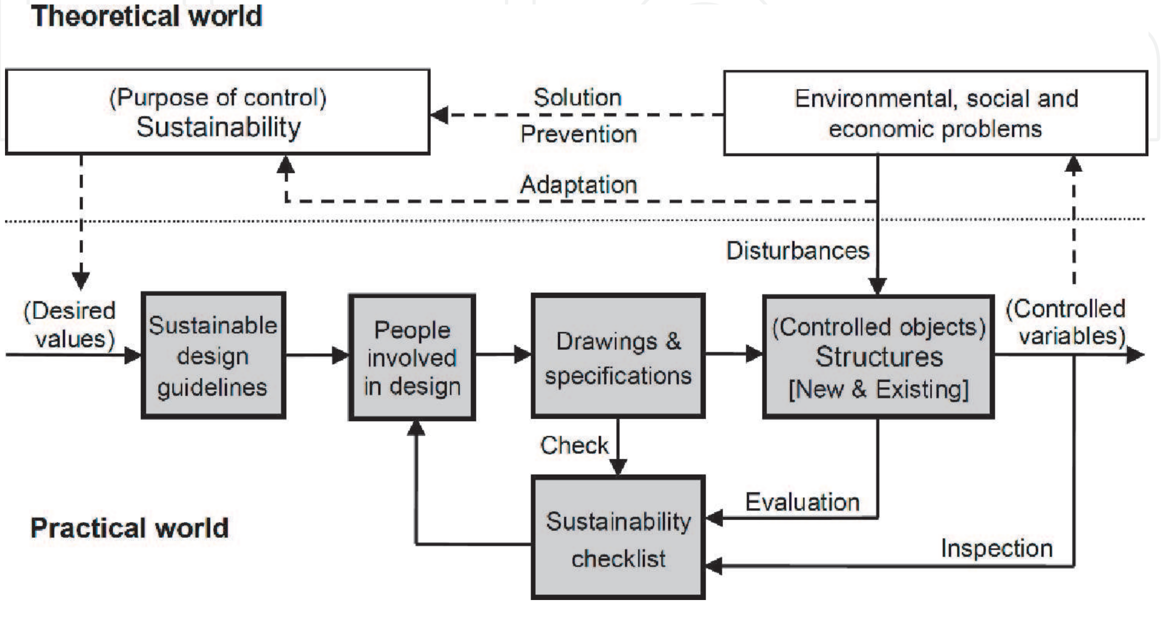

Figure 1.
Control system for promoting sustainable structure design.

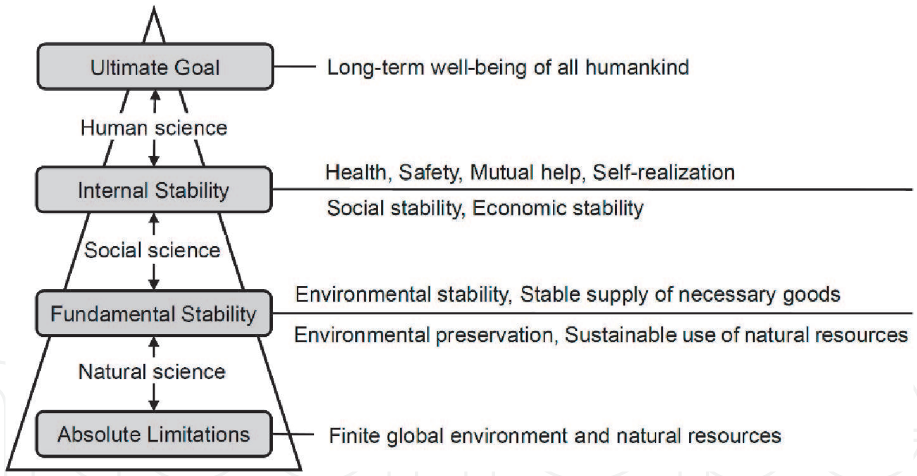

Figure 2.
Model of sustainability [9].

conditions for internal stability are "health," "safety," "mutual help," and "self-realization," which are essential for the humans' well-being [9].

"Controlled variables" mean the variables that relate to controlled objects and are necessary to be controlled for chiefly solving or preventing the problems or adapting to disturbances [10, 11]. On the other hand, "desired values" are extracted from the purpose of control, that is, sustainability. The control objective of this control system is to adjust the controlled variables to their desired values.

In the practical world, the subjects of control are "people involved in design." The subjects vary depending on types of structures. For example, if controlled objects are houses, people involved in design are homeowners, architects, designers, and homebuilders. Meanwhile, in case of the whole city, people involved include city planners, administrative staff, and representatives of the city residents.

In this control system, people involved in design adjust the controlled variables to their desired values, by using the "sustainable design guidelines" and "sustainability checklist." The design guidelines and checklist have nearly the same expressions, that is, elements, variables, and desired values. But the checklist is formed to smoothly compare measured or estimated variables to the desired values and search for controlled variables [10, 11].

When new structures are objects, information about the desired values first reaches "people involved in design" through the "sustainable design guidelines." People involved prepare "drawings and specifications," so that the variables of structure's elements can satisfy their desired values to the maximum. At significant phases in the design process, people involved in design check the drawings and specifications by seeing the "sustainability checklist" [10, 11].

In the case where objects are existing structures, the design process starts with "inspection" on the structure as an object. Referring to the "sustainability checklist," the "people involved in design" measure or estimate each element's variables of that structure. After finishing the inspection, the people involved mostly prepare "drawings and specifications" for improvement, so that controlled variables meet their desired values to full potential [10, 11].

3. Process of producing and revising sustainable structure design guidelines

The process of producing and revising the sustainable structure design guidelines and sustainability checklist is demonstrated in **Figure 3**. The upper area of the figure is the theoretical world; the lower area is the practical world.

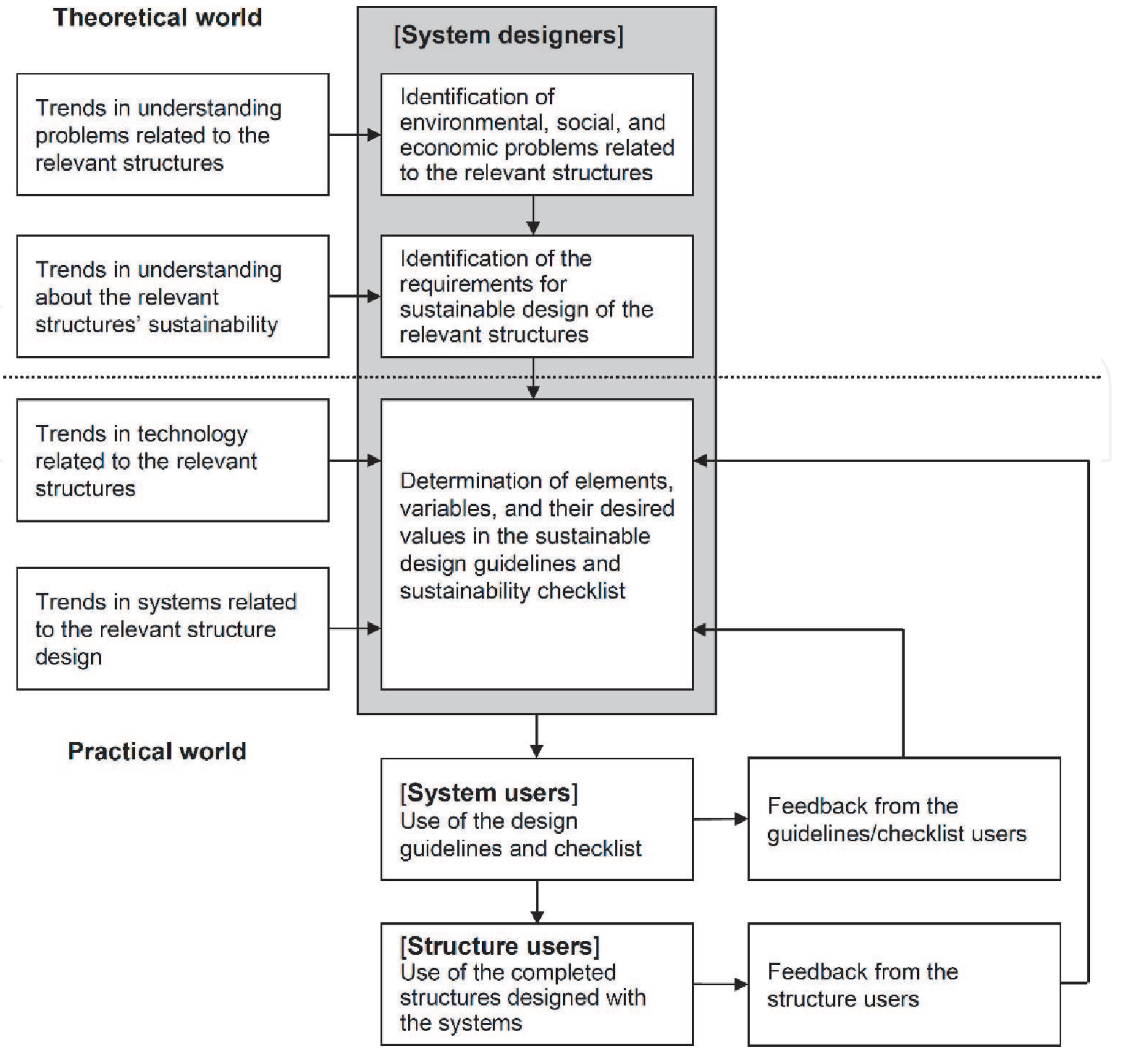

Figure 3.
Process of producing and revising the sustainable structure design guidelines and sustainability checklist.

The middle part shows the route of preparing and utilizing the "sustainable design guidelines" and "sustainability checklist." System designers first produce or revise the design guidelines and checklist through the process of three stages. After that, system users employ the design guidelines and checklist. Subsequently, structure users utilize the completed structures that have been designed with the guidelines and checklist.

The four blocks on the left side demonstrate the items to check when producing or revising the design guidelines and checklist. The contents of these four blocks can change over time. On the other hand, the two blocks at the lower right demonstrate the items to check when revising the systems, on the basis of the feedbacks from the guidelines/checklist users and the structure users.

3.1 Production process of the design guidelines and checklist

The production process of the design guidelines and checklist is composed of three stages: (1) identification of environmental, social, and economic problems related to the relevant structures, (2) identification of the requirements for sustainable design of the relevant structures, (3) determination of elements, variables, and their desired values in the design guidelines and checklist [12].

3.1.1 Identification of problems related to the relevant structures

In the first stage, system designers identify environmental, social, and economic problems related to the relevant structures, while observing trends in understanding such problems. The basis for the identification is that the problems affect the total six stability conditions shown in **Figure 2**, such as health, safety, and environmental preservation. When identifying problems, system designers take up local/particular problems in their country or region, in addition to global/general problems [12].

3.1.2 Identification of the requirements for sustainable design

Next, based on the specified problems, system designers identify the requirements for sustainable design of the relevant structures. For example, if "global warming and climate change" are specified as problems in the first stage, "energy saving," "use of renewable energy," and "conservation of green spaces" can be specified as the requirements.

3.1.3 Determination of elements, variables, and their desired values

In the third stage, system designers convert the requirements for sustainable design into the framework of "element-variable-desired value," which can be found in the design guidelines and checklist. The aim of this conversion is the convenience of system users. The framework of "element-variable-desired value" concretely shows design targets of each part of the relevant structures; thus, it enables the system users to quickly find what should be designed and the design courses [12].

First, system designers determine "elements," considering both the standard structures and the requirements for sustainable design. Structures in one category consist of almost the same component parts; accordingly, system designers can select important parts of the standard structures as elements. Moreover, they may add necessary elements to cover all of the requirements for sustainable design. For example, when "use of renewable energy" is identified as one of the requirements, "equipment for harnessing renewable energy" should be added as an element, even if it is not common in current ordinary structures [9].

Next, system designers determine "variables" by examining the relationships between each element and the relevant stability condition(s), as well as the related requirement(s) for sustainable design. For instance, if "equipment for harnessing renewable energy" is an element, its relationships with the relevant stability conditions, namely environmental preservation and sustainable use of natural resources, as well as the related requirement, namely use of renewable energy, should be examined. Consequently, "harnessed renewable energy" can be determined as its variable.

After that, system designers set the variables' "desired values" to meet the relevant stability conditions. If "harnessed renewable energy" is the variable, its desired value can be set at "100% or more of the total energy usage." When determining "desired values," system designers also consider trends in technology and systems related to the relevant structures.

3.2 Revision process of the design guidelines and checklist

The "sustainable design guidelines" and "sustainability checklist" need to be revised, adjusting to changing situations, and higher user-friendliness and accuracy. The revision process can be divided into three spheres: (1) changes in the theoretical world, (2) changes in the practical world, (3) feedback from the users [12]. After making preparations from the above three perspectives, system designers modify the guidelines and checklist tables.

3.2.1 Changes in the theoretical world

Obvious changes over time in the theoretical world need to be reflected into the design guidelines and checklist [12]. First of all, searching for recent changes in environmental, social, and economic problems, system designers can modify the list of problems related to the relevant structures. Based on the modified list of problems, the system designers can also amend the list of the requirements for sustainable design of the relevant structures. When amending these two lists, it is also necessary to observe the latest trends in "understanding problems related to the relevant structures" and "understanding about the relevant structures' sustainability." Subsequently, system designers examine amendments to the "element-variable-desired value" expressions of the design guidelines and checklist.

3.2.2 Changes in the practical world

Changes over time in the practical world are also necessary to be reflected in the guidelines and checklist. Changes in the practical world include "changes in technology related to the relevant structures" and "changes in systems related to the relevant structure design" [12].

3.2.3 Feedback from the users

"Feedback from the guidelines/checklist users" and "feedback from the structure users" also need to be examined, as shown at the lower right of **Figure 3** [12]. The feedback from the guidelines/checklist users is information on reactions to the guidelines and checklist, such as comments about the user-friendliness and validity of these systems. Such information is utilized as a foundation for the improvement of the systems. On the other hand, the feedback from the structure users is information on reactions to the completed structures designed with the guidelines and checklist. Such information, including comments on the structures' amenities and sustainability performance, is also useful for improving the systems.

4. Sustainable housing design guidelines

We produced the sustainable housing design guidelines and sustainability checklist, mainly for use in Japan. After that, we made revisions on the design guidelines and checklist. This section briefly explains the process of producing and revising the sustainable housing design guidelines, anew following the procedure demonstrated in **Figure 3**. In addition, this section has been organized based on Section 4 of our latest study results, "Comprehensive strategy for sustainable housing design."

4.1 Sustainable housing design guidelines produced in Japan

4.1.1 Identification of problems related to housing

Producing the design guidelines begins with identifying environmental, social, and economic problems related to houses. In this case, we selected global/general problems and local/particular problems observed in Japan. Significant problems are shown in the second column of **Table 1**. Global/general issues include global warming and climate change, and increased medical and nursing care expenses due to aging population. Meanwhile, Japan's local/particular problems include poor indoor thermal performance, and earthquake damage.

4.1.2 Identification of the requirements for sustainable housing design

After specifying the housing-related problems, we identified the requirements for sustainable housing design. For instance, "poor indoor thermal performance" requires "improvement of indoor thermal performance." In addition, relevant stability conditions are demonstrated in the right column of **Table 1**.

4.1.3 Determination of elements, variables, and their desired values

In the third stage, we first specified "elements," considering both the standard housing and the requirements for sustainable housing design. When considering the standard housing, we analyzed two factors: "material" and "space" [10, 11]. "Material" regards housing as the complexity of material elements, such as framework, exterior, thermal insulation, windows and doors, interior, and piping. "Space" considers housing as the complexity of spatial elements, such as rooms and areas

Type of problems	Main environmental, social, and economic problems related to housing	Requirements for sustainable housing design	Stability conditions
Global/ general problems	• Global warming and climate change	• Energy saving • Use of renewable energy • Conservation of green spaces	• Enviro-preservation • Sustainable resources
	• Depletion of natural resources • Waste	• Extension of housing lifespan • Use of resource-saving or waste-prevention materials	• Sustainable resources
	• Harmful influences caused by climate change	• Adaptation measures	• Health • Safety
	• Flood risks due to rainwater flowing out • Water shortage risks	• Rainwater permeation into the ground • Water saving • Use of rainwater	• Enviro-preservation • Sustainable resources • Health • Safety
	• Increased medical and nursing care expenses due to aging population	• Accessible and universal design	• Health • Safety
Local/ particular problems (in Japan)	• Poor indoor thermal performance	• Improvement of indoor thermal performance	• Health • Enviro-preservation • Sustainable resources
	• Earthquake damage	• Higher resistance to earthquakes	• Safety

Table 1.
Problems related to housing and requirements for sustainable housing design identified for the design guidelines produced in Japan [extracts] [12].

[10, 11]. Moreover, in order to cover all of the requirements for sustainable housing design, we added necessary elements, such as "equipment for harnessing renewable energy."

After specifying the elements, we identified the variables and their desired values. Choosing one element, namely "thermal insulation," the rest of this section explains the details of identifying the variable and its desired value. First of all, we determined "thermal insulation performance" as the variable, considering two requirements, that is, "energy saving" and "improvement of indoor thermal performance," as well as the relevant stability conditions. Higher thermal insulation performance contributes to "environmental preservation" and "sustainable use of natural resources" due to a decrease in energy usage for air-conditioning and heating, as well as residents' better "health."

When specifying the desired value, we observed trends in technology and systems related to housing thermal insulation performance. Japanese housing thermal performance has traditionally been low. Japan's building codes have not stipulated the standards of housing thermal insulation performance. Meanwhile, since 2000, a national voluntary system, namely the Japan Housing Performance Indication Standards (JHPIS), have provided four-level thermal insulation performance grades. Consequently, we determined the desired value to be the highest level in the thermal insulation performance grades of the JHPIS.

4.2 The latest revision of the design guidelines

The above sustainable housing design guidelines produced in Japan have recently been revised. This latest revision has dealt with the three aspects as mentioned before: (1) changes in the theoretical world, (2) changes in the practical world, (3) feedback from the users.

4.2.1 Changes in the theoretical world

First of all, observing recent trends in understanding problems related to houses, we have searched for problems which affect stability conditions. Consequently, as shown in the second column of **Table 2,** we have specified additional problems that

Type of problems	Environmental, social, and economic problems related to housing	Requirements for sustainable housing design	Stability conditions
Global/general problems	• Breakdown risks in electricity systems due to increasing wind and solar power generation	• Storage of electricity	• Sustainable resources • Health (in crises) • Safety (in crises)
	• Insufficient considerations for homeworking, telecommuting, and lifelong learning	• Considerations for homeworking, telecommuting, and lifelong learning	• Self-realization
Local/particular problems (in Japan)	• Problems resulting from insufficient communication	• Floor planning suitable for good communication among residents	• Mutual help • Self-realization

Table 2.
Additional problems and requirements for sustainable housing design identified for the latest revision of the design guidelines [extracts] [12].

should be dealt with. Based on these problems, additional requirements for sustainable housing design have also been identified. After that, these additional requirements have been incorporated into the framework of "element-variable-desired value."

Choosing one requirement, namely "storage of electricity," the following describes the essentials of the identification and incorporation processes. In order to curb global warming, the utilization of renewable energy, particularly wind and solar power generation, is quickly increasing in many countries [13]. But the quantity of electricity extracted from solar and wind sources varies chiefly with the time of day, weather, and season. Therefore, a surge in wind and solar power generation is also raising the risks of power failures [14, 15]. In order to cope with such changing circumstances, we have added "storage of electricity" as a requirement for sustainable housing design. Besides, storing electricity leads to securing an emergency power source, which is one of the adaptation measures against climate change.

When incorporating the "storage of electricity" into the guidelines, we have added "storage battery" as a new material element. Subsequently, we have identified two variables of this new element: "type" and "linkage." The desired value of "type" has been specified as "stationary battery or electric vehicle battery." Meanwhile, the desired value of "linkage" has been determined to be "interconnection with the home electrical system."

4.2.2 Changes in the practical world

Observing recent trends in housing-related technology and systems, we have found noticeable changes, mainly in thermal insulation performance. Japanese housing thermal performance has been gradually improving, due to progress in technology and requirements for energy saving and occupants' health. As a result, recently, a new national voluntary system, the "net-zero energy house (ZEH) certification standards," has emerged and shown higher thermal performance criteria than usual criteria [16]. Recognizing these changes, we have lifted the desired value of "thermal insulation performance" of the two material elements: "thermal insulation" and "windows and doors." To be concrete, we have revised the desired value from the highest level in the JHPIS's thermal insulation performance grades to the relevant criterion stipulated in the ZEH certification standards.

4.2.3 Feedback from the users

After finding a constructive opinion in recent feedback from the system users, we have determined to include it in the latest revision. This opinion's gist is that lighting fixtures utilized in living spaces should be products with brightness and color adjustment functions, for energy conservation and residents' health. The necessary brightness of indoor artificial lighting changes depending on circumstances, including residents' visual comfort and natural lighting through windows. Meanwhile, exposure to bright lights and blue light before bedtime suppresses melatonin secretion and can affect sleep and potentially cause diseases [17, 18]. Accordingly, especially in living spaces, lighting fixtures fitted with brightness and color adjustment functions are beneficial for energy conservation and residents' health. Therefore, when revising the guidelines this time, we have added an explanatory note to "LED," the desired value of lighting fixtures' type, saying "lighting fixtures used in the living spaces are fitted with brightness and color adjustment functions."

Finally, all of the above revision items have been incorporated into the table of the "element-variable-desired value" framework. The final revised version of the guidelines has been shown in **Table 3** in our latest study results, "Comprehensive

Element	Variable	Desired value
Framework	Resistance to earthquakes	JHPIS 1–1: Grade 2 or over
	Durability	JHPIS 3.1: Grade 3
	Materials	CASBEE LR_H2 1.1: Level 4 or over
Exterior (outer wall, roof, etc.)	Fire resistance (outer wall)	JHPIS 2–6: Grade 3 or over
	Shape and color	Consideration for the landscape
Thermal insulation	Thermal insulation performance	*Thermal performance criteria stipulated in the net zero energy house (ZEH) certification*
Windows and doors	Thermal insulation performance	*Thermal performance criteria stipulated in the ZEH certification*
	Sunlight adjustment capability	CASBEE Q_H1 1.1.2: Level 4 or over
	Protection of glass against impacts	With shutters
Piping	Measures for maintenance	JHPIS 4.1: Grade 3
Lighting fixtures	Type of light	LED *(lighting fixtures used in the living spaces are fitted with brightness and color adjustment functions)*
Equipment for harnessing natural energy	Harnessed natural energy	100% or more of the total energy usage
Storage battery	*Type*	*Stationary battery or electric vehicle battery*
	Linkage	*Interconnection with the home electrical system*
Specified bedroom (Bedroom for elderly and wheelchair users)	Routes to toilet and bath area, dining room, kitchen, and entrance	Accessible without steps
Living/dining room and kitchen area	*Place in the home*	*Between the entrance and private room area*
	Type of kitchen	*Open or semi-open*
Area(s) for working and learning	*Place(s) in the home*	*In or near the living/dining room and kitchen area*
Areas relating to water use and hot-water supply	Areas in the home	Placing them closer
Position and area of windows	Natural ventilation	CASBEE Q_H1 1.2.1: Level 5
Doorways	Differences in level	No differences
	Width	75 cm or more (Bath: 60 cm or more)
Garden area	Ratio of the garden area to the exterior area	40% or more

(1) Material elements are from "framework" to "storage battery;" spatial elements are from "specified bedroom" to "garden area."
(2) JHPIS means the Japan Housing Performance Indication Standards (for new homes).
(3) CASBEE means CASBEE for Detached Houses (for new construction) – Technical Manual 2018 Edition.

Table 3.
The latest revised version of the sustainable housing design guidelines [extracts] [12].

strategy for sustainable housing design." Extracts from this latest revised version are demonstrated in **Table 3**. The added and modified descriptions in the latest revision are written in *italics*.

5. Sustainable urban design guidelines

This section outlines how to produce sustainable design guidelines for the whole city. **Figure 4** shows the process of producing and revising sustainable urban design guidelines. This diagram has been drawn based on **Figure 3** in Section 3. First, the descriptions of "relevant structures" in **Figure 3** have been replaced with "cities" or "urban." Moreover, three items have been added to the box of "Determination of elements, variables, and their desired values in the design guidelines and checklist."

5.1 Problems related to cities and requirements for sustainable urban design

5.1.1 Problems related to cities

As shown in the upper central part of **Figure 4**, producing the design guidelines starts with identifying environmental, social, and economic problems related to

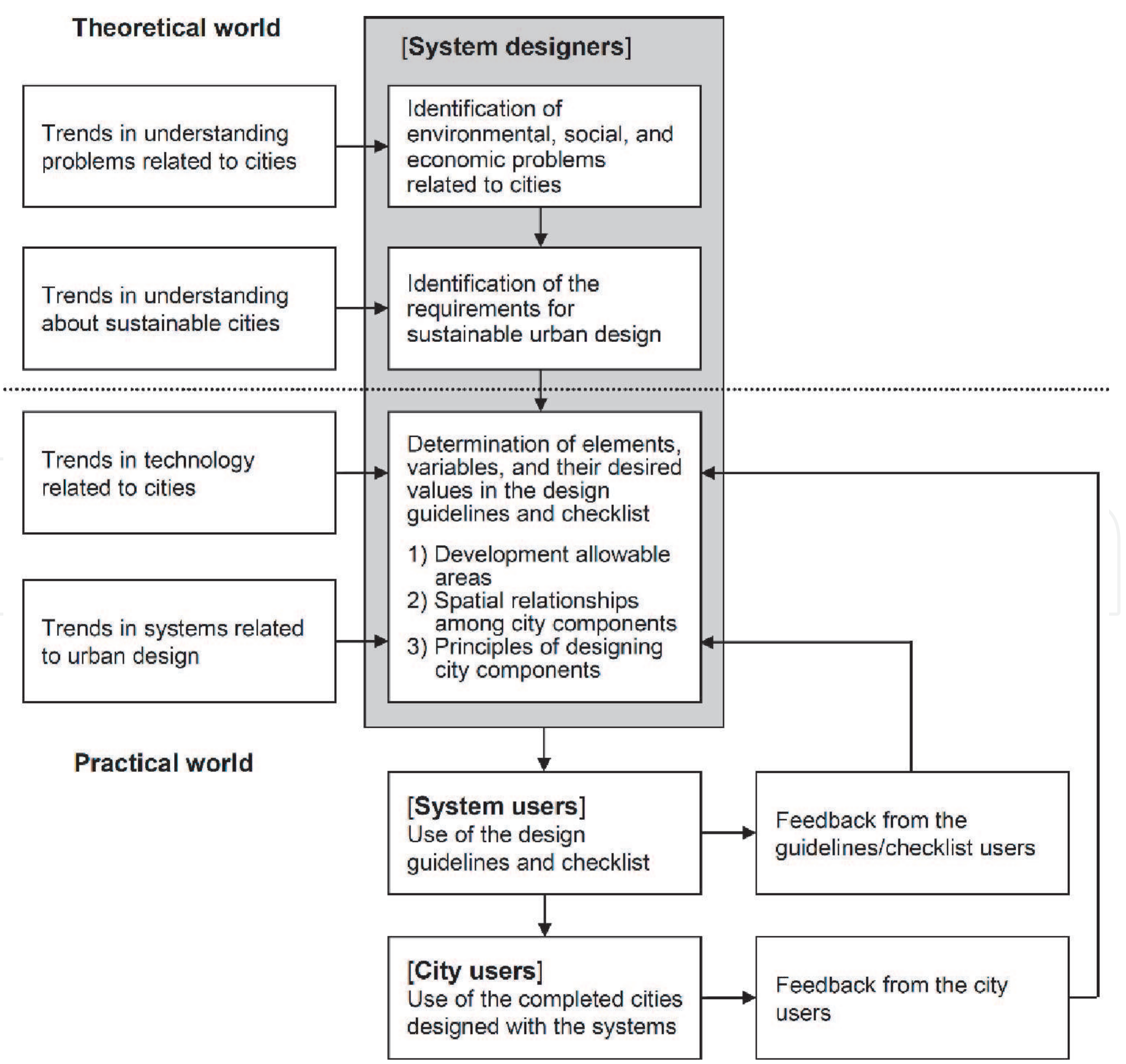

Figure 4.
Process of producing and revising the sustainable urban design guidelines.

Environmental, social, and economic problems related to cities (Main global/general problems)	Requirements for sustainable urban design	Stability conditions
• Urban sprawl • Environmental destruction • Biodiversity loss	• Prevention of urban sprawl • Environmental protection • Biodiversity conservation	• Enviro-preservation
• Global warming and climate change	• Energy saving • Use of renewable energy • Conservation of green spaces	• Enviro-preservation • Sustainable resources
• Damage caused by natural disasters • Harmful influences caused by climate change	• Exclusion of natural disaster danger areas from development areas • Measures for disaster damage prevention or reduction	• Safety • Health
• Urban heat island	• Increase in green spaces • Reduction in waste heat from buildings, vehicles, etc.	• Enviro-preservation • Health
• Depletion of natural resources • Waste • Environmental pollution	• Extension of the lifespan of constructions and products • Use of resource-saving or waste-prevention materials • Proper waste management	• Enviro-preservation • Sustainable resources
• Traffic congestion • Automobile pollution	• Shifts from automobile to mass transit, walking and biking	• Enviro-preservation • Sustainable resources • Health
• Lack of physical activity	• Inducement to walking and biking • Safe streets • Recreational facilities and places	• Health • Safety
• Sluggish economy • Less social cohesion • Crimes	• Consideration for increasing economic vitality • Consideration for encouraging social interaction • Increase in people's "eyes on the street"	• Safety • Mutual help • Self-realization
• Increase of medical and nursing care expenses due to aging population	• Accessible and universal design	• Health • Safety

Table 4.
Main global/general problems related to cities and requirements for sustainable urban design.

cities. While observing trends in understanding city-related problems, system designers search for the problems that should be identified. In this section, only typical global/general problems have been extracted and demonstrated in **Table 4**.

5.1.2 Requirements for sustainable urban design

In the second stage, based on the selected problems related to cities, system designers identify the requirements for sustainable urban design. Identified requirements for sustainable urban design are demonstrated in the second column of **Table 4**. For example, "damage caused by natural disasters" and "harmful influences caused by climate change" require "exclusion of natural disaster danger areas from development areas" and "measures for disaster damage prevention and reduction."

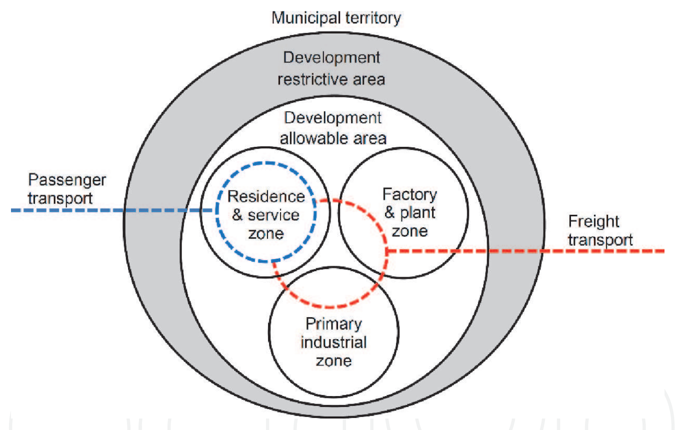

Figure 5.
Concept diagram for considering sustainable urban design.

Element	Variable	Desired value	Remarks
Development allowable areas	Risk of biodiversity loss	Lower risk of biodiversity loss	
	Risk of natural disasters	Lower risk of natural disasters	• Examples of natural disasters: flood damage, landslides, drought damage, and forest fires.
	Gradient of the topography	Flat or gently-sloping topography	

Table 5.
Sustainable urban design guidelines (1) development allowable areas [essentials].

5.2 Sustainable urban design guidelines

In the third stage, the requirements for sustainable urban design are converted into the "element-variable-desired value" framework of the design guidelines. When designing the whole city, people involved must consider the extent of land development areas, the placement of city components, and city components' design principles. The requirements in **Table 4** also extend over these three spheres. Therefore, as shown in **Figure 4**, we have divided the third stage into three steps: (1) development allowable areas, (2) spatial relationships among city components, (3) principles of designing city components.

5.2.1 Development allowable areas

The first step focuses on the relationship between land development and natural features. As demonstrated in **Figure 5**, a municipal territory can be divided into development restrictive areas and development allowable areas. "Development allowable areas" are areas where land development can be permitted.

Table 5 shows the essentials of the first part of the sustainable urban design guidelines. At first, we have identified "development allowable areas" as the element. Next, we have determined its three variables: (1) risk of biodiversity loss, (2) risk of natural disasters, (3) gradient of the topography. When defining "development allowable areas," it is necessary to select areas where all these three variables meet their desired values.

Element	Variable	Desired value	Remarks
Residence and service zones	Facilities placed in the residence and service zones	Facilities for people's use and related facilities	• Examples of facilities for people's use: housing, buildings for various services, streets, and parks.
	Extent of the residence and service zone from a station of passenger transport	1. Within walking distance of an interurban railway station 2. Within short walking distance of a local transport (tram/bus) line's station	• At least one of the two desired values must be satisfied. • Walking distance should be set at 1000 m or less. • Short walking distance should be set at 500 m or less.
Main streets	Layout	Well-connection to essential facilities	• Examples of essential facilities: interurban railway stations, and large-scale public facilities.
Residential streets	Access to main streets	Convenient	
Routes of local public transport (tram/bus)	Relation with streets	On main streets, in principle	
Lots for larger buildings	Relation with streets	Connected to main streets	
Lots for smaller buildings	Relation with streets	Connected to residential streets	
Lots for frequently used facilities	Relation with passenger transport	In close vicinity to passenger transport stations	
Factory and plant zones	Facilities placed in the factory and plant zones	Facilities for large-scale production and related facilities	• Examples of the facilities for large-scale production: manufacturing factories, and power plants.

Table 6.
Sustainable urban design guidelines (2) spatial relationships among city components [extracts].

The first variable, "risk of biodiversity loss," is mainly related to two requirements shown in **Table 4**, namely "environmental protection" and "biodiversity conservation." Considering these two requirements and their related stability condition, namely "environmental preservation," we have determined its desired value as a "lower risk of biodiversity loss." This means that areas with a higher risk of biodiversity loss, such as Key Biodiversity Areas, must be excluded from development allowable areas. According to the International Union for Conservation of Nature (IUCN), Key Biodiversity Areas are sites contributing significantly to the global persistence of biodiversity [19].

The second variable, "risk of natural disasters," is connected with another requirement in **Table 4**, "exclusion of natural disaster danger areas from development areas." Considering this requirement and its related stability conditions, "safety" and "health," we have specified its desired value as a "lower risk of natural disasters." Examples of natural disasters are flood damage, landslides, drought damage, and forest fires. When estimating natural disaster risks, system designers should also consider future risks caused by climate change, in addition to current risks.

Element	Variable	Desired value	Remarks
Main streets	Main divisions of the street surface	Sidewalk, planting zone, bike lane, roadway	
	Design of spaces for pedestrians	Accessible and universal design	
	Roadway space	Considerations for the passage of public transport (tram/bus)	
Residential streets	Passage	Pedestrians, bicycles, vehicles for the residents	• Priority to pedestrians
Larger buildings	Energy usage of the building	Net zero energy building	• High energy efficiency • Use of renewable energy
	Height limits for construction	Not high	• Hight for several-floor buildings at the maximum
	Uses of the building's street-level floor	Priority to service uses	
Smaller buildings	Energy usage of the building	Net zero energy building	• High energy efficiency • Use of renewable energy
	Height limits for construction	Low	• Hight for a-few-floor buildings
Public open spaces (parks, etc.)	Green coverage ratio	High	
Manufacturing factories	Raw materials used for manufacturing	Priority to locally produced materials and used materials	
Energy production plants	Type of energy resources	Renewable energy	

Table 7.
Sustainable urban design guidelines (3) principles of designing city components (extracts).

Meanwhile, the third variable, "gradient of the topography," is associated with two requirements in **Table 4**, "environmental protection" and "accessible and universal design." Considering these requirements and their related stability conditions, namely "environmental preservation," "health," and "safety," we have determined its desired value as "flat or gently-sloping topography." When steep slopes are disturbed by removing vegetation and developing the hillside or mountainside, significant environmental issues can arise. Potential consequences can include soil erosion, landslides, an increase in downstream runoff, and flooding [20–22]. Moreover, slopes become steeper, the provision of infrastructure and accessible design becomes more difficult and expensive [21]. Accordingly, areas with steep slopes should be excluded from development allowable areas.

5.2.2 Spatial relationships among city components

The second step, spatial relationships among city components, focuses on the placement of land development sites and facilities. Land development sites need to be situated in development allowable areas. As shown in **Figure 5**, land development sites can be divided into three major zones: (1) residence and service zone,

(2) factory and plant zone, (3) primary industrial zone. The "residence and service zone" contains facilities for people's use, such as housing, buildings for various services, streets, and parks. The "factory and plant zone" contains facilities for large-scale industrial production, such as manufacturing factories and power plants. The "primary industrial zone" includes farmlands and planted forests. In addition, the "factory and plant zone" and "residence and service zone" are closely connected to the "secondary industry" and "tertiary industry," respectively. Meanwhile, facilities for interurban and local transport are also significant as city components. Accordingly, we have added typical transport routes to **Figure 5**, dividing them into passenger transport and freight transport.

Bearing standard cities in mind, we have specified important spatial relationships among city components. Extracts of such relationships are shown in **Table 6**. Choosing one element, that is, "residence and service zone," the rest of this section explains a key variable and its desired value. First, we have identified "extent of the residence and service zone from a station of passenger transport" as the key variable. Next, we have determined its two desired values: (1) within walking distance of an interurban railway station, (2) within short walking distance of a local transport (tram/bus) line's station. At least one of the two desired values need to be met.

Satisfying the above desired value contributes to meeting many of the requirements shown in **Table 4**. First, limiting the residence and service zones within walking distances of public transportation stations leads to environmental protection by preventing urban sprawl. It also promotes the shift from automobile to mass transit systems, walking, and biking, which reduces traffic congestion, pollution, and CO_2 emissions. Meanwhile, an increase in walking and biking leads to better health. Furthermore, lively pedestrian traffic contributes to increasing economic vitality and social interaction, as well as preventing crimes through an increase in people's "eyes on the street" [23–25].

5.2.3 Principles of designing city components

The third step shows the principles of designing city components. In this step, first, main city component types are identified as elements. Next, items that strongly influence urban sustainability are determined as variables. Part of such elements and variables are demonstrated in **Table 7**.

Choosing one element from this table, that is, "larger buildings," the rest of this section comments on the selected three variables and their desired values. Meeting these desired values helps to fill various requirements for sustainable urban design.

Concerning the first variable, "energy usage of the building," we have identified its desired value as "net-zero energy building." Achieving this desired value requires buildings' high-level energy efficiency and the use of renewable energy. In addition, installing equipment for using renewable energy, such as solar panels, is a measure for disaster damage reduction, since such equipment can provide emergency electricity.

Meanwhile, we have determined the desired value of "height limits for construction" to be "not high," more specific "height for several-floor buildings at the maximum." There are many disadvantages in constructing tall buildings, including skyscrapers. The taller the buildings become, the more difficult they achieve net-zero energy buildings. Installing solar panels on the roof is a common way to use renewable energy at building sites; however, high-rise buildings inevitably increase the ratio of total floor area to the roof area. Besides, high-rise buildings often block surrounding buildings from the sun and make it difficult to use renewable energy. Furthermore, controlling buildings' height uniform with neighbors also contributes to better landscapes.

Regarding the third variable, "uses of the building's street-level floor," we have identified its desired value as "priority to service uses." If the street-level floor of residential buildings facing main streets is allocated for service uses, such as shops, pedestrian traffic can increase. Lively pedestrian traffic helps economic vitalization, social interaction, and crime prevention [23–25].

6. Conclusion

This chapter illustrated the system-control-based methodology for sustainable structure design, with the examples of housing and urban design. Section 2 showed the "control system for promoting sustainable structure design." The third section demonstrated the "process of producing and revising sustainable structure design guidelines." The fourth section included the extracts of the sustainable housing design guidelines produced and revised in Japan. Lastly, Section 5 outlined a way of producing sustainable urban design guidelines. Unlike the design of city components, such as houses, the design of the whole city needs extensive spatial planning. Accordingly, the final stage of producing sustainable urban design guidelines consists of the three steps: (1) development allowable areas, (2) spatial relationships among city components, (3) principles of designing city components.

As already shown in our previous studies, this methodology has the following four characteristics: (1) visualization of the whole picture for promoting sustainable design, (2) user-friendliness, (3) comprehensiveness, (4) adaptability to different and changing situations [26]. The first characteristic originates in the schematization of the control system (**Figure 1**) and the process of producing and revising the design guidelines (**Figure 3**). Besides, this chapter has included two new diagrams, namely **Figure 4** and **Figure 5**, which are expected to help understand the whole picture for promoting sustainable urban design.

The second feature, "user-friendliness," originates from the "element-variable-desired value" framework in the sustainable design guidelines. Elements in the design guidelines are equivalent to actual parts of structures. Therefore, the system users can smoothly design the structures by comparing the actual structure or drawings with the design guidelines. Meanwhile, the third feature, "comprehensiveness," means that this methodology can deal with various environmental, social, and economic issues. This feature results from the model of sustainability (**Figure 2**), which has been incorporated in the control system for promoting sustainable structure design (**Figure 1**).

The fourth characteristic, "adaptability to different and changing situations," originates in the process of producing and revising the design guidelines. As demonstrated in **Tables 1** and **2**, local/particular problems in a country or region can be included in producing and revising the design guidelines. As a result, the produced and revised guidelines naturally become adaptable to that country's or region's situation. Meanwhile, Section 3.2 and Section 4.2 have shown the process of revising the design guidelines and its concrete instance, respectively. These study results include theoretical and practical ways to adapt the guidelines to changing situations over time.

Our main future work is further research on sustainable urban design. First, we must complete the sustainable urban design guidelines for practical use. After that, it is also necessary to revise the design guidelines by following the revision process shown in **Figure 4**. Through such future work, we are aiming to refine this methodology for designing sustainable structures.

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