SYSTEM DYNAMICS MODEL FOR LIFE CYCLE ASSESSMENT (LCA) OF RESIDENTIAL BUILDINGS

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ABSTRACT
An evaluation method for life cycle energy (LCE) and CO_2 ($LCCO_2$) of houses by the system dynamics (SD), a method for understanding how all the objects in a system interact with one another, was presented. The building design strategies to predict and reduce the environmental loads for the several types of construction and building materials were investigated. As a result of the simulation, the long-life and energy efficient house was more effective in regard to life cycle assessment (LCA) than the typical houses. Moreover, possibility of life cycle cost (LCC) of the houses and a carbon dioxide flow SD model were also addressed.

INTODUCTION
In recent years, issues related to building for environmental and economic sustainability have been recognized and current building design, engineering method, manufacturing technologies, and construction techniques need to be altered to accommodate requirements for sustainable construction. To help resolve the complex and multidisciplinary problem, LCA can be useful tool for the sustainable development.

Life cycle of a product or assembly includes the manufacturing, construction, use and maintenance, repair and renewal as well as demolition, recycling and disposal of these items. An evaluation method for LCE and $LCCO_2$ of houses by SD, a method for understanding how all the objects in a system interact with one another, was presented. The SD was devised by Forrester in 1956 and industrial dynamics [Forrester, 1961], urban dynamics [Forrester, 1968], world dynamics [Forrester, 1971] etc. have been developed ever since.

The present method to evaluate the indices by the SD method is applicable to more complicated systems, and also easy to modify and develop the system. The building design strategies to predict and reduce the environmental loads for the several types of construction and building materials, long-life type, energy efficient type and conventional type of Japanese typical wooden house, were investigated.

The life cycle inventory analysis on the compilation and quantification of inputs and outputs, for the product system related to the model house throughout its life cycle, were addressed. Then a SD model for LCE and $LCCO_2$ of houses was developed. Moreover, possibility of LCC of the houses and a carbon flow SD model were also discussed.

SYSTEM DYNAMICS MODEL
System Dynamics Method
The basic building block of SD is the stock or the level, which is used to represent anything that accumulates. The second building block is the flow or the rate, which is used to represent activities that will change the magnitude of stock in a system. The third one is called connectors to transmit information and inputs that are used to regulate flows. The last building block is the converter, which contain equations to generate an output value for each time period, and often take in information and transform it for use by another variable in the model. They are also handy for storing constant values.

The systems thinking tool, STELLA by High Performance Systems Inc. is used here to make a SD model and simulate it. STELLA is the software, which executes the simulation model coded by visual programming based on the SD for personal computer.

Life Cycle Inventory Analysis
Life cycle inventory (LCI) analysis is defined as the phase of life cycle assessment involving compilation and quantification of inputs and outputs, for a given product system throughout its life cycle.

Figure 1 shows the life cycle inventory SD model for a wooden detached house. The specification of the reference model is shown in Table 1. The embodied energy and CO_2 of the house in its life cycle process were estimated from the existing literature [KKJ, 1998]. The annual values of maintenance and renewal stage were converted from the input and output data in the life.

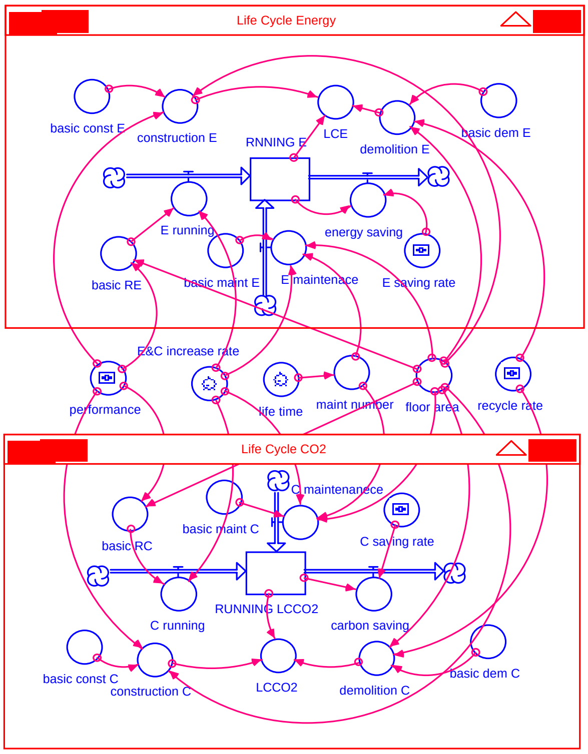

Figure 1 LCI SD Model

Table 1 Embodied energy and CO_2 of the reference house in the life cycle process

Life cycle process	*Embodied energy (Mcal/m^2)*	*Embodied CO_2 (kg-C/m^2)*
Construction	0.87	83.7
Operation *	0.113	7.4
Maintenance *	0.0001	0.0
Renewal *	0.0063	0.67
Demolition	0.082	6.98

(* : per year)

The variable parameters related to LCE and $LCCO_2$ are *housing performance ratio*, *floor area*, *price increase rate*, *energy saving rate and recycle rate*. The housing performance ratio is the proportion of thermal performance for that of the reference model. It is assumed that energy and CO_2 are proportional for the housing performance ratio in the construction stage and is in inverse proportion in the operational stage. The floor area is 120m^2, and the other parameters are shown in Table 2. Numerical integration is carried out by the Euler's method.

Table 2 Parameters of LCI SD model

Parameter	*Value*
Housing performance ratio	1
Service life	30 years
Energy & CO_2 increase rate	0
Recycle rate	0.2
CO_2 saving rate	0
Energy saving rate	0

The equation of stock RUNNING_CO2 is coded as follows,

```
RUNNING_CO2(t) = RUNNING_CO2(t - dt) + (C_running + C_maintenanece - carbon_saving) * dt
INIT RUNNING_CO2 = 0

INFLOWS:
C_running = basic_RC*(1+E&C_increase_rate)
C_maintenanece=basic_maint_C*floor_area*maint_number*(1+E&C_increase_rate)

OUTFLOWS:
carbon_saving = basic_RC*C_saving_rate
```

Figure 2 shows $LCCO_2$ vs. elapsed time curves for the reference model. The performance ratios of line number 1, 2 and 3 are respectively 1.0, 1.15 and 1.3. While $LCCO_2$ of high performance model is larger than that of the lower one in the short period, the magnitude correlation of the values is reversed after about 15 years.

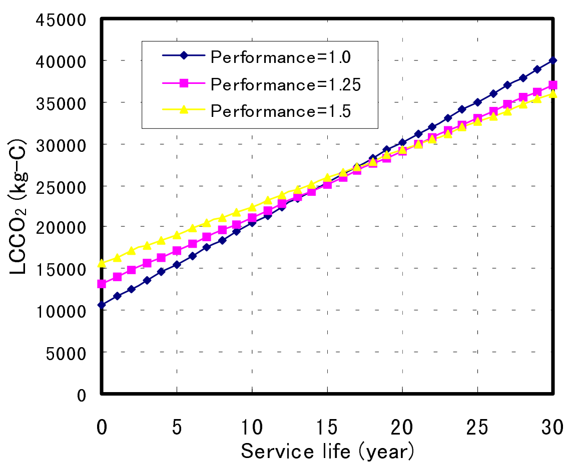

Figure 2 LCCO2 vs. service life (reference model)

Figure 3 shows $LCCO_2$ vs. elapsed time curves if the energy and CO_2 increase rate is 0.1. The $LCCO_2$ is 1.08 times larger than the reference model.

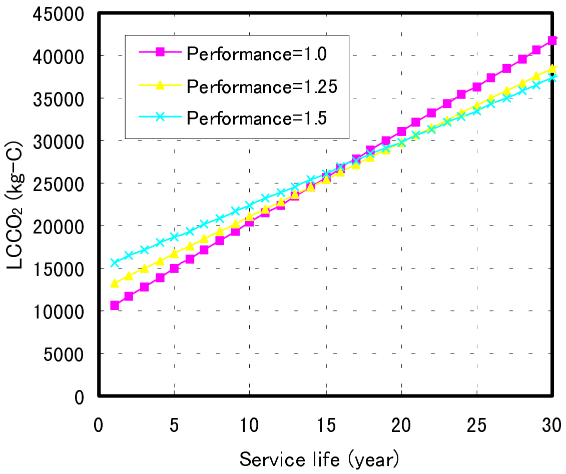

Figure 3 LCCO2 vs. service life
(energy and CO2 increase rate=0.1)

Moreover the simulation result of 50 years service life model is shown in Figure 4. The $LCCO_2$ is about 1.43 times larger than the reference model.

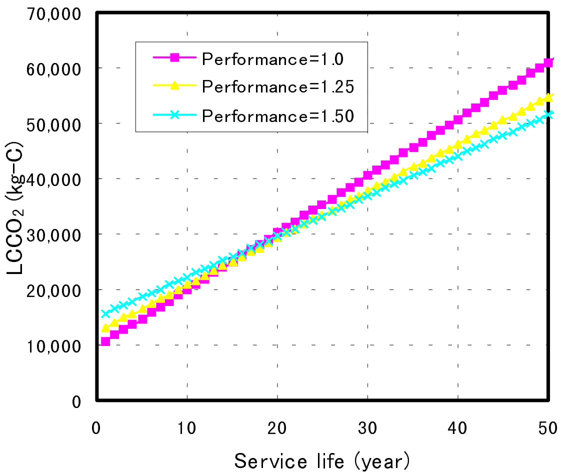

Figure 4 LCCO2 vs. service life
(long life type)

LCC Model

For LCC of buildings and houses, social and economical factors such as environmental loads and the cost of construction or operation are otherwise included. Though SD is useful for such a model, a simple SD model without social and economical factors for LCC of houses is presented here. Table 3 shows the basic cost of the typical Japanese model in the life cycle stage of a wooden detached house.

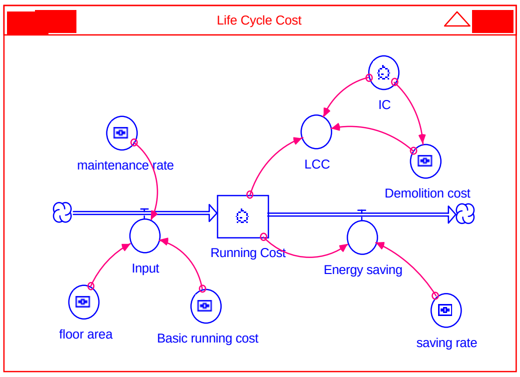

Figure 5 LCC SD Model

Table 3 Basic cost in the life cycle stage of a wooden detached house

Life cycle process	*Cost (x10^3 JY/m^2)*
Construction	150
Operation *	5
Maintenance & Renewal *	3.8
Demolition	1

(* : per year)

The variable parameters of the SD model are *price increase rate*, *floor area*, *energy saving rate* and *recycle rate*. The parameters for the reference model are shown in Table 4.

Table 4 Parameters of LCC SD model

Parameter	*Value*
Floor area	150 m^2
Energy saving rate	0
Recycle rate	0.1
Price increase rate	0

The equation of the stock *Running_Cost* is as follows,

Running_Cost(t) = Running_Cost(t - dt) + (Input - Energy_saving) * dt
INIT Running_Cost = 0

INFLOWS:
Input = Basic_running_cost+maintenance_C

OUTFLOWS:
Energy_saving=basic_RC_per_floor_area*floor_area*saving_rate

Figure 6 shows LCC vs. elapsed year curves for the reference model. The energy saving rates of line number 1, 2 and 3 are respectively 0.0, 0.15 and 0.3. The LCC difference of the reference model and the model with 30% energy saving in the operation stage is about 5 million Japanese Yen for 30 years.

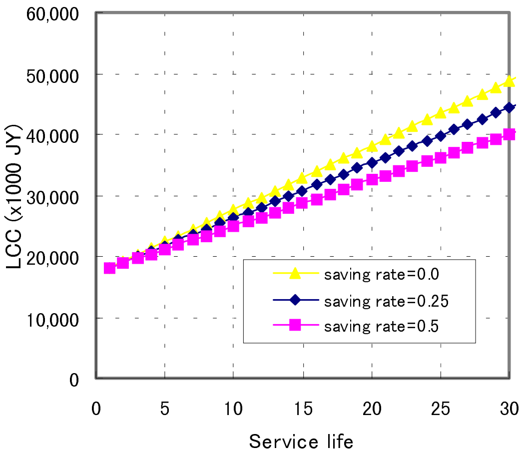

Figure 6 LCC vs. service life (reference model)

Figure 7 shows LCC vs. elapsed year curves if the recycle rate is 0.8. This value is assumed to reduce the demolition cost, and its cost is very low compared to the construction and the operation cost. Therefore LCC of this model is almost same as the reference case.

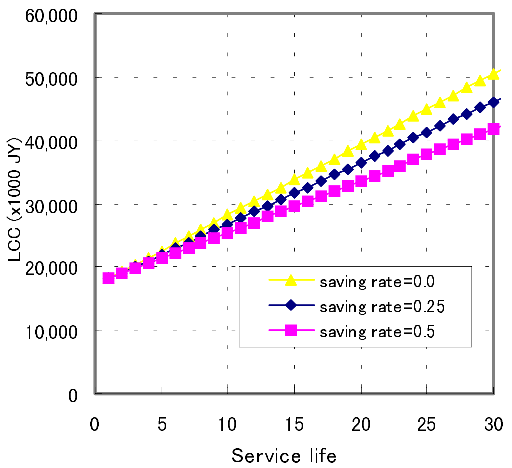

Figure 7 LCC vs. service life (price increase rate=0.1)

CO_2 Flow Model

The last SD model is addressed to simulate carbon dioxide flow of wooden materials from production to disposal in houses. Seven stocks, FOREST, TIMBER, HOUSES, PIECES, STOCK, REUSE and LCCO2 are set (see Table 5), and 14 flows and 38 converters are used. REUSE includes the disassembly woods of houses, the remainder material in the stage of the lumbering and the woods turned from the disassembly to the disposal to reuse.

Figure 8 shows the carbon flow SD model for houses. The parameters used in the reference model are shown in Table 6.

Table 5 Definition of the stocks

Stocks	*Definition*
FOREST	Carbon stock in forest
TIMBER	Carbon stock of wooden products
HOUSES	Carbon stock in houses
PIECES	Carbon stock of disassembly woods from houses
STOCK	Carbon stock of disposal woods
REUSE	Carbon stock of recycle woods
LCCO2	Life cycle CO_2 of houses

Table 6 Parameters of carbon flow SD model

Parameter	*Value*
Demolition rate	0.02
Disposal rate	0.5
Recycle rate	0.3
Reuse rate	0.7
Storage rate	0.3
Reform rate	0.5
Rest rate	0.3
Burn rate	0.3

The stock equations of HOUSES is as follows,

```
HOUSES(t) = HOUSES(t - dt) + (CONST + RECON - DEMOL) * dt

INIT HOUSES = 14800

INFLOWS:
CONST = C1+C2
RECON = REUSE*reuse_rate
OUTFLOWS:
DEMOL = HOUSES/(life_time/30)*demo_rate
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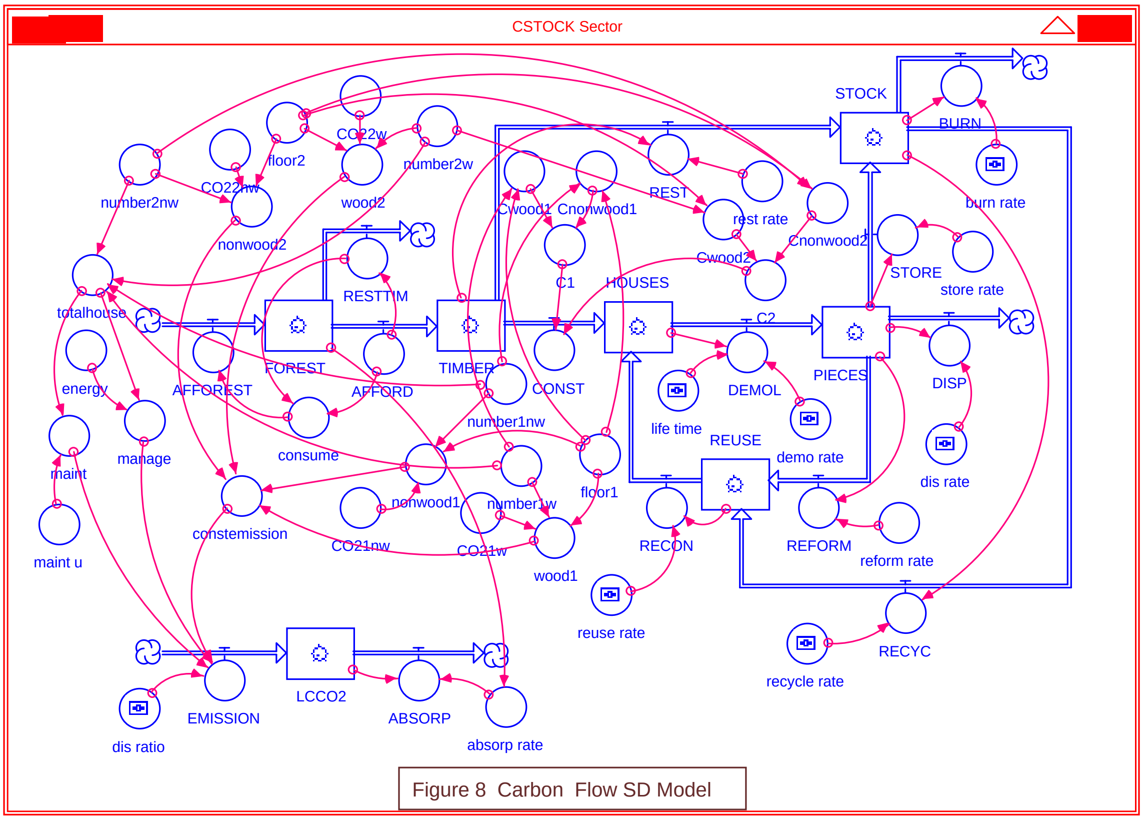

Figure 8 Carbon Flow SD Model

Figure 8 Carbon flow SD Model

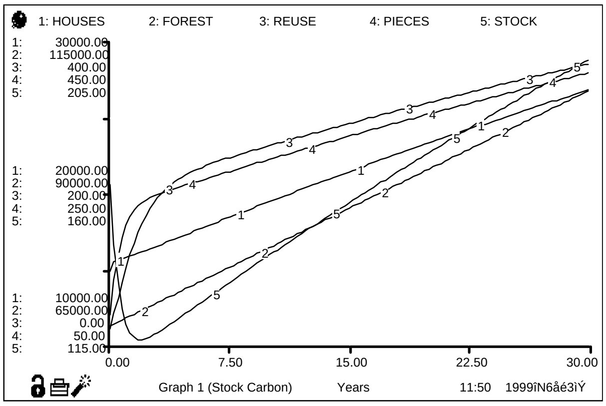

Figure 9 Carbon stock vs. elapsed year curves

(Reference model)

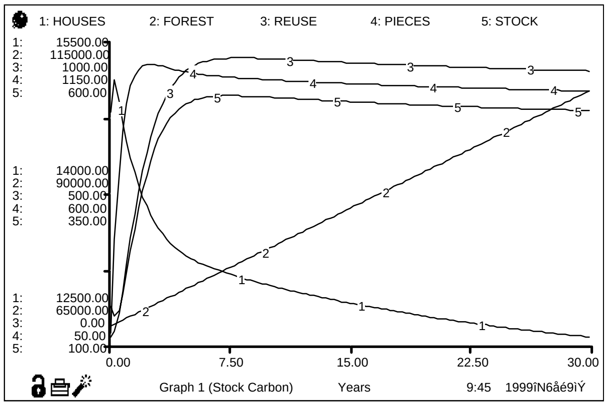

Figure 10 Carbon stock vs. elapsed year curves

(Demolition rate=0.1, reuse rate=0.7)

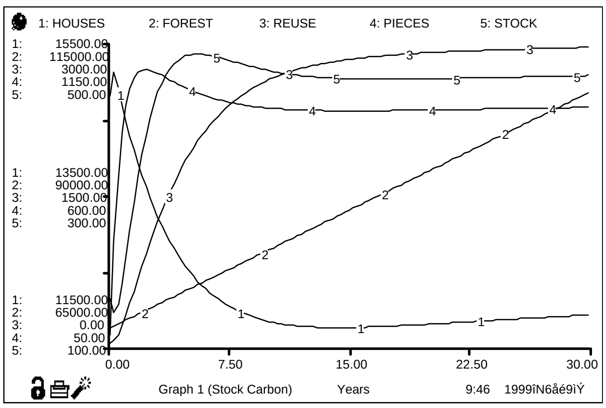

Figure 11 Carbon stock vs. elapsed year curves

(Demolition rate=0.1, reuse rate=0.2)

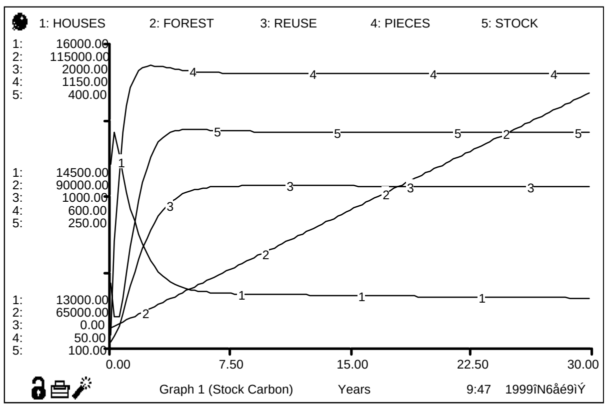

Figure 12 Carbon flow vs. elapsed year curves

(Demolition rate=0.1, recycle rate=0.7)

Figure 9 shows carbon stock vs. elapsed year curves for the reference model. All the stocks are increased as the elapsed year. The unit of the vertical axis in Figures 9-12 is 10^7 ton-C. For example, the carbon stock in HOUSES is about two times larger than the initial value after 30 years.

Figure 10 shows the carbon stock vs. elapsed year if the demolition rate and the reuse rate are respectively 0.1 and 0.7. The carbon stock in HOUSES is decreased as the elapsed year and the stocks in REUSE, PIECES and STOCK are almost stable after 5 years.

Figure 11 shows the result of the model with the reuse rate 0.2. The result tends to be almost similar to Figure 9 except for the stock HOUSE. The stock is changed to the rise after 10 years.

Moreover the model with the demolition rate 0.1 and the recycle rate 0.7 was investigated as shown in Figure 12. All the stocks are stable after 5 years except the stock FOREST.

DISCUSSIONS

Lots of good data are required for LCI of residential buildings in all the life stage. Therefore the accuracy of LCI is depend on the data.

SD is a dynamic system simulation method to model and simulate complicated systems including social and economical factors and human decision making as well. For example, the price increase rate related to LCC for houses is affected by many economical factors involved human decision-making.

To make a comprehensive SD model, it is very important to understand the real system and model it correctly. Then it is necessary to carry out the sufficient verification.

CONCLUSIONS

The effectiveness was confirmed by the application of the system dynamics method for the LCI of the residential buildings. Building is a complicated system composed of lots of building materials and member subject. It was shown that the SD method was suitable to model and simulate the LCA. In the modeling by SD, expansion and change of the system model are possible for the easiness, and the sensitivity analysis of various parameters can be also easily carried out.

The results of the simulation of SD model for some wooden construction housing showed that LCE and $LCCO_2$ were consequentially decreased by the improvement in the housing performance. Moreover a simple LCC SD model for houses and carbon flow SD model to simulate carbon dioxide flow of wooden materials from production to disposal in houses were addressed.

ACKNOWLEDGEMENTS

This study is partially supported by TOSTEM Foundation for Construction Materials Industry Promotion. I express the gratitude for Yuko Yamamoto and Takashi Kondo cooperatively received for the data collection and reduction.

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