Evaluating CO_2 Emissions in the Residential Sector: Life Cycle Assessment (LCA) using Regional Forestry Design Models in System Dynamics (SD)

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This study used a sub-model within system dynamics to simulate and quantify CO_2 emissions in the residential sector, focusing on the Nishikawa forestry region in Saitama Prefecture. The model evaluated emissions from the life cycle of houses, including production, transportation, use, maintenance, and disposal. The business as usual (BAU) scenario projects annual new housing inflows. The woody biomass utilization (WBU) scenario showed a 10% carbon reduction over 30 years by replacing new housing with timber construction, despite increased emissions from new constructions. The study highlights the economic benefits of utilizing carbon credits to support reforestation, making it possible to secure the sustainability of regional forestry to supply timber materials to the residential sector.

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INTRODUCTION

The world is facing a serious climate crisis, and fundamental change is urgently needed to prevent irreversible damage (Morris *et al.* 2021). Many industries must reduce their energy use and resulting carbon emissions, as outlined in the Paris Agreement, to limit global warming to below 2 °C by 2100 (Plakitkina *et al.* 2021). The construction industry is a field that plays an important role in carbon generation, emitting 30% of energy-related greenhouse gases and consuming 40% of global energy (UNEP 2020). One of the strategies to minimize the impact of construction on the environment is to use materials that consume less energy and generate less carbon emissions during the building's life cycle (de Serres-Lafontaine *et al.* 2024). Life cycle assessment (LCA) is an internationally recognized method for quantifying the global warming potential (GWP) and other environmental impacts of construction products and can be used to compare wood-based buildings with functionally equivalent non-biobased structures (Morris *et al.* 2021). Along with research on timber structure and materials used in timber construction, research has been conducted on the architectural environment (Kim *et al.* 2014). Research has also been conducted on the life cycle of timber structure buildings, but the number and scale are very small (Arehart *et al.* 2021). In addition, research on LCA including Life Cycle Energy Assessment or Life Cycle Carbon Emissions Assessment has made predictions by defining the inventory to be analyzed, in which the coefficients of emission activities are measured (Chau *et al*. 2015). However, previous LCA analyses have often adopted static data and have lacked time consideration (Beloin-Saint-Pierre *et al*. 2020), causing a problem that few studies performed long-term predictions. In this study, a sub-model that performs LCA of the regional residential sector was attached to a regional forestry model using system dynamics (SD). The strength of SD is that it can simulate the behavior of a system that changes over time. Also, the SD model can construct a timber harvesting scenario, which can be applied to the residential sector (Kaneko *et al*. 2023). From the above, the advantages of SD are: 1) It can dynamically reflect regional timber production, which fluctuates throughout the year, and 2) It enables long-term prediction of carbon balance.

This study utilized a sub-model connected to SD (Stella® model) to simulate and quantify CO_2 emissions in the residential sector based on regional forestry design models. The sub-model employs Life Cycle Assessment (LCA) to calculate emissions throughout the lifecycle of houses, assuming that increased regional log production will boost demand for timber construction. It evaluates both operation and embodied energy, considering emissions from material production, transportation, residential use, maintenance, large-scale renewals, demolition, and disposal. The model focuses on the residential sector in the Nishikawa forestry region, located in Hanno City, Saitama Prefecture. Known for its timber production and local sawmills, Nishikawa supports the assumption of local production for local consumption.

METHODOLOGY

To quantify the impact of outcomes produced by regional forestry design models on the residential sector, we constructed an SD sub-model, which is connected to the base model performing regional forestry scenario planning (Kaneko *et al*. 2023). The base model can simulate forestry scenarios in which operations are sustainably carried out, from planting to harvesting, and predict timber production. Among the forestry operations set up in the model, it is assumed that wood harvested from the second commercial thinning, final cutting, and long-term cutting can be used as building material. The sub-model developed in this study is an LCA model that calculates the CO_2 emissions occurring during the life cycle of each house, under the assumption that an increase in the production of regional logs will expand the demand for timber construction. The sub-model focuses solely on the residential sector of the region and evaluates both operation energy and embodied energy, including carbon dioxide emissions from material production, material transportation, residential use, maintenance, large-scale renewals, demolition, and disposal (Fig. 1). The calculation approach involves understanding the floor area of inflow (construction phase), stock (residential phase), and outflow (demolition phase) of residential buildings in the region and multiplying the amount of carbon dioxide emitted at each stage. For the initial conditions, it is assumed that the age distribution of residential buildings in the region is uniform and all buildings are two-story model houses. During the simulation, all buildings undergo demolition uniformly after reaching 60 years old. The stock of residential buildings S_i(m^2) existing in the region in the i-th year is expressed by Eq. 1.

$$S_i = S_{i-1} + I_{i-1} - \frac{S_{i-1}}{60} \qquad (1)$$

where I_i (m^2) represents the new construction area in the i-th year. The above equation (Eq. 1) can be represented in an SD model by categorizing the term S_i as stock and the other terms as flow. In terms of implementation, the sub-model is added using Stella®'s module functionality, allowing for the immediate response of output results from the regional forestry design model.

To compare the carbon reduction effects, two scenarios were set: Business as Usual (BAU) and Woody Biomass Utilization (WBU). Generally, BAU refers to a scenario where no significant changes are made to the system, and the current dynamics continue. In this case, the scenario assumes that the current demand for housing by structure continues, and the same number of new houses are built each year. On the other hand, WBU assumes the use of regional logs for structural materials in construction and replaces the expandable portion with timber construction, in order of existing reinforced concrete (RC) and steel frame structures, depending on the needs of each. This is because, based on Table 1, the lifecycle emissions per unit area for each structure are calculated as follows: RC is the highest at 2.10 t-CO_2, followed by steel at 1.90 t-CO_2, and timber at 1.28 t-CO_2 (Fig. 2).

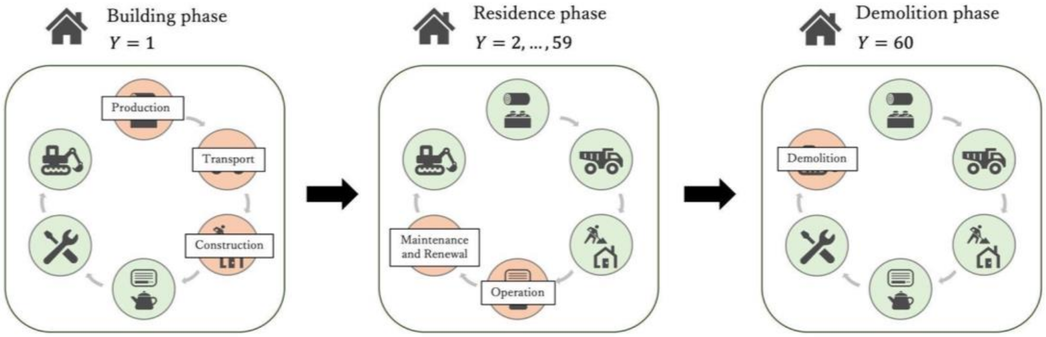


Fig. 1. Housing life cycle and corresponding emission activities

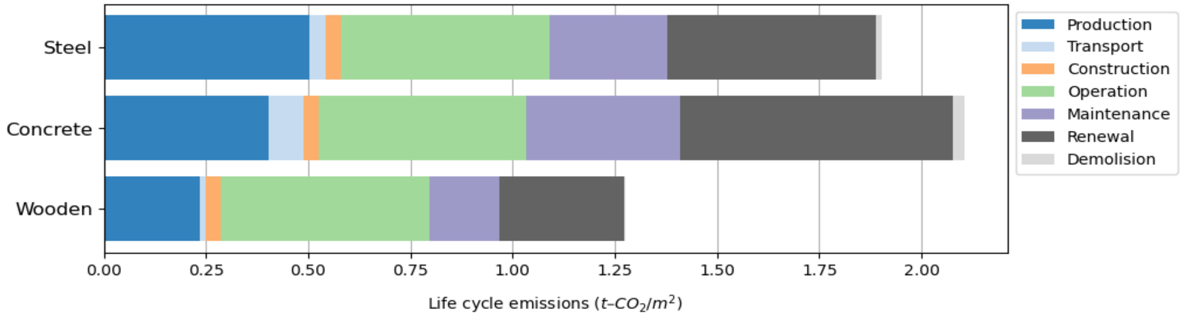


Fig. 2. Breakdown of emissions per unit area of each structure

The amount of timber available as building materials in the i-th year, v_{bi} (m^3), is determined following J-credit, a certification system in Japan for carbon credits, regulations as follows in Eq. 2,

$$v_{bi} = r_s\, r_b\, r_p\, v_{pi} \tag{2}$$

where r_s is the yield from sawtimber to sawmilling, r_b is the building ratio, r_p is the yield from sawmilling to final product, and v_{pi} (m^3) is the log production volume (stem volume) in the i-th year. The values of each coefficient are set as r_s= 0.637, r_b= 0.78, and r_p= 0.9 (J-Credit System Homepage 2023). Note that the use of Japanese cedar plywood is assumed in this study. The volume of timber per unit floor area is set at 0.1537 m^3/m^2, and the area of additional floor space can be calculated from the amount of timber harvested. The simulation period is set to 30 years, aiming for the carbon-neutral target of 2050.

The total emissions from the entire region's timber construction, reinforced concrete, and steel frame structures sector during the period, respectively $W_{emission}$, $C_{emission}$, $S_{emission}$, are expressed as follows.

$$\begin{aligned} W_{emission} &= \sum_{i=1}^{30} \left\{ I_{wi}\,(p_w + t_w + c_w) + S_{wi}\,\left(o_w + m_w + \frac{r_w}{60} + \frac{d_w}{60}\right)\right\} \\ &\quad - W_{storage} \\ C_{emission} &= \sum_{i=1}^{30} \left\{ I_{ci}\,(p_c + t_c + c_c) + S_{ci}\,\left(o_c + m_c + \frac{r_c}{60} + \frac{d_c}{60}\right)\right\} \\ S_{emission} &= \sum_{i=1}^{30} \left\{ I_{si}\,(p_s + t_s + c_s) + S_{si}\,\left(o_s + m_s + \frac{r_s}{60} + \frac{d_s}{60}\right)\right\} \end{aligned} \tag{3}$$

where I_{wi}, I_{ci}, I_{si} are respectively the timber construction, reinforced concrete, and steel frame structures area in the i-th year, S_{wi}, S_{ci}, S_{si} are the total timber, concrete, and steel floor area in the i-th year, and the other coefficients correspond to the abbreviations shown in Table 1. Most of these coefficients are retrieved from Sakai *et al*. (1996), which is still referenced in recent studies (Wang *et al*. 2024). Since the reference article did not provide emissions related to the manufacture of timber structure materials, we calculated it by substituting emissions from cement, a structural material used in concrete construction, for that of plywood. The weight of a timber structure house was calculated based on Shimizu *et al*. (2009), to calculate the carbon dioxide emitted during transportation. Additionally, the amount of carbon stored in all Harvested Wood Products (HWP) is also taken into account. The fixed carbon amount of newly constructed timber structure houses over 30 years $W_{storage}$ can be expressed by the following equation, Eq. 4,

$$W_{storage} = \sum_{i=1}^{30} \frac{44}{12}\, d_w\, v_{bi}\, r_c \tag{4}$$

where, d_w(t/m^3) is the density of timber and r_c is the carbon content of timber, with $d_w =$ 0.33, $r_c = 0.5$. We note that because the simulation period is 30 years in this case, it is not required to consider the carbon dioxide released into the atmosphere when the timber building is demolished 60 years after construction.

The model is applied to the Nishikawa forestry region, which is located in Hanno City in Saitama Prefecture. Nishikawa region is famous for its timber production and also has sawmills within the area, making it conducive to the assumption of local production for local consumption. The initial housing stock consists of 2,883,000 m^2 of timber

Kaneko *et al.* (2024). "CO₂ emissions, LCA," ***BioResources*** 19(4), 7072-7079. 7075

construction, 526,251 m^2 of RC construction, and 126,749 m^2 of steel frame construction. The demand (inflow) in the BAU scenario is estimated to be 14,727 m^2, 5,007 m^2, and 9,720 m^2, respectively. These estimates are based on e-Stat data published from the Japanese government. In addition, it is assumed that there is no exchange of logs outside the region, and the produced logs in the regional forestry scenario are consumed only for additional construction instead of existing demand.

Table 1. List of Emission Coefficients (Sakai *et al.* 1996; Shimizu *et al.* 2009)

Emission Type (kg–C/m^2)	Timber Structure		Reinforced concrete		Steel	
	Abbreviation	Value	Abbreviation	Value	Abbreviation	Value
Production	p_w	64	p_c	137	p_s	110
Transport	t_w	3.8	t_c	10.8	t_s	23.0
Construction	c_w	10.2	c_c	10.2	c_s	10.2
Operation	o_w	2.3	o_c	2.3	o_s	2.3
Maintenance	m_w	0.8	m_c	1.6	m_s	1.4
Renewal	r_w	83.3	r_c	169.6	r_s	150.8
Demolition	d_w	1.2	d_c	7.5	d_s	3.5

* The coefficients for the operation are estimated from materials from the Ministry of Land, Infrastructure, Transport and Tourism and the Ministry of the Environment.

RESULTS

In the WBU scenario, a carbon reduction effect of approximately 200,000 t-CO_2, representing about a 10% reduction compared to the BAU scenario, was achieved over the simulation period. Figure 3 shows the carbon emissions and the storage volume from timber construction by structure over 30 years. The brown dashed lines represent the carbon storage volume, while the colored areas represent the actual emissions by structure. The harvested wood in the forest management scenario can replace all new housing demand with timber construction, resulting in the construction of 29,454 m^2 of solely timber structure houses annually. Therefore, although the emissions increased in timber structure houses in the WBU scenario due to the increase in new constructions, aggregate emissions could stay low because new construction work was not required in other structures. The emissions by stage are summarized in Fig. 4. In all structures, emissions from operation energy, maintenance, and large-scale renewals accounted for the majority. As mentioned earlier, in the WBU scenario, all new constructions over the 30 years were completely replaced with timber structure houses construction. Therefore, the inflow remained constant over the period, and the emissions from the production and transportation of materials accumulated constantly each year. In addition, the total demolition amount in the initial year slightly exceeded the annual new construction demand of 29,454 m^2, at 59,933 m^2/year (calculated as 3,536,000 m^2 divided by 60 years), resulting in a gradual decrease in the overall housing stock in the region over the period. While this demolished area will decrease in the long term in line with the decline in the local housing stock, it can be considered almost constant during the simulation period because its ratio to the total area is small. This does not contradict the assumption that the distribution of building ages is uniform as an initial condition and that houses that reach 60 years old are demolished.

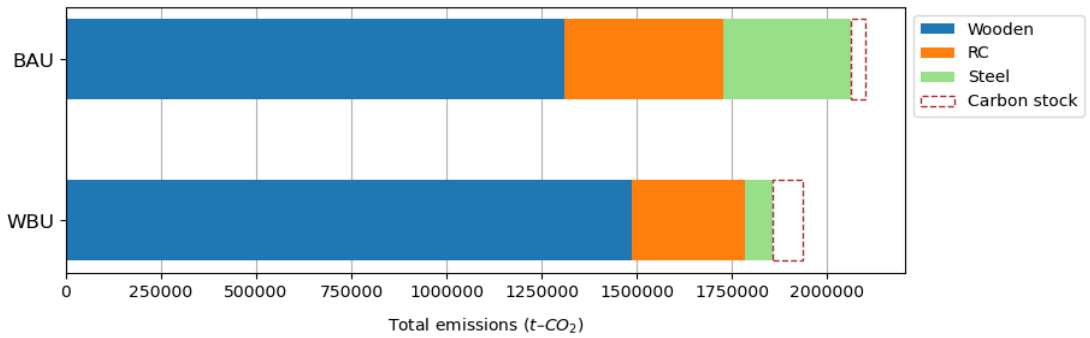
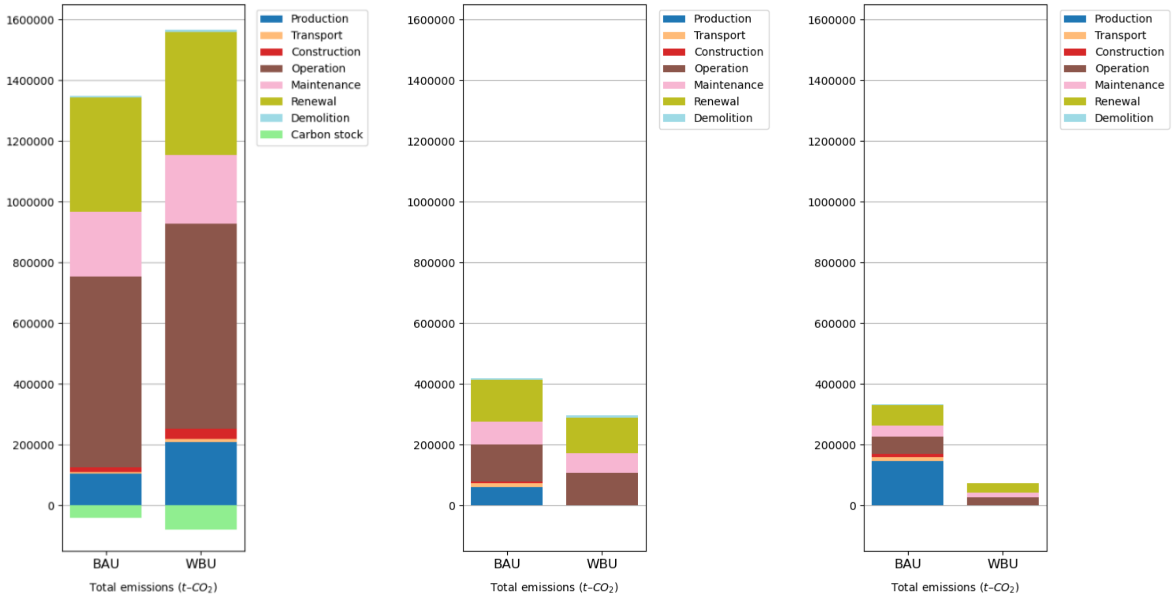


Fig. 3. Total CO_2 emissions over 60 years



(a) Timber structure **(b)** RC (reinforced concrete) **(c)** Steel

Fig. 4. Carbon dioxide emissions balance by structure

DISCUSSION

Although the choice of wooden buildings is becoming more common due to the evolution of engineered wood, the low profitability of the wood production sector is a barrier to raw material procurement in Japan. If the carbon storage quantified in this paper is to be monetized as credits, the following scenarios are conceivable to address the issue. The carbon price in the Tokyo Emissions Trading System in cooperation with Saitama Prefecture is set at 1,000 yen/t-CO_2. If credits are traded based on the reduction from this simulation over a 30-year project period, a profit of 200 million yen would be generated (Arimura 2022). While there is room for discussion regarding the distribution of this profit among project participants—whether to distribute it equally or based on costs—it is assumed that the entire amount can be allocated to the upstream side. One of the economic barriers to forest management is the cost of reforestation. Assuming an initial reforestation cost of 1.8 million yen/ha, the profit obtained could be used to reforest 111 ha. Referring to the results of the regional forest design model, due to the necessity of 410 ha of reforestation in the first 30 years, roughly 30% can be covered by credit profits. It is believed that project composition utilizing these frameworks contributes to the utilization of cyclic forest resources.

Another discussion is the further carbon reduction. Regarding operation energy, which accounts for a large portion of emissions, the construction of efficient heat utilization systems at the regional level is worth noting. While the unused forest biomass was not considered in this simulation, resource utilization is environmentally and economically effective including small timber and logging residue (Yoshioka 2020). Also, reducing the frequency of renewals and substituting for low-carbon materials can increase the reduction in emissions. Even in the case of RC and steel structures, increasing carbon storage by using wooden materials during renewals is possible. In terms of model applicability, expanding the scope of measuring carbon balance within the region, such as by incorporating high-rise buildings into the model, would effectively increase the model's usefulness. Also, presenting multiple scenarios through sensitivity analysis may be useful for policymaking. This includes changing the proportions of the wooden parts of the house. The effectiveness and reality of the model can be increased by incorporating technological trends that support these scenarios and the latest emission coefficients.

CONCLUSIONS

This paper introduced a sub-model that calculates the carbon balance of the regional residential sector, which is incorporated into a system dynamics design model of regional forestry. The advantages of the model are the following. First, it can dynamically feedback the carbon reduction potential of regional timber production to the residential sector. Second, it is possible to predict long-term carbon dioxide emissions. The prediction shows that if regionally produced timber is applied to the residential sector, it is expected to reduce carbon dioxide emissions by about 10% compared to a BAU scenario. The model can quantify carbon dioxide emissions from upstream forestry and downstream residential sectors. This may be useful for local governments that are required to make efforts to achieve carbon neutrality. Specifically, it can be used as a decision-making tool for governments that support timber production and consumption. Future challenges include proposing further emission reduction options by replacing operational energy with carbon-neutral resources derived from wood and any other way. These will make it possible to build a model that comprehensively evaluates the carbon reduction potential of the regional timber industry.

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